
Tchaikazan Valley, Ts'yl-os Provincial Park. Photo: Colin Mahony

Shifting, Novel, and Disappearing Climates

The BC Parks system and the projected climates of the 21st Century

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British Columbia BC Parks

Executive Summary

Climate change is an emerging disruption to British Columbia's protected areas system. It is widely understood that climate change will have profound impacts on ecosystems and ecosystem services. The challenge for BC parks planners and managers is to understand the scope of the problem for the BC Parks system and the idiosyncratic ways that climate change will affect individual parks. This report and its accompanying spatial data provide BC parks planners with an overview of likely 21st-century climatic shifts in the BC parks system.

This report interprets climate change in terms of climate analogs— locations whose climate at some point in time matches the climate of another location at another point in time. Climate analogs are useful for management because they relate abstract climate model output to observable, even familiar, ecosystems. This study presents two distinct approaches to identifying climate analogs. The first approach employs a climatic distance metric to compare the dissimilarity between 20th and 21st century climates. This distance metric is used to detect the emergence of novel climatic conditions at scales ranging from individual parks to North America, to identify locations whose climates are projected to disappear at these various spatial scales over the course of the century. The second approach uses units of the Biogeoclimatic Ecosystem Classification (BEC) as analogs for the future climatic conditions of BC Parks. This second approach essentially interprets climate change as spatial shifts in currently described climate zones.

The results indicate substantial climatic displacement throughout the BC Parks system by mid-century, even under the RCP4.5 scenario of moderate global emissions reductions:

- Turnover in ecosystem climates is already underway. By 2050, essentially none of the climates of the BC Parks will be in their historical climatic zones (i.e., Biogeoclimatic subzones and variants).
- Shifts in climates are not simply uphill and northwards. Some parks will experience the emergence of climates that are novel to the individual park, the BC parks system, or even to North America.
- By mid-century, 75% of the BC parks system is projected to be occupied by climates that are novel to and disappearing from individual park boundaries. Analogs for the climates of the second half of the 21st century will generally be sourced from outside of the boundaries of individual parks. Further, most parks will be unable to provide optimal climatic refugia for all of their current biotic communities.

This report provides a framework for responding to the many challenges of climate change in BC parks. The climate change metrics presented in this report and its accompanying spatial data can be used in the following ways for climate change adaptation planning:

- Biogeoclimatic projections can be interpreted for first-approximation assessments of climate change impacts on a wide range of species, ecosystems, and ecosystem services;
- Locations with disappearing climates are at elevated risk of habitat loss within park boundaries, and are a priority for vulnerability assessments.

- Novel climates at the scale of individual parks indicate locations that are more likely to require migration, and possibly even translocation, of species and population from outside park boundaries.
- Novel climates at the scale of BC or North America are locations where species distribution models and other empirical climate change impact assessments are most likely to be unreliable.

This report supports the following recommendations for BC Parks:

- Incorporate the identified disappearing climates as a risk factor in species-level vulnerability assessments.
- Ensure potential errors due to novel climates are factored into climate change impact assessments that rely on projections of future climates.
- Provide training on the Biogeoclimatic Ecosystem Classification (BEC) to BC parks staff. BEC is a versatile framework for understanding local climates and communicating climate change impacts.
- Expand on the case study framework presented in this report to provide a suite of climate change information for management plans and other planning processes.

Acknowledgements

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Contents

1 Introduction

How will the climates of British Columbia's parks change over the course of the 21st century? How will their ecosystems respond? Park managers increasingly weigh these questions in their management decisions, and find different answers depending on the parks, ecosystems, and human uses they are considering (Scott et al. 2002, Araújo et al. 2011). The complexity of climate change and its ecological impacts can be daunting. Nevertheless, some analytical approaches have emerged over the past two decades that provide traction and tangible ecological insights. The goal of this report and its accompanying spatial data is to provide parks managers with a framework for engaging with questions of climate change at scales ranging from individual species to the entire BC Parks system.

1.1 Study objectives

The primary objective of this project is to provide a suite of information on 21st-century climate change information for BC Parks that can be used in a variety of impact and adaptation assessments. The spatial data that accompany this report are a key outcome of the project and will allow parks managers to assess climate impacts for a variety of spatial scales and management objectives. The purposes of this report are to describe the methods by which the spatial data were developed, summarize the results for the BC Parks system, and demonstrate the interpretation of the spatial data using case studies of individual parks. The Garibaldi parks complex (Garibaldi, Golden Ears, and Pinecone-Burke Provincial Parks and the Mkwal'ts Conservancy) is the primary case study in the main report. Case studies for 8 complexes and 4 individual parks are provided in separate reports accompanying this report.

1.2 Climate analogs

This project interprets climate change through the lens of climate analogs—locations whose climate at some point in time matches the climate of another location at another point in time (Brown and Katz 1995). Climate analogs are a way of relating abstract, quantitative climate change projections to observable ecosystems that we can visualize and learn from. The most common climate analog analysis identifies locations whose current or historical climates are similar to the projected future climate of a location of interest. This approach tells us where a park's future climates are coming from. The corollary approach is also informative: by finding future analogs for historical climates, we can gain insights into where the park's historical climates are going to (Batllori et al. 2017). This place-based view of climate change provides insights into the environmental stressors and migration needs of biotic communities.

1.3 Biogeoclimatic projections

Climate analogs are most informative when they are accompanied by an ecological knowledge base. In this respect, the Biogeoclimatic Ecosystem Classification for British Columbia (BEC; Pojar et al. 1987, Haeussler 2011) is an important asset to ecosystem managers in British Columbia. BEC is a province-wide structured knowledge system that includes, as one of its central pillars, a hierarchical climate classification with 16 zones (Figure 1), ~90 subzones, and ~210 subzone-variants. The full names and descriptions of each biogeoclimatic unit used in this report are available from the BECweb website. The BEC climate classification provides a pool of candidate analogs that are richly embedded with documentation and practitioner knowledge on potential vegetation, wildlife habitat, natural disturbance regimes, and management strategies. As a result, projections of biogeoclimatic units into future periods (Hamann and Wang 2006, Wang et al. 2012) are becoming a widespread tool in climate change adaptation in British Columbia. Biogeoclimatic projections have the potential to become an important tool in the park manager's toolbox. In this study, we use the biogeoclimatic system as a structure for summarizing climate change information and as a pool of climate analogs for future conditions.

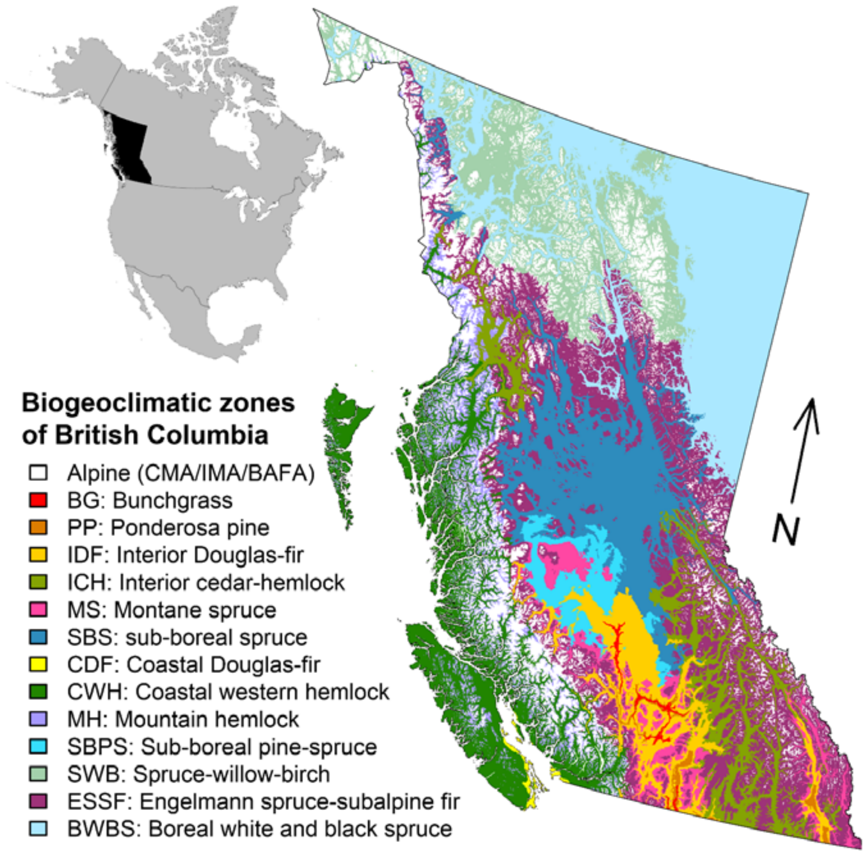

Figure 1: Biogeoclimatic zones of British Columbia, the highest level of the BEC climate classification.

1.4 Novel and disappearing climates

Climate analog analyses face an important problem that some future climatic conditions may not have a good analog amongst the historical climates of the study area (Williams and Jackson 2007). Identification of novel climates is important to climate analog analysis because it avoids putting confidence in climate analogs that are a poor match for future conditions. Novel climates also indicate situations that require climatically suitable biota and management strategies to be sourced from outside an individual park, the parks system, or the province. Detection of novel climates directly in biogeoclimatic projections has not yet been developed (Mahony et al. 2018). Instead, climatic novelty is typically measured as a climatic distance between the projected climate and its closest historical analog (Williams et al. 2007, Mahony et al. 2017). We use this approach to identify novel climates in biogeoclimatic projections.

The corollary of the novel climate measurement—the distance from the historical condition of the location of interest and its best future analog—is called climatic disappearance (Williams et al. 2007).

Disappearing climates are historically present climatic conditions that are projected to be absent from the study area in the future. Novel and disappearing climates have distinct implications for conservation and management. For example, novel climates (often in valley bottoms) are conditions for which predictions based on ecological models are more likely to be wrong, while disappearing climates (often on mountain tops) are conditions whose associated organisms have no climatically suitable habitat in the future (Hamann et al. 2015). Disappearing climates are given substantial consideration in this report because of their concrete implications for *in situ* conservation of biotic communities. We use biogeoclimatic projections and climatic distances as two independent ways of assessing climatic disappearance in the BC park system.

1.5 Climate velocity

Climate velocity (Loarie et al. 2009) is the geographical distance between a location and its analog. Climate velocity indicates the minimum distance an organism must travel to maintain its climatic equilibrium. Climatic velocity can be measured *forwards*—to future analogs for a location's historical climate—or *backwards*—to historical analogs for a location's future climate (Hamann et al. 2015). Forward climate velocity, for example, is the minimum distance an organism has to migrate to find a projected future climate that matches the historical climate to which it is adapted. Geographical distance to the best analog in the novelty and disappearance assessments represent measures of backward and forward velocity, respectively. Climate velocity is provided as supporting information in the case studies for individual protected areas.

1.6 Analog pools

Novel and disappearing climates have distinct implications depending on the spatial scale of the analog search. For example, climates that are novel to an individual park require the migration of populations and species from outside the park, while climates that are novel to North America are conditions for which established ecosystem management strategies might not be available. Climates projected to disappear from the BC Parks protected areas system may be a criteria for strategic acquisition of new protected areas to as climatic refugia. Projected disappearance of a climate type from British Columbia or North America could be the basis for proactive conservation measures for vulnerable species associated with that climate. In this study, we measure novel and disappearing climates relative to four analog pools: Individual parks, the BC Parks system as a whole, British Columbia, and North America. Measuring novelty and disappearance at this broad range of spatial scales will allow BC Parks planners to address specific management concerns as they arise.

1.7 Global emissions scenarios

The spatial data delivered with this project includes novelty and disappearance calculations for each of the RCP4.5 and RCP8.5 scenarios of global anthropogenic greenhouse gas emissions over the 21st century (van Vuuren *et al.* 2011). The RCP4.5 scenario roughly corresponds to a global 2.7^{o}C (2.1-3.2^{o}C) temperature rise by the year 2100, and is consistent with the conditional Intended Nationally Determined Contributions of the Paris Agreement. The RCP8.5 scenario roughly corresponds to a 4.1^{o}C (3.1-4.8^{o}C) warming consistent with an absence of emissions policies (Rogelj *et al.* 2016). In this report, I only present results for the RCP4.5 scenario. The reason for featuring RCP4.5 is that RCP8.5 represents a level of extreme climate disruption and uncertainty for which proactive adaptation is likely to be largely futile. RCP4.5 is a scenario that ecosystem managers must be prepared for; RCP8.5 is a scenario that must be avoided.

1.8 Spatial data deliverables

The spatial data summarized in this report are available in CSV and geoTIFF file format. The following layers are available for all protected areas, parks, ecological reserves and recreation areas in the BC Parks system. The spatial data and analysis in this report currently do not include conservancies. An update to the spatial data to include conservancies will be made available in early 2019.

- Biogeoclimatic projections (375m and 750m resolution):
  - 1980s, 1990s, 2020s, 2050s, 2080s; RCP4.5.
- Climatic novelty, disappearance, and velocity (750m resolution); 96 layers:
  - 4 metrics: Novel and disappearing climates, forward/backward velocity
  - 4 analog pools: single parks, BC Parks system, BC, North America
  - 3 time periods: 2020s, 2050s, 2080s
  - 2 emissions scenarios: RCP4.5 & RCP8.5
- Input data (375m and 750m resolution)
  - Digital Elevation Model
  - Seasonal ClimateBC data: 1980s, 1990s, 2020s, 2050s, 2080s; RCP4.5 & RCP8.5
  - BEC (version 10), Ecoregions, Parks, lakes

2 Methods in brief

There are two complementary types of analysis used in this study: biogeoclimatic projections and climatic distance metrics. The climatic distance metrics (climatic novelty and disappearance) are useful in their own right, but also are an important qualification on biogeoclimatic projections. In particular, climatic novelty indicates locations where the biogeoclimatic projection is not reliable. This section provides an overview of these methods and the terminology used in this study. A comprehensive methodology is provided in Section 6.

2.1 Method 1: Biogeoclimatic projections

A biogeoclimatic projection is made by using the Random Forest machine learning algorithm (Breiman 2001) to quantify the multivariate climate conditions associated with each biogeoclimatic unit. The model is then used to classify new climatic conditions, e.g. across the same landscape another time period, as biogeoclimatic units. In this study, a bioclimatic model was generated by training a Random Forest model on a province-wide 2-km grid of biogeoclimatic units and 1971-2000 climate normals for 36 seasonal climate variables. This province-level model was then used to make biogeoclimatic projections at higher resolutions across the BC Parks system (750m grid) and individual parks (375m grid). Projections were made for five time periods: 1971-2000 (“1980s”), 1981-2010 (“1990s”), 2011-2040 (“2020s”), 2041-2070 (“2050s”), and 2071-2100 (“2080s”).

The term *biogeoclimatic unit*s conventionally refers to the finest level of the BEC climatic hierarchy in any location, which can be the subzone (e.g. CDFmm), subzone-variant (e.g. CWHxm1), or phase (e.g., IDFdk1a). There are >230 BGC units in BC, a level of detail that is not warranted for this study. To simplify the analyses and interpretations in this study, I have generalized the classification to the subzone level in the interior of BC, and the subzone-variant level on the coast (CWH, CDF, and MH zones). For convenience, the resulting 103 map units are called biogeoclimatic units in this report.

2.2 Method 2: Distance-based detection of novel and disappearing climates

Climatic novelty and disappearance are measured in this paper using a multivariate climatic distance between climatic conditions at each location of interest and the best analog for these conditions in the climates of another specific time period. In this scheme:

- **Climatic distances** are measured using a Mahalanobis distance (Mahalanobis 1936) scaled to local interannual climatic variability, as described in Mahony et al. (2017) and illustrated in Figure 2. The climates of different locations are differentiated from each other using six climate variables: seasonal precipitation (PPT) and seasonal mean daily maximum and minimum temperatures (Tmax, Tmin) in the winter (Nov-Dec-Jan) and summer (Jun-Jul-Aug). These variables are standardized relative to each other in terms of local interannual variability, which serves to express climatic differences at scales that are relative to the year-to-year variation in climatic conditions. Mahalanobis distances have no units since each variable in the climate space is standardized to unitless z-scores.
- **Climatic novelty** is the distance from a projected climate to its best historical analog. More specifically, climatic novelty for a given location is the climatic distance from the projected climate of that location to its closest analog in the historical climates of the relevant analog pool. A novelty distance of 1.5 is roughly equivalent to the distance between closely-related BGC subzones in interior BC (Mahony et al. 2018), and is used in this report as a threshold to define novel climates, where necessary.
- **Climatic disappearance** is the distance from a historical climate to its best projected analog. More specifically, climatic disappearance for a given location is the distance from the historical climate of that location to its closest analog in the projected climates of the relevant analog pool. A disappearance distance of 1.5 is used as a threshold to define disappearing climates, where necessary.
- **Historical climates** are the observed climate normals (30-year averages) for the 1971-2000 period, which is referred to in this paper as the “1980s” for convenience. These normals are obtained via ClimateBC from the PRISM climate database, which is derived from climate station observations.
- **Projected climates** are global climate model output for the 2011-2040, 2041-2070, and 2071-2100 periods (“2020s”, “2050s”, and “2080s”, respectively). These normals are obtained via ClimateBC. Each projection is an ensemble mean—the average of separate projections of 15 global climate models. Separate analyses are provided for two emissions scenarios: RCP4.5, which prescribes a progressive reduction of global anthropogenic greenhouse gas emissions from the 2030s to the 2070s; and RCP8.5, which prescribes increasing emissions throughout the 21st century. Only the results for RCP4.5 are summarized in this paper.
- **The analog pool** is the geographical area from which analogs can be selected. Four analog pools are used in the paper: individual parks, the BC Parks system (including National Parks), British

Columbia, and North America. The grid resolution of each of these analog pools is different for computational feasibility: 1.5km, 1.5km, 4km, and 8km, respectively. In case studies of complexes of multiple parks, the term “single park analog pool” refers to the entire complex as a single analog pool.

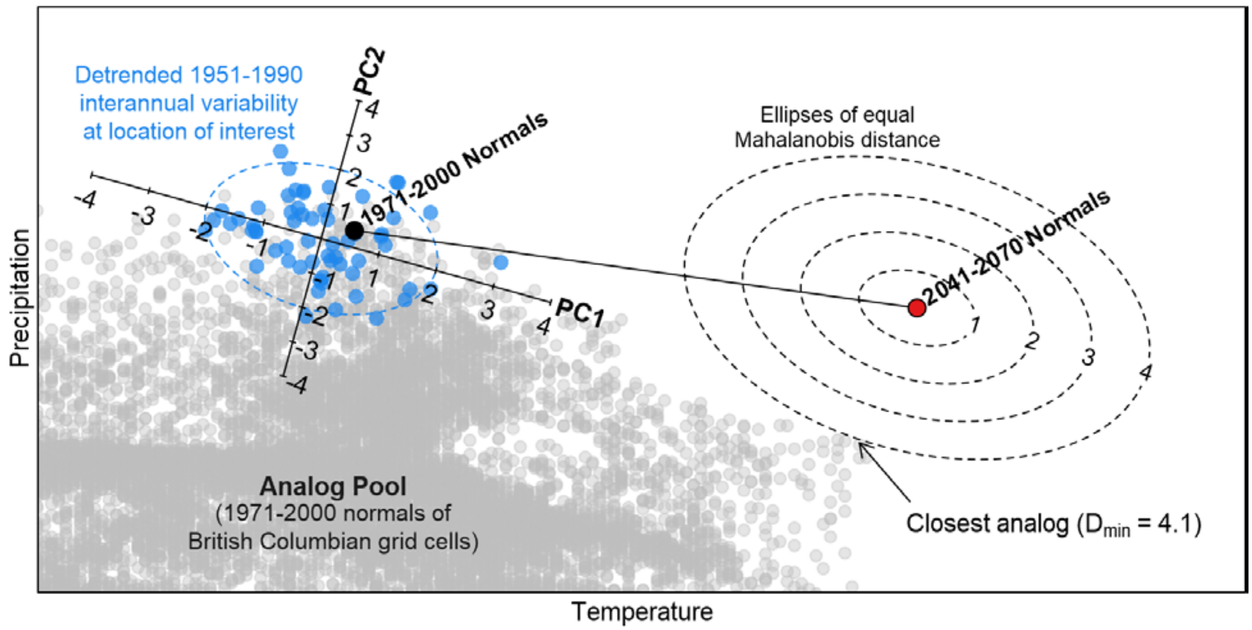

Figure 2: Illustration of the method for measuring climatic novelty and disappearance as distance to the best analog (excerpted from Mahony et al. 2018). In this case, the measurement is of climatic novelty. The local historical interannual climatic variability (blue dots) of a location of interest is used to scale a Mahalanobis distance (dashed ellipses) to identify the closest end-of-20th-century analog (grey dots) for the projected future climate (red dot) of the location of interest.

3 Results

3.1 The shifting climate envelope of the BC Parks system

Shifts in the climate envelope of the BC Parks system illustrate the concept of novel and disappearing climates (Figure 3). Note that the 2-dimensional climate envelope plots presented in this section are not a formal analysis, but an illustration of the concepts used in this study. The distance measurements and biogeoclimatic projections presented in subsequent sections are done in many more dimensions (6 and 36, respectively), to capture the many aspects of climate that make one location different from another. Since it is impossible to visualize a 6- or 36-dimensional climate envelope, the 2-dimensional plots are simply a visual aid, rather than an analysis in themselves.

A climate envelope is the range of climatic conditions, measured in any number of climate variables, occupied by a spatial unit such as a continent, jurisdiction, study area, or species range. Figure 3a shows the winter temperature-precipitation climate envelope of the BC Parks system situated within the larger climate envelopes of British Columbia and North America. The BC Parks envelope overlaps with much of the BC envelope, suggesting that the BC Parks system is generally representative of the climatic diversity of the province.

Climate change causes the winter climate envelope of the BC Parks system to shift into warmer and wetter conditions (Figure 3b). The leading edge of the shifting climate envelope moves into novel climatic conditions that are not represented in the historical climates of BC and the BC Parks system. Most of these locally novel climates overlap with the climate envelope of North America, and so are not novel at the continental scale. However, the projected climates of the temperate rainforest (top right of the BC Parks climate envelope) are conditions that are poorly represented even at the scale of North America. This illustrates that climatic novelty must be understood relative to a specified analog pool (e.g. BC vs. North America) and historical time period (in this case, the 1971-2000 average—the "1980s").

Converse to the emergence of novel climates at the leading edge of the climate envelope, there are climatic conditions at the trailing edge that are left behind by the shift in the BC Parks climate envelope. These are the so-called disappearing climates: historical conditions that cease to be present in the BC Parks system. The similarity of the BC Parks and BC climate envelopes suggests that climates projected to disappear from BC Parks will also disappear from BC. However, the degree to which the climates of BC Parks disappear at the continental scale is unclear from this two-dimensional representation of climate envelopes, and requires the higher-dimensional distance measurement presented below.

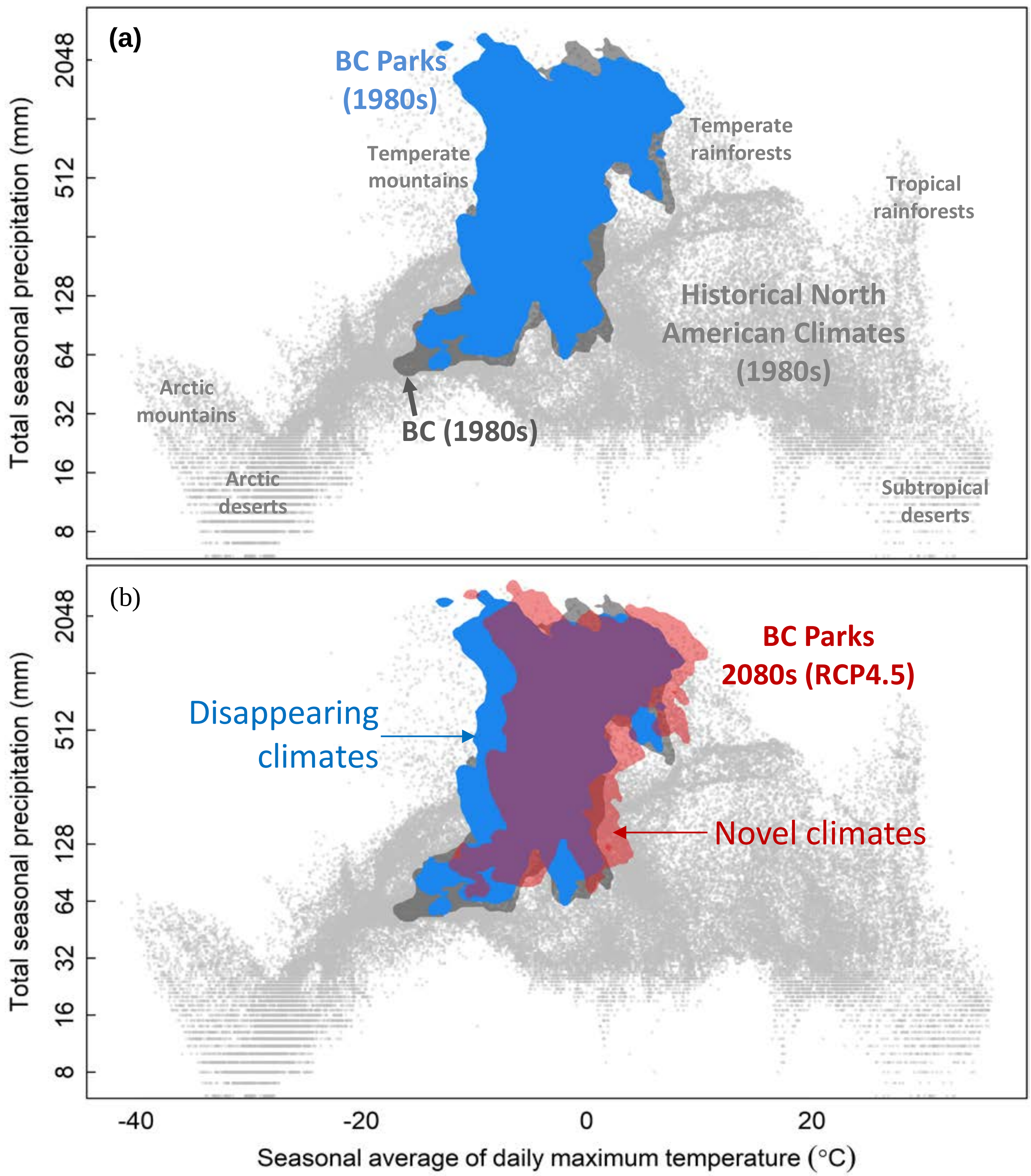

Figure 3: The shifting climate envelope of the BC Parks system, in terms of winter temperature and precipitation. (a) The historical BC Parks climate envelope of the 1980s (blue polygon) largely overlaps with that of BC (grey polygon). (b) The leading edge of the projected future BC Parks climate envelope of the 2080s (red polygon) includes conditions that are novel to the parks system, BC, and North America. The trailing edge of the BC Parks climate envelope includes disappearing climates that are not represented in the projected future climates of the parks system and BC.

Novel and disappearing climates can also be relevant at the scale of individual parks and parks complexes. Figure 4 shows shifts in the summer and winter climate envelopes of Tashish Kwois Provincial Park and the Garibaldi Parks Complex, which comprises Garibaldi, Golden Ears, and Pinecone-

Burke Provincial Parks and the Mkwal'ts Conservancy. The Garibaldi Parks complex is geographically large, highly topographically diverse and spans the coast-interior transition. Consequently, it has a large climate envelope that provides climate analogs for many of its projected climatic conditions. Nevertheless, some of the novel climates of this park are also outside the historical BC climate envelope, and therefore novel to BC. Further, the high alpine climates at the trailing edge of the shifting climate envelope appear susceptible to disappearance at the Provincial and even North American scales.

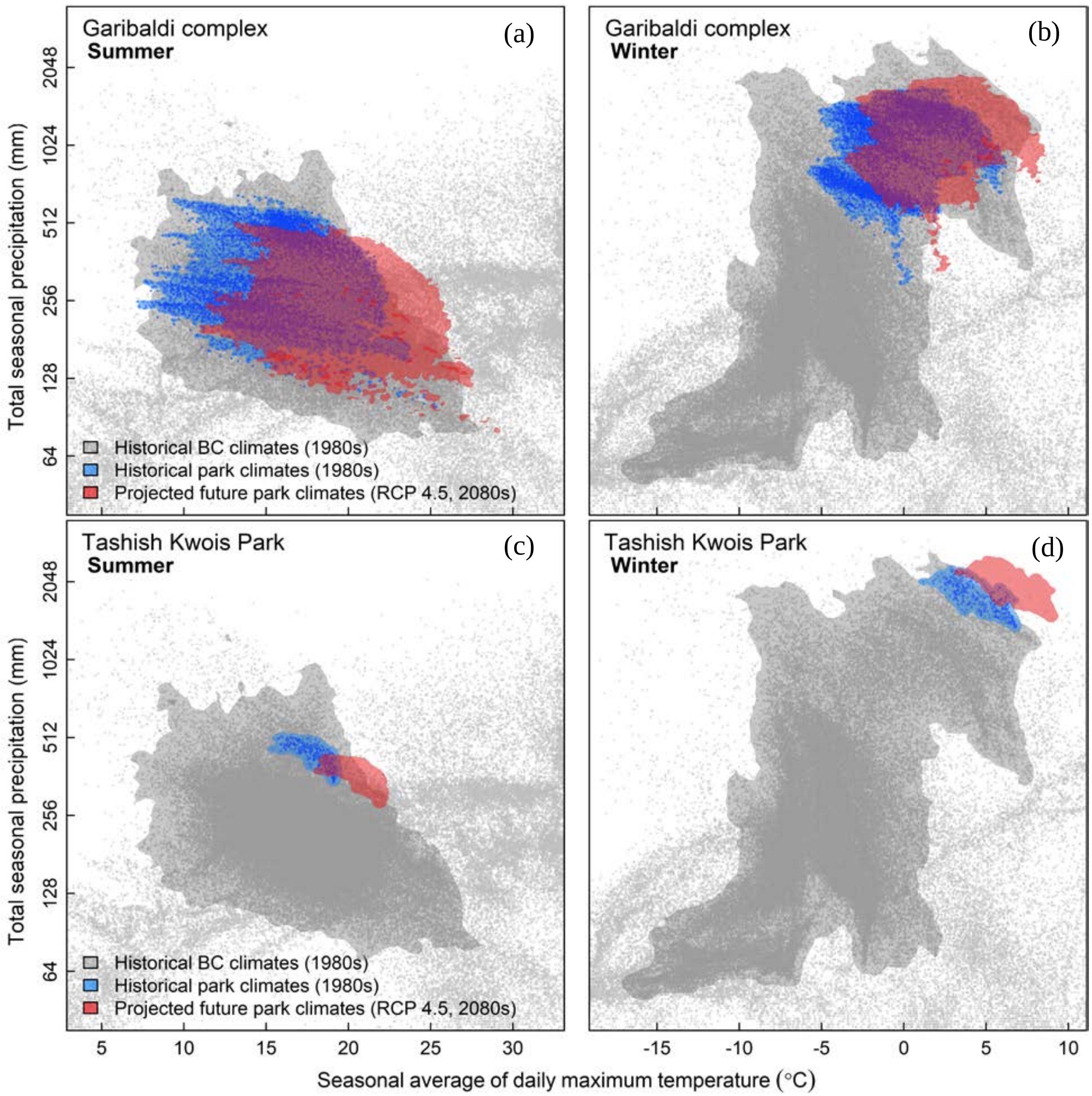

Figure 4: The shifting climate envelope of individual parks: the Garibaldi parks complex (a,b) and Tashish Kwois Provincial Park (c,d) in summer (a,c) and winter (b,d). The historical (1980s) climate envelope of North America (grey dots) and BC (grey polygon) are shown for reference. The blue polygon indicates the historical (1980s) climate envelope of the park, and the red polygon indicates the climate envelope of the RCP4.5 ensemble mean projection for the 2080s.

In contrast to the Garibaldi Parks complex, Tashish Kwois Provincial Park is a medium-sized park with only moderate topographic diversity. As a result, the projected climate change over the 21st century induces a nearly complete displacement of the historical and projected climate envelopes of this park. The current climates of the park mostly disappear from its boundaries, and the future climates are mostly novel to the park. From the perspective of larger analog pools, the summer climates of Tashish Kwois Park appear to have analogs in British Columbia. However, the projected winter climates are mostly novel to British Columbia, and appear to be poorly represented even in the North American analog pool.

The two-dimensional representations of climate envelope shifts presented in this section help to illustrate the concepts of novel and disappearing climates. In particular, they demonstrate how the analog pool is essential context for interpreting novelty and disappearance. However, 2-dimensional climates are not sufficient to detect novelty and disappearance in spatially explicit way. The next section is a description of a formal assessment of novelty and disappearance using a higher-dimensional representation of climate.

3.2 Distance-based detection of novel and disappearing climates

Novel and disappearing climates are found in distinct regions of British Columbia (Figure 5). Under RCP4.5, climates novel to British Columbia emerge by mid-century in the Chilcotin Plateau, northeastern BC, the north coast, and the major valley-bottoms of the southern interior and south coast (Figure 5a). Expanding the analog search to all of North America substantially reduces novelty in Northeast BC, the Chilcotin Plateau (Central BC), and Rocky Mountain Trench (Southeast BC) (Figure 5c). However, the pattern and magnitude of novel climates on the coast and the southern interior is similar for the BC and North American analog pools, indicating the emergence of continental-scale climatic novelty in these locations.

Climates projected to disappear from British Columbia by mid-century are primarily located in Northern BC, the Chilcotin plateau, the hypermaritime areas of the North Coast, and the Georgia Basin (Figure 5b). Expanding the analog search to North America substantially reduces climatic disappearance in Northeastern BC, but not in the other regions. It is notable that several regions show high levels of both novelty and disappearance at the BC and North American analog pools. This emphasizes that these two metrics, despite being analytical opposites, do not necessarily produce corollary spatial patterns.

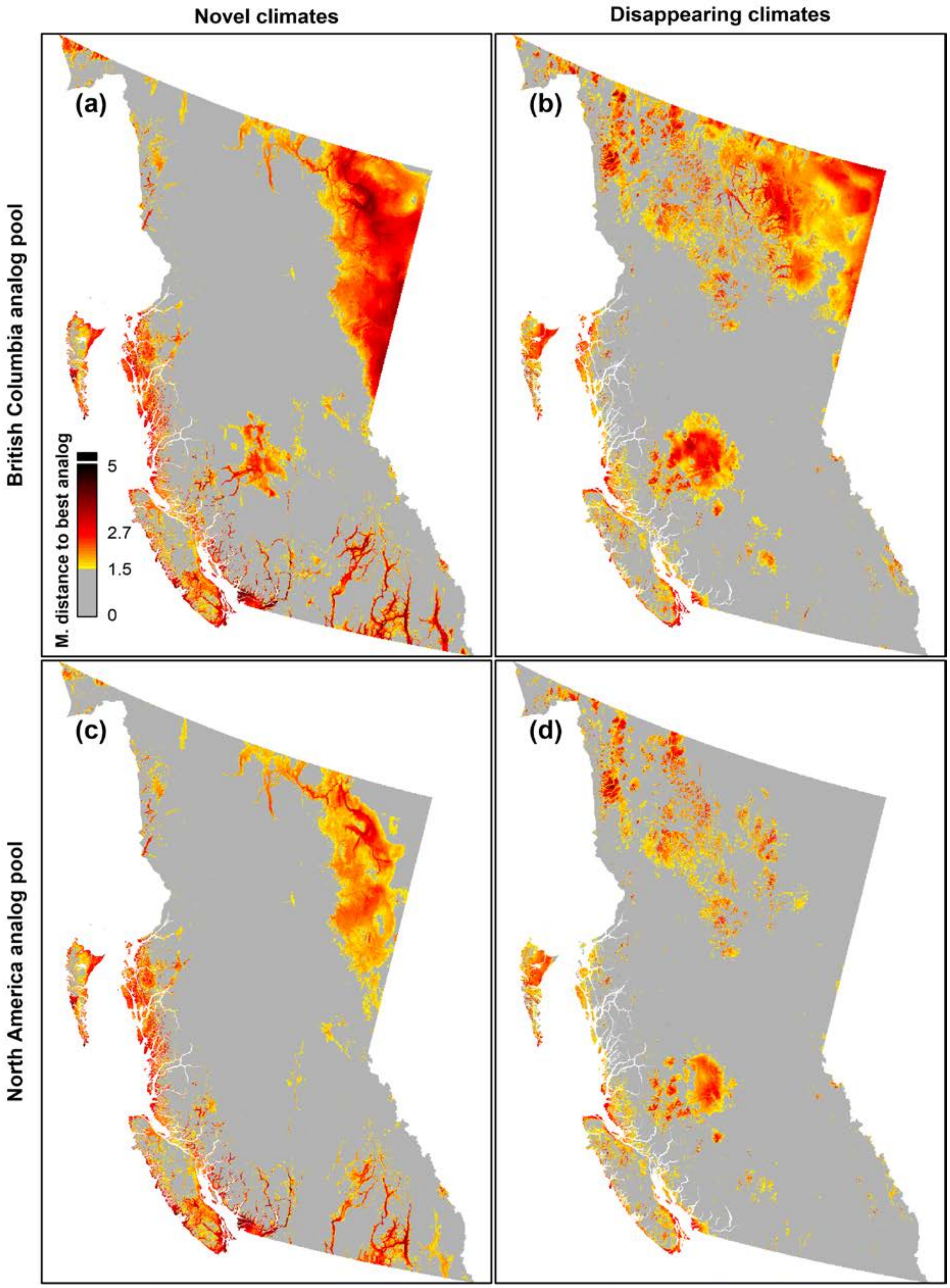

Figure 5: Projected novel (a,c) and disappearing (b,d) climates of British Columbia, relative to the (a,b) British Columbian and (c,d) North American analog pools. The climate change projection is the RCP4.5 ensemble mean for the 2041-2070 period.

The Garibaldi parks complex provides a good scale to investigate the effect of different analog pools on climatic novelty and disappearance (Figure 6 and Figure 7). Highly locally novel climates, i.e. relative to the analog pool of the park itself, are projected to emerge in many of the valley bottoms of the Garibaldi parks complex by the end of the century (Figure 6a). The emergence of novel climates at low elevations is expected, since these are areas without downhill analogs for their warming climates. However, locally novel climates are projected along the midslopes but not the valley bottoms in the northwestern portion of Garibaldi Park. The reason for this unexpected pattern is unclear, but it may be associated with persistent atmospheric inversions in this area. Expanding the analog pool (Figure 6b-d) substantially reduces the degree of novelty, though the spatial pattern largely remains.

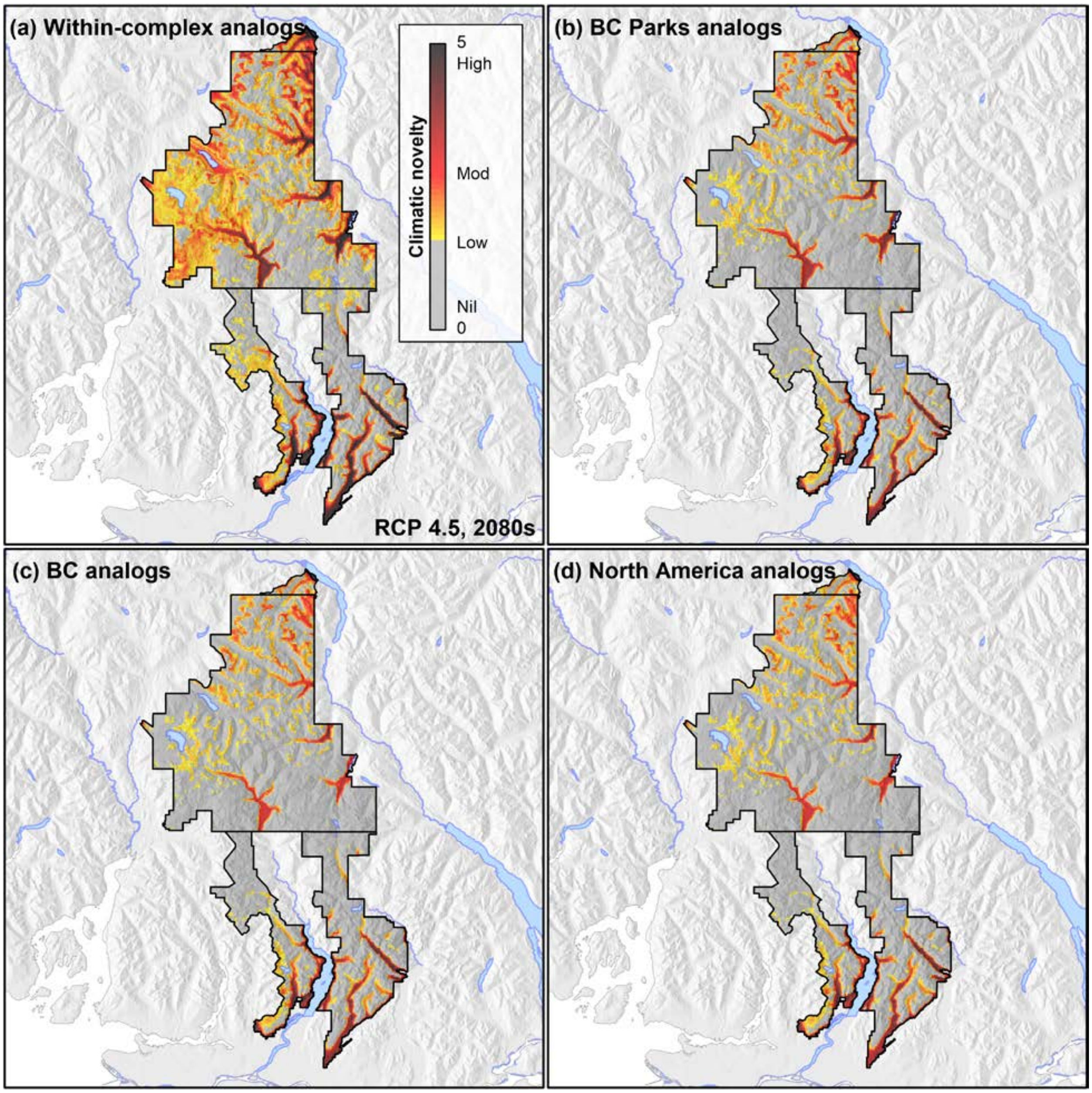

Figure 6: Projected climatic novelty in the Garibaldi Parks complex relative to the four analog pools: (a) the climates of the parks complex only, (b) the entire BC Parks system, (c) British Columbia, and (d) North America. The climate change projection is the RCP4.5 ensemble mean for the 2071-2100 period.

Climates projected to disappear from the Garibaldi parks complex by end-of-century are primarily located at higher elevations (Figure 7a). The strong association between elevation and local climatic disappearance is expected since uphill climate analogs are required to maintain climatic equilibrium in a warming climate. Several climates of the Garibaldi complex are projected to disappear from the BC Parks system (Figure 7b) but not from British Columbia or North America (Figure 7c-d).

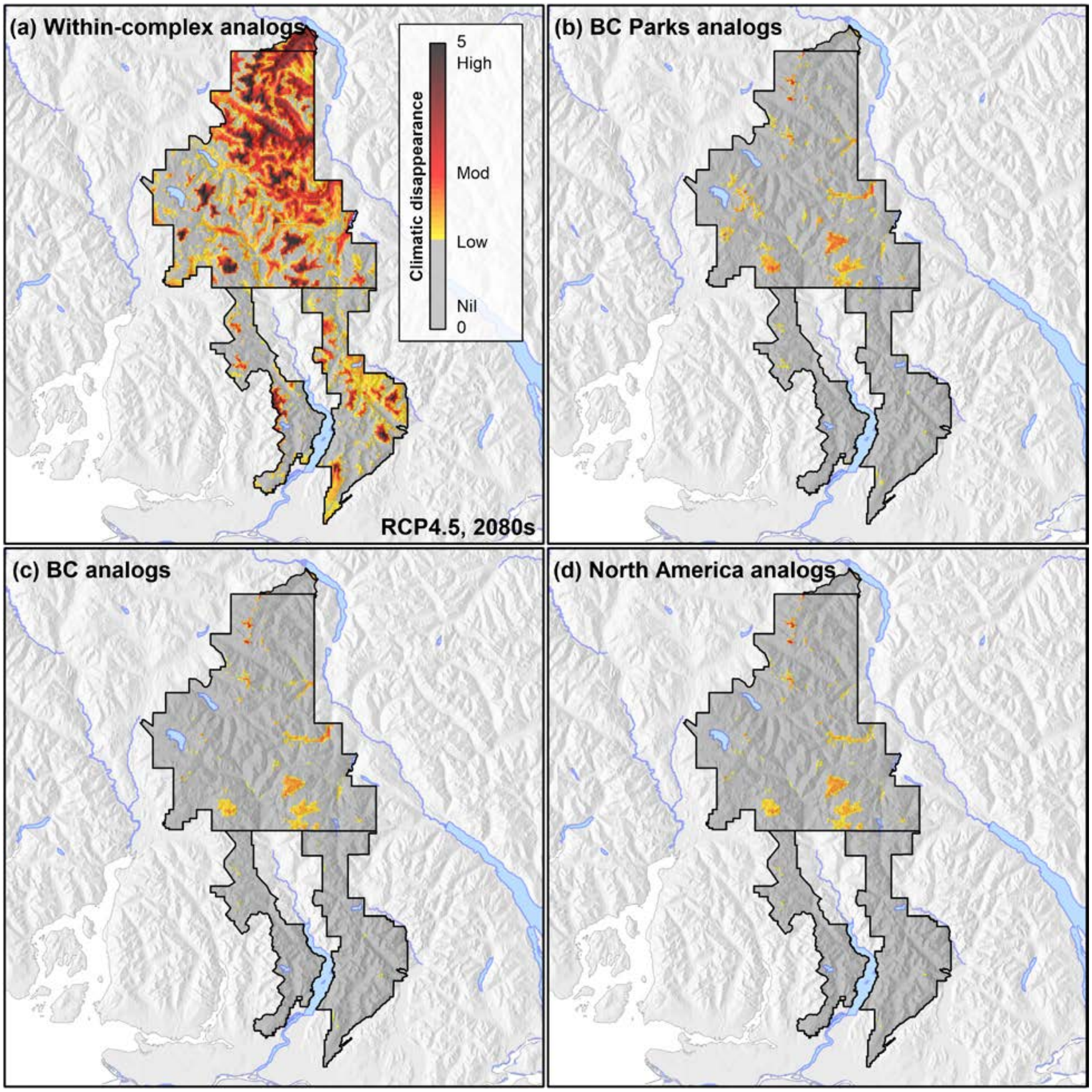

Figure 7: Projected climatic disappearance in the Garibaldi Parks complex relative to the four analog pools: (a) the climates of the parks complex only, (b) the entire BC Parks system, (c) British Columbia, and (d) North America. The climate change projection is the RCP4.5 ensemble mean for the 2071-2100 period.

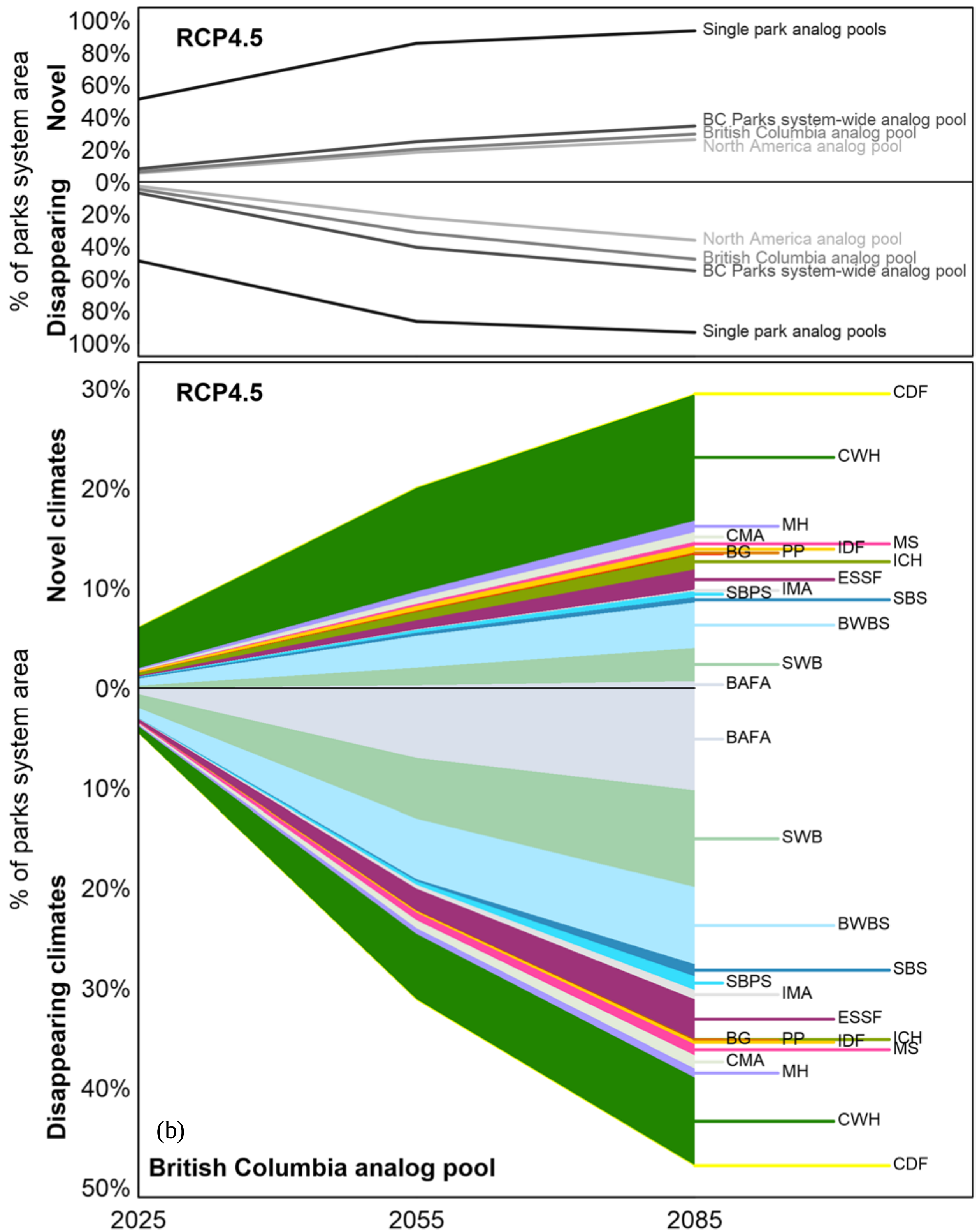

Figure 8: Projected increase in novel and disappearing climates within the BC Parks system over the 21st century, under the RCP4.5 ensemble mean. (a) Total percentage of parks system area in novel and disappearing climatic condition relative to each of the four analog pools. (b) The currently mapped biogeoclimatic zone in which the novel and disappearing climates relative to the BC analog pool are located.

Figure 8 summarizes the projections of novel and disappearing climates across the BC Parks system. With respect to single-park analog pools, novel and disappearing climates each occupy approximately one-third of the BC Parks system in the 2020s. This proportion increases to approximately 75% by the 2050s, and 88% by the 2080s. Novel and disappearing climates are not as extensive with respect to larger analog pools but do occupy a substantial portion of the BC Parks system by the end of the century. The area of disappearing climates is approximately double the area of novel climates in all time periods and in all analog pools except for the single park analog pools (Figure 8a). This is a result of the expansive areas of disappearing climates in Northern BC (BAFA, SWB, BWBS, and (non-exclusively) ESSF zones), which are not mirrored by similarly extensive areas of novel climates in Southern BC. Several other zones, particularly the CWH, ICH, and IDF, show an opposite pattern of novel climates exceeding the occurrence of disappearing climates (Figure 8b).

Individual BEC zones within the BC Parks system have diverse patterns of novel and disappearing climates (Figure 9). As would be expected, the alpine zones are strongly skewed towards disappearing climates over novel climates, though the CMA has approximately equal amounts of each. The BAFA zone (Northern BC) has much higher rates of disappearing climates than the IMA zone (Southern Interior) and CMA zone even with a North American analog pool. Several zones are not strongly sensitive to the analog pool; namely the CDF, CWH, ICH, PP, and the alpine zones. For the other zones, however, the analog pool is an important factor in the extent of novel and disappearing climates. Novel climates only emerge in the SBPS, for example, with respect to the BC Parks and BC analog pools and are absent when the North American analog pool is available. The discrepancy between the BC Parks and BC analog pools with respect to disappearing climates in the SWB, BWBS, and SBPS zones suggests that there are future climatic refugia for the current inhabitants of these zones that are not represented in the BC Parks system. The discrepancy between the BC Parks and BC analog pools with respect to novel climates in the SBPS and BG zones suggests that ecologically suitable biotic communities for these zones within BC Parks will be sourced from outside the BC Parks system.

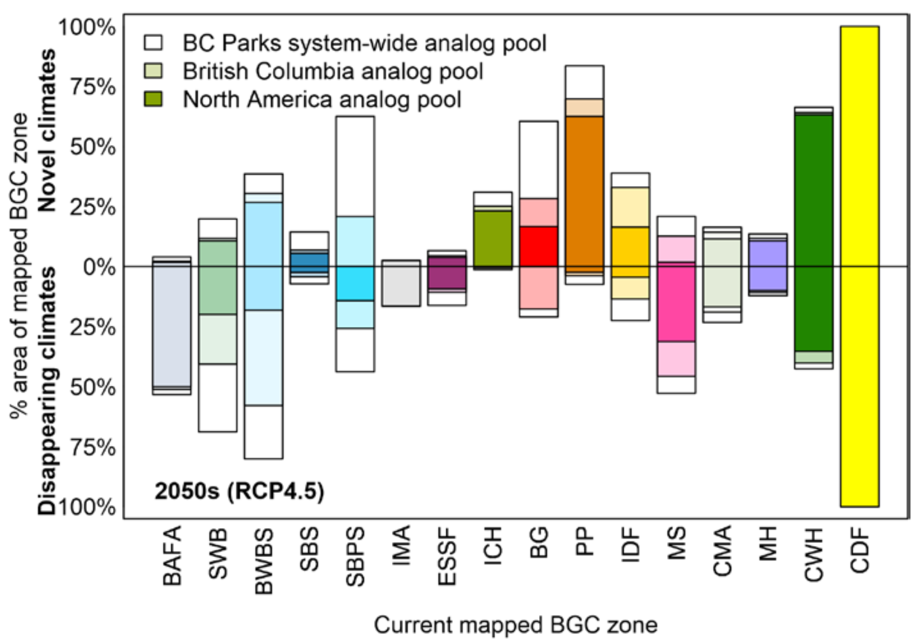

Figure 9: The projected proportion of each BGC zone occupied by novel & disappearing climates in the 2050s

Summarizing novel and disappearing climates at the scale of the biogeoclimatic subzones/variants provides additional resolution on the climate types within the BC Parks system that are most affected (Figure 10). This plot indicates, for example that the IDFdw—the valley-bottom climate of the southwest Chilcotin Ranges—is an outlier amongst IDF subzones for climates projected to disappear from the BC Parks system by mid-century.

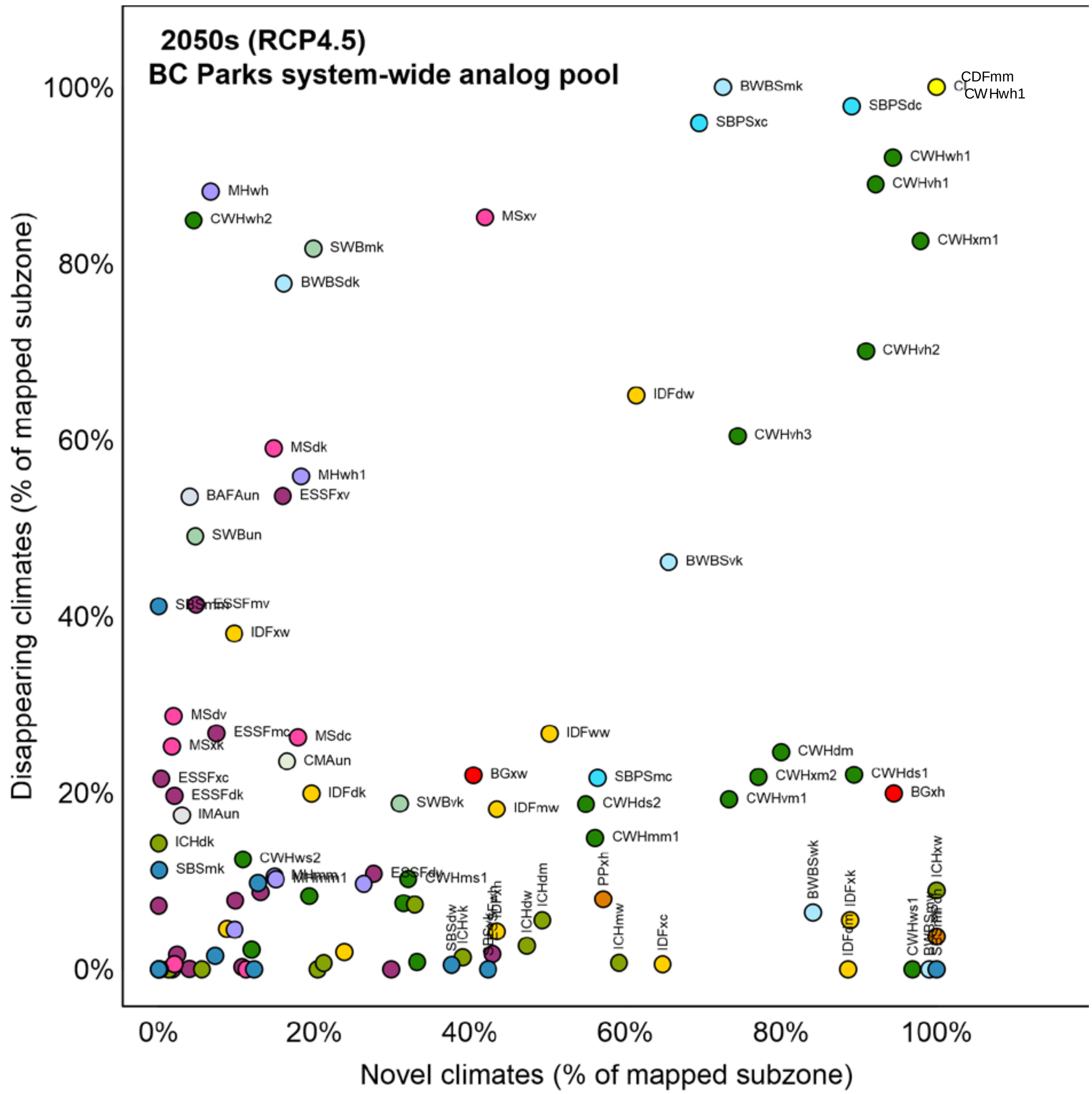

Figure 10: the projected proportion of each BGC subzone (Interior BC) or subzone-variant (Coastal BC) occupied by novel and disappearing climates in the 2041-2070 period. Results for the BC Parks system analog pool are shown.

3.3 Biogeoclimatic unit projections

This section presents biogeoclimatic unit projections for two protected areas, the Garibaldi parks complex and Ts'yl-os Provincial Park. The purpose of these two case studies is to show contrasting outlooks for climatic shifts within BC parks. Garibaldi is projected to undergo uphill shifts in its 20th-century climate types. Ts'yl-os, in contrast, undergoes an almost complete substitution of its native climates with climate types currently found outside its boundaries. Novel climates are extensive in Garibaldi but are minimal in Ts'yl-os. The descriptions of these case studies also are designed to assist readers with interpretations of the other case studies provided as appendices and the spatial data for the entire parks system that accompanies this report.

Biogeoclimatic projections for the Garibaldi parks complex are shown in Figure 11. The prediction for the 1980s (Figure 11b) serves an important role in this analysis as a baseline for detection of climate change. Minor discrepancies between the prediction for the 1980s (Figure 11b) and the training data (Figure 11a) are expected because the model is trained at a provincial level using a small subset of the map gridpoints. Indeed, certain discrepancies provide a form of qualitative validation against overfitting if they have a climatic logic. The substitution of CWHds1 for CWHvm1 at the head of the Pitt Valley in southern Garibaldi Park, for example, indicates that the model is not simply copying the spatial distribution of the CWHvm1 via overfitting. Instead, the model is describing the particular local climate of this maritime-submaritime transition zone by providing a submaritime valley-bottom equivalent to the CWHvm1. Another discrepancy is the substitution of ESSFmw for MHmm2 on the southern aspects of central Garibaldi Park (e.g., the Cheakamus Valley). The climatic nuances that produce these small occurrences of the ESSFmw—which are geographically isolated from the rest of the unit—are unlikely to be reflected in the climate data used for model training. These examples illustrate that some discrepancies to the BEC mapping are expected even in the absence of climate change, simply due to the translation of the BEC map into a bioclimatic model. For this reason, projected climate changes are best detected by comparison to the model prediction for the 1980s rather than the original BEC map.

The projected climate changes over the 21st century in the Garibaldi parks complex (Figure 11d-f) are primarily an uphill shift of biogeoclimatic units that are historically present in the protected area. This uphill shift occurs at the expense of the CMA zone, which shrinks from 1843 km^2 to 329 km^2 over the course of the century. The uphill expansion of the CWHvm1 is dramatic: as early as the 2050s, the CWHvm1 expands into the lower reaches of what is now the MHmm1 in Golden Ears and Pinecone-Burke parks. The expansion of the CWHds1 and CWHvm1 into the valleys of the northern and southern portions of the parks complex, respectively, is accompanied by the emergence of highly novel climates in their wake. The MHmm1 retains most of its size via uphill expansion. However, the MHmm2 shrinks to less than 10% of its currently mapped distribution, and is replaced with a moderately novel subalpine climate that is not currently described by the BEC system. Moderately novel climates also emerge in currently alpine areas surrounding Garibaldi Lake. Exotic BGC units (the CWHxm2/mm1/mm2, which currently occur on eastern Vancouver Island) are limited to approximately 2% of the parks complex. Climate change in the Garibaldi Parks complex is characterized by uphill expansion of native BGC units by 1-2 BGC variants, plus the extensive emergence of climates that are novel to BC in the valley bottoms, subalpine, and alpine areas.

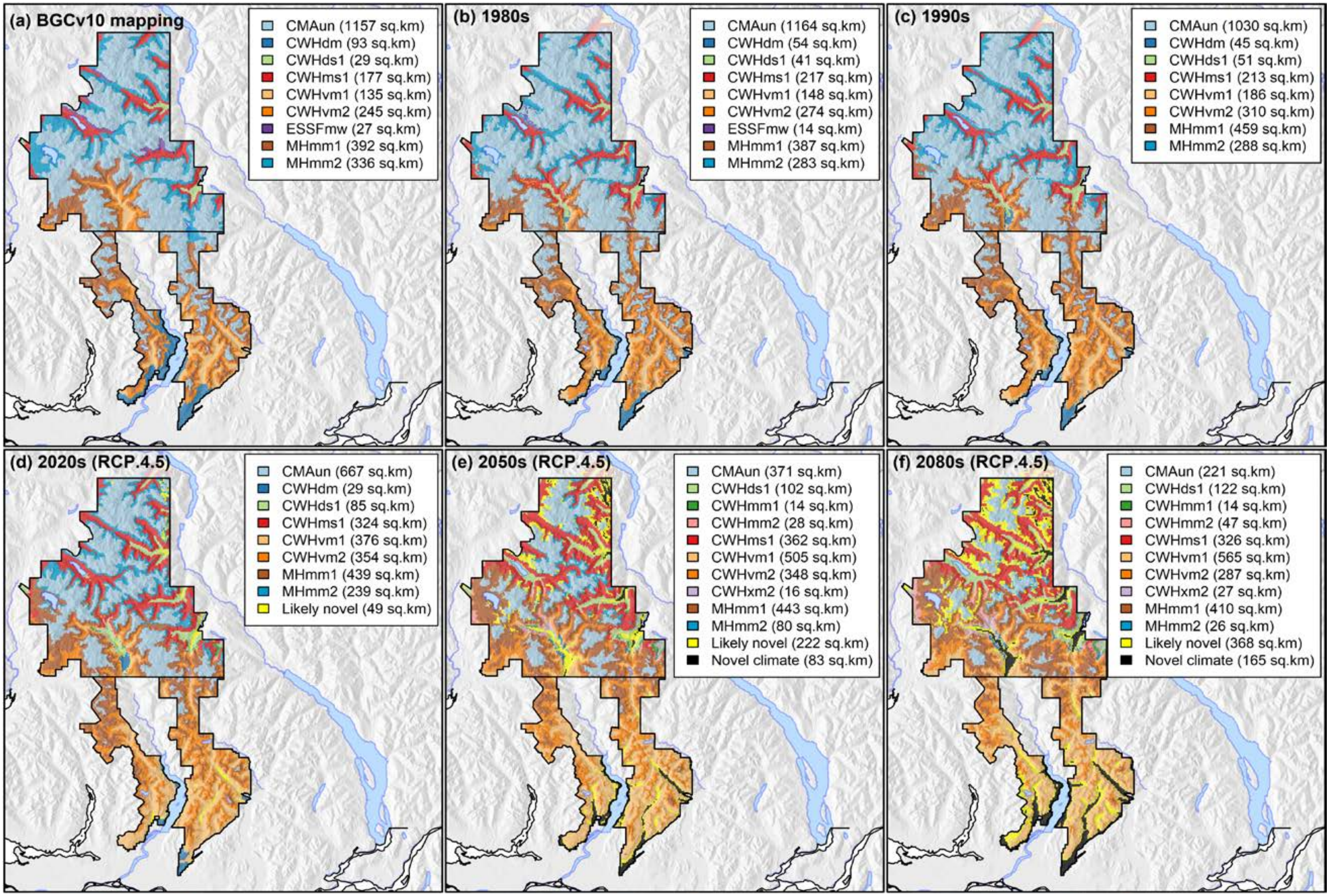

Figure 11: 21st-century Biogeoclimatic unit projections for the Garibaldi parks complex, using the RCP4.5 ensemble mean. The bioclimatic model is trained on current BGC mapping (a) across British Columbia and climate variables for the 1970-2000 period (“1980s”). The model prediction for the 1980s (b) provides a baseline for comparison to other time periods (c-f). “Likely novel” and “novel” correspond to climatic distances of 1.5 and 2.7.

The 21st century climatic shifts projected for the Garibaldi parks complex can be summarized graphically in terms of the degree of spatial displacement of each unit (percentage of 1980s area unchanged) and the change in total area of each unit within the protected area (Figure 12). The 1990s shows minor changes relative to the 1980s, with the exception of the loss of the ESSFmw. By the 2020s, the CWHvm2, MHmm1, and MHmm2 have been displaced from more than two-thirds of their original spatial distribution but their total area remains the same, indicating an uphill shift. By the 2080s, the CWHvm2, CWHms1, MHmm1, and MHmm2 have been completely displaced from their original locations. Further, the majority of the projected climates classified in the biogeoclimatic projection as MHmm2 are detected as novel climates by the distance-based novelty measurement. The CWHvm1 and CWHds1 expand their area fourfold while retaining a majority of their original area. However, a large minority of this projected area is detected as novel, and therefore the persistence of these units in their original locations should be viewed as an artefact of climatic novelty rather than a lack of change.

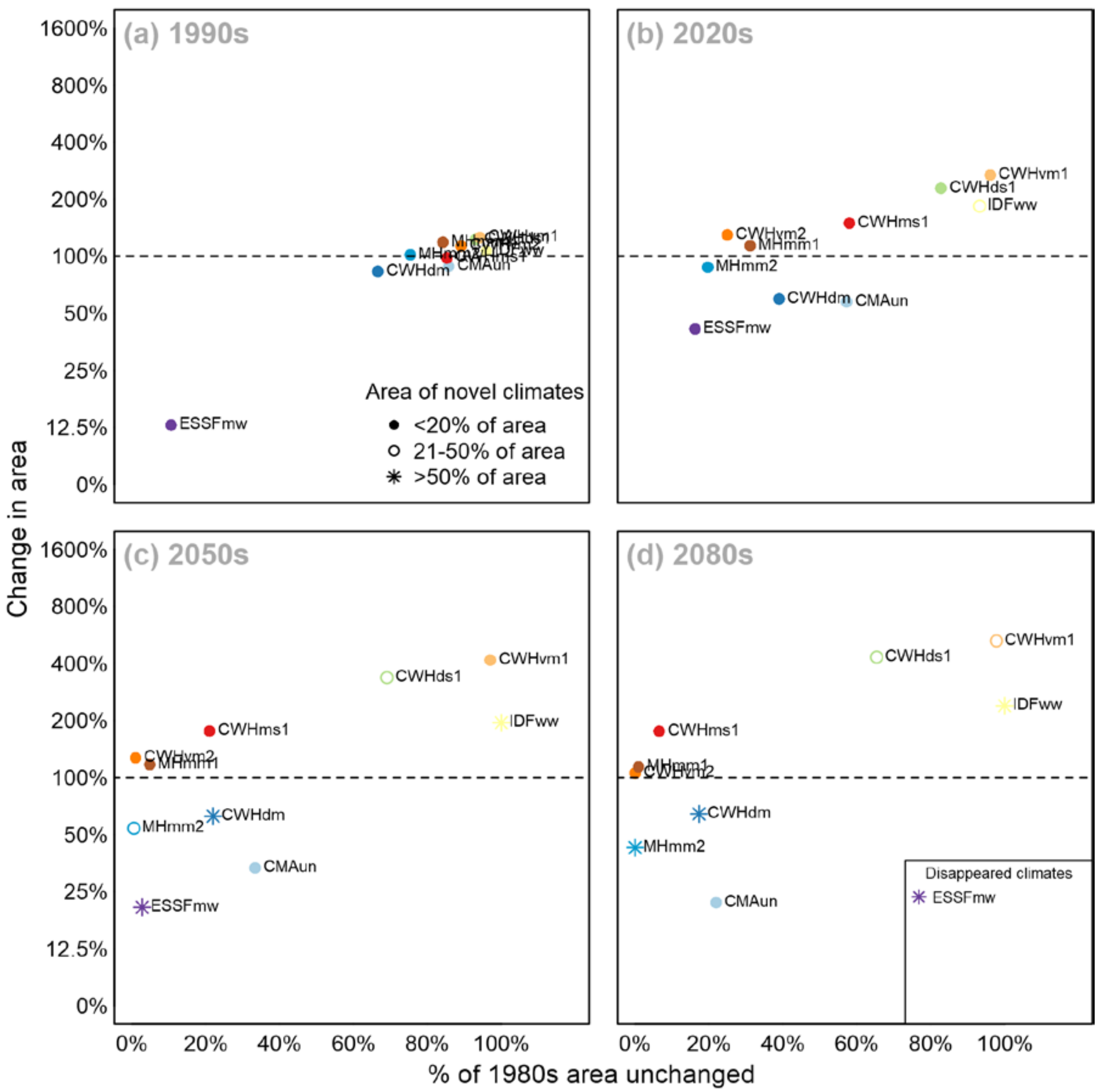

Figure 12: Shifts in the spatial distribution and relative area of the biogeoclimatic units of the Garibaldi parks complex, relative to their predicted distribution in the 1970-2000 period (“1980s”).

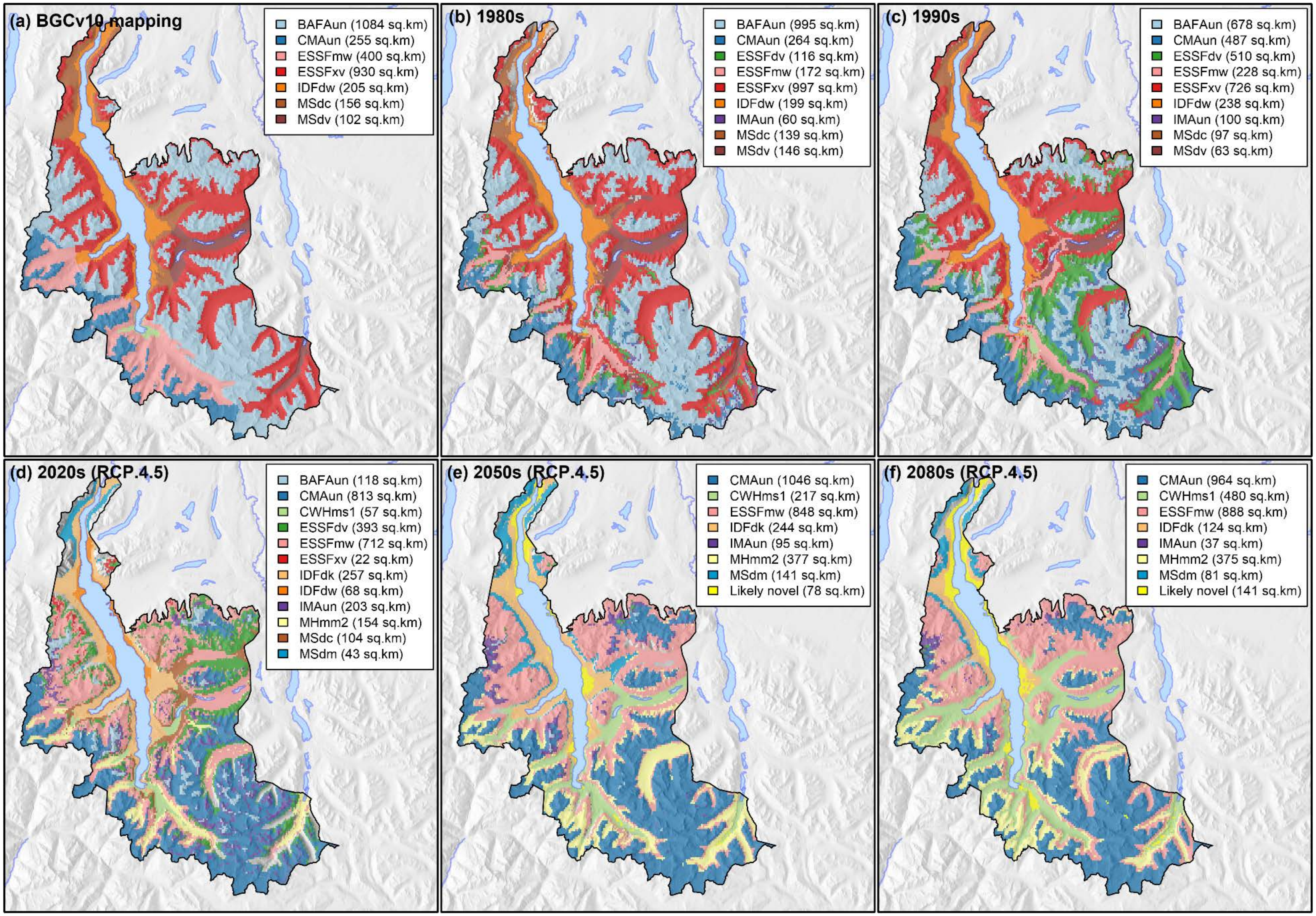

Figure 13: 21st-century Biogeoclimatic unit projections for Ts'yl-os Provincial Park, using the RCP4.5 ensemble mean.

The nature of the climatic shifts projected for Ts'yl-os Provincial Park (Figure 13) are very different from those of the Garibaldi parks complex. By the 2050s, uphill shifts of endemic climate types do occur, such as the large shift of the ESSFmw from the western valley bottoms into the subalpine and alpine positions both east and west of Chilco Lake. However, most of the park is projected to take on the character of exotic biogeoclimatic units, such as the substitution of ESSFxv for the MHmm2 in the southeast valley bottoms (e.g., the Tchaikazan valley), CWHms1 for MSdv in the Yohetta valley, and IDFdk for IDFdw on the shores of Chilco Lake. Very little novelty is evident in the projected climates. The influx of CWH and MH units, as well as the complete substitution of BAFA for CMA in the high alpine, suggests a shift towards a more coastal "flavor" of climate in this park. Further, the combination of coastal and interior units results in unusual elevational sequences of biogeoclimatic units. While these climate shifts may seem unlikely to some observers, the lack of novelty detected in these projected climates supports the credibility of the biogeoclimatic unit projections.

Figure 14 summarizes the climate shifts across the entire BC Parks system. The projections of the 1990s indicate generally subtle climate shifts, with most units retaining close to 100% of their original area. The loss of substantial area from some of the units in this time period is more likely due to modeling artefacts than climate change. By the 2020s, however, most units have been displaced from more than 50% of their original boundaries, and eight units have disappeared, i.e., have shrunk to less than 5% of their area in the 1980s. By the 2050s, most units are completely displaced from their boundaries. This indicates a climatic shift equivalent to at least one subzone by the 2050s across the parks system. Most of the units that retain a majority of their original area in the biogeoclimatic projections (e.g., the CWHdm, BGxh, and CDFmm) are dominated by novel climates (as detected in the distance-based novelty measurement), and therefore should not be misinterpreted as being climatically stable. 17 and 23 units have disappeared from the BC Parks system by the 2050s and 2080s, respectively. By the 2080s, four units have hyper-expanded, i.e., grown by a factor of 20 or more. Two of these units, the CWHms2 and SBPSmk, have more than 50% of their projected area detected as novel climates. This preponderance of novel climates suggests that these units are poor analogs for the projected climates they are being classified as, and that their large expansion should not be taken at face value.

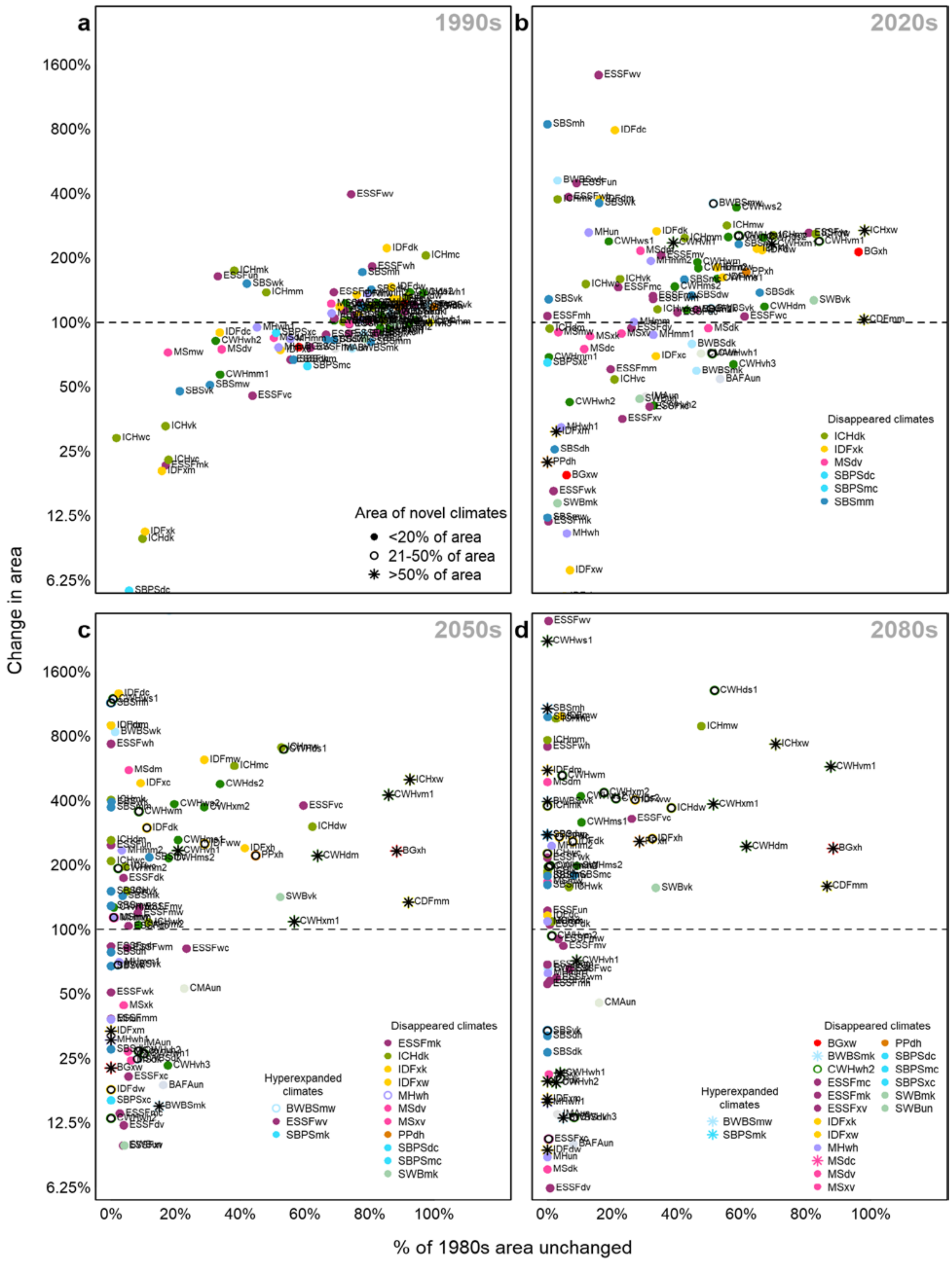

Figure 14: Shifts in the spatial distribution and relative area of the biogeoclimatic units of the BC Parks system, with respect to their predicted distribution in the 1970-2000 period ("1980s").

The distance metric and the biogeoclimatic unit projections provide two essentially independent means of identifying disappearing climates. There is a moderate (r=0.55) positive relationship between these two measures of climatic disappearance (Figure 15). There are few “false-negative” discrepancies in which BGC units are projected to remain stable yet are detected as having a high mean disappearance distance (CDFmm, CWHxm1/vh1). These types of discrepancies can be explained as artefacts of novel climates. In these cases, novel climates in the parks system are being classified as the unit by the bioclimatic model due to lack of a better alternative, even as the climatic conditions associated with the unit disappear from the BC Parks system. There are seven “false positive” discrepancies in the lower right of the plot, in which the biogeoclimatic units are projected to disappear from the parks system yet have low disappearance distances of between 1.0 and 1.5. These mismatches may be due to the persistence of climatically similar units in the BC parks system, or due to disagreement between the linear (distance-based) and non-linear (random forest) measurement of climatic differences.

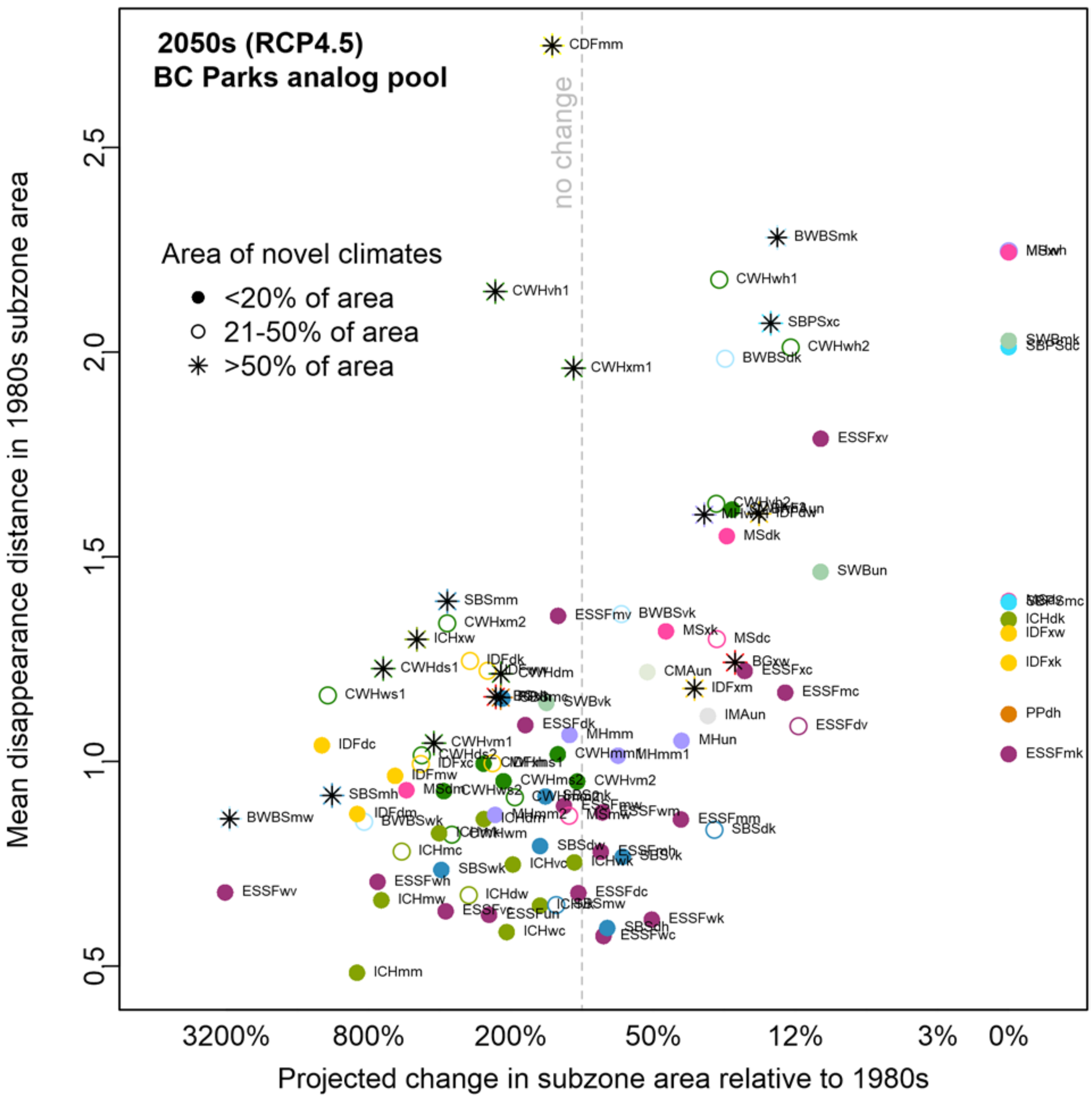

Figure 15: Comparison of two ways of measuring disappearing climates: change in projected future area of BGC units relative to their predicted distribution in the 1980s (x-axis), and the mean disappearance distance within the predicted 1980s subzone area (y-axis).

4 Discussion

Summary of analysis approaches

This study has used two distinct approaches to evaluate the character of 21st-century climate change in the BC Parks system. The first approach uses climatic distances to detect the emergence of climatic conditions that are novel to individual parks, the BC Parks system, the province of BC, and North America. Climatic distances are also used to identify locations whose climates are projected to disappear over the course of the century at these four spatial scales. The second approach uses biogeoclimatic units as analogs for the future climatic conditions of BC Parks. This approach translates quantitative climate change projections into spatial shifts in biogeoclimatic map units. Together, these two approaches provide a base of information to support adaptation planning in BC Parks.

Novel and disappearing climates—Individual parks

By the 2050s, climates that are novel to and disappearing from individual park boundaries are projected to cover more than 75% of the area of the BC Parks system. This very high rate of novel and disappearing climates with respect to the analog pools of individual parks indicates substantial climatic displacement throughout the BC Parks system by mid-century. In the context of novel climates, it suggests that analogs for the climates of the second half of the 21st century will generally be sourced from outside of the boundaries of individual parks. In the context of disappearing climates, it suggests that most parks will be unable to provide optimal climatic refugia for their current biotic communities. The implication of these findings is that migration connectivity is increasingly important in ecological adaptation to 21st century climate change, particularly in the context of protected areas. Further, it suggests an emerging necessity for active translocation to maintain the climatic equilibrium of vulnerable species and populations in BC Parks.

Novel and disappearing climates—Parks system

Climates that are novel to and disappearing from BC and North America are isolated to distinct regions of the province—primarily northeastern BC, the Chilcotin Plateau, the North Coast, and the low elevations of the southern interior and the Georgia Basin. As a result, these types of climate risk only affect a subset of BC parks. Nevertheless, the novel climates of the southern interior and Georgia basin coincide with the ecosystems of the Coastal Douglas Fir (CDF), Ponderosa Pine (PP), and Bunchgrass (BG) biogeoclimatic zones, which are particularly vulnerable to human development and invasive species. Novel climates represent an additional challenge for the management of parks in these zones, because they are conditions for which historical data on ecosystem responses to climate can be uninformative or misleading. Management approaches based on historical data, such as species distribution models, should be used with particular caution in these areas of projected novel climates.

Climatic turnover indicated by BGC projections

By the 2020s, one-third of biogeoclimatic units are projected to be fully displaced from their original boundaries within the BC Parks system. By the 2050s, nearly all units are displaced by other biogeoclimatic units or climates that are novel to the BEC system. This complete shift of climates illustrates the necessity for parks managers to begin adjusting their understanding of the ecosystem processes and services that are present in each location. Climate analogs are useful for these necessary updates to the park manager’s knowledge base. However, the character of climatic displacement is highly variable across parks. For example, the Garibaldi parks complex is projected to undergo uphill shifts of its native climates, with influx of novel climates, while Ts’yl-os Provincial Park is projected to undergo replacement of its endemic climates with climates historically found outside its boundaries. The emergence of novel climates and exotic climate analogs indicates that the implications of climate change will be much more difficult to interpret in some locations than in others.

Role of climatic shifts in vulnerability assessment

This report provides key input for vulnerability studies. Biogeoclimatic projections facilitate first approximations of climate impacts for a vast array of individual species, values, and ecosystem services. For example, the loss of a seasonal snowpack is suggested by a transition from the MHmm1 (deep snowpack) or CWHvm2 (shallow snowpack) to CWHvm1 (intermittent or absent snowpack). This first approximation could be followed up with more specialized snowpack modeling if resources permit.

Disappearing climates have direct ecological impacts, as they represent habitat that is no longer present in an individual park, the parks system, and even the continent. This report has identified a set of biogeoclimatic units with a high degree of climatic disappearance. Vulnerability assessments could benefit from a survey of species that are associated with these disappearing climates for at least part of their life cycle.

The role of novel climates in vulnerability assessments is more abstract than that of disappearing climates, but important nevertheless. Novel climates are conditions for which direct baseline data is unavailable. Any assessment framework that relies on observed biological responses to climate is susceptible to making wrong and even misleading assessments for novel climates. At a general level, climate change vulnerability assessments can be informed by the general pattern of novel climates emerging at the lowest elevations of any landscape. The spatial data that accompanies this report can be used to indicate more precisely where and when novel climates are likely to be a critical consideration in vulnerability assessments.

Utility of the BEC system

This report demonstrates the enormous utility of the BEC system in interpreting climate change. BEC provides a framework for summarizing metrics such as the distance-based analyses of novel and disappearing climates. More importantly, though, it is a source of richly documented climate analogs. Each BEC unit is accompanied by extensive descriptions of climatic stressors, potential vegetation, and biotic interactions; primarily the BEC field guides (e.g., MacKillop and Ehman 2016). As a result, biogeoclimatic projections are useful to a variety of conservation applications, such as wildlife habitat modeling (via browse species), natural disturbance regimes, and even recreation opportunities (e.g., via snow cover and seasonality). Biogeoclimatic projections also allow ecosystem managers to draw on their personal, place-based ecological knowledge to understand climate change impacts in their familiar landscapes. Familiarity with local biogeoclimatic units and with the theory of the BEC system will be an asset to parks managers as they work to adapt the BC parks system to climate change.

5 Conclusions and Recommendations

This report provides an assessment of the scale of climate change in the BC Parks system, assuming the RCP4.5 scenario of moderate global emissions reductions. High-level results are:

- Turnover in ecosystem climates is already underway. By 2050, essentially none of the climates of the BC Parks will be in their historical climatic zones (i.e., Biogeoclimatic subzones and variants).

- Shifts in climates are not simply uphill and northwards. Some parks will experience the emergence of climates that are novel to the individual park, the BC parks system, or even to North America.
- By mid-century, 75% of the BC parks system is projected to be occupied by climates that are novel to and disappearing from individual park boundaries.

The climate change metrics presented in this report and its accompanying spatial data can be used in the following ways for climate change adaptation planning:

- Biogeoclimatic projections can be interpreted for first-approximation assessments of climate change impacts on a wide range of species, ecosystems, and ecosystem services;
- Locations with disappearing climates are at elevated risk of habitat loss within park boundaries, and are a priority for vulnerability assessments.
- Novel climates at that scale of individual parks indicate locations that are more likely to require migration, and possibly even translocation, of species and population from outside park boundaries.
- Novel climates at the scale of BC or North America are locations where species distribution models and other empirical climate change impact assessments are most likely to be unreliable.

This report supports the following recommendations for BC Parks:

- Incorporate the identified disappearing climates as a risk factor in species-level vulnerability assessments.
- Ensure potential errors due to novel climates are factored into climate change impact assessments that rely on projections of future climates.
- Provide training on the Biogeoclimatic Ecosystem Classification (BEC) to BC parks staff. BEC is a versatile framework for understanding local climates and communicating climate change impacts.
- Expand on the case study framework presented in this report to provide a suite of climate change information for management plans and other planning processes.

6 Technical methods

6.1 Distance-based detection of climatic novelty and disappearance

The linear novelty detection method in this study follows the general approach of Williams et al. (2007) and the specific metric of Mahony et al. (2017). I calculated linear novelty (D_{min}) as the Mahalanobis distance (Mahalanobis 1936) between the projected 21st-century climate of a location of interest and its closest analog among the observed end-of-20th-century (1971-2000) climates of the analog pool (Figure 2). This Mahalanobis distance is scaled to the historical interannual variability of the climate variables for the location of interest, as described in more detail below. Novelty distances are interpreted in terms of the minimum distances between BEC units: I used a distance of 1.5 as a threshold of novelty and disappearance because it is roughly equivalent to the distance between closely-related BGC subzones in interior BC, using the methods described here (Mahony et al. 2018).

6.1.1 Observed and projected climate normals

I used six climate variables for climate distance measurement: mean daily minimum and maximum temperature (T_{min}, T_{max}) and log-transformed total precipitation (PPT) for winter (Dec-Jan-Feb) and summer (Jun-Jul-Aug). I obtained the gridded climate normals for the 1971-2000 and future periods using ClimateBC v5.50, except for the North American climate data, which I obtained from ClimateNA v5.10 (Wang *et al.* 2016). In both ClimateBC and ClimateNA, observed 1971-2000 climate normals are interpolated from the PRISM climate surfaces for British Columbia (Pacific Climate Impacts Consortium and PRISM Climate Group 2014). Projected climate normals are the ensemble mean of the 15 CMIP5 projections (Taylor *et al.* 2012; Table 1) available in ClimateBC. The ensemble mean projection is calculated from the mean monthly anomaly for each variable in all 15 models.

Table 1: CMIP5 models included in the RCP8.5 and RCP4.5 ensemble mean projections. The model projection is an average of several model runs, as specified in the last column.

Modeling Center (or Group)	Institute ID	Model Name	# runs
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0	1
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2	5
National Center for Atmospheric Research	NCAR	CCSM4	5
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(CAM5)	3
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5	1
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0	10
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3	1
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-R	5
Met Office Hadley Centre	MOHC	HadGEM2-ES	4
Institute for Numerical Mathematics	INM	INM-CM4	1
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR	1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM	1
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5	3
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-LR	3
Meteorological Research Institute	MRI	MRI-CGCM3	1

6.1.2 Local interannual climatic variability

I estimated local interannual climatic variation using weather station data from the CRU TS3.23 (Harris *et al.* 2014) source observations. Precipitation stations were assigned the temperature time series of the nearest temperature station, and discarded if no temperature station was available within 60km. I discarded stations with fewer than 20 years of complete records. This process selected 91 CRU TS3.23 stations within British Columbia. I calculated Mahalanobis distance (novelty) separately for each of the four stations nearest to the location of interest, then averaged these values.

6.2 Biogeoclimatic projections.

I trained Random Forest models to classify Biogeoclimatic units from climate variables. Each model comprised 500 trees. Six variables were tried at each tree node. There were 103 classes in the class variable, composed of Biogeoclimatic subzones in the interior zones and subzone variants in the coastal zones as the class variable. There were 12 predictor variables, made up of three climate elements (Tmax, Tmin, PPT) in all four seasons. Training observations were a 2-km grid of British Columbia in North American Equidistant Conic projection. To balance the training data, I limited the number of gridpoints available for bootstrap sampling in each tree for all BGC units with >200 gridpoints (Figure 16). The number of randomly sampled gridpoints (n_i) in BGC variant i with total gridpoints N_i>200 that was made available to each tree was calculated as follows:

$n_i = t + N_i * \ln(a/N_i)/b - t * \ln(a/t)/b$

where a and b are tuning coefficients with values of 150000 and 7, and t is the minimum threshold of 200 gridpoints.

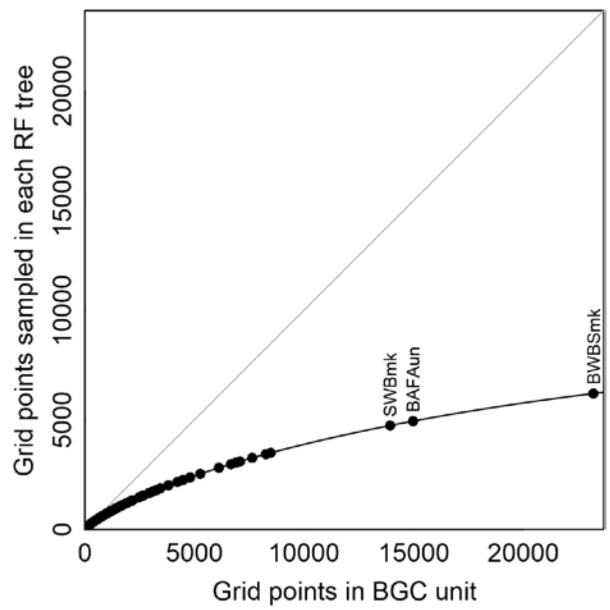

Figure 16: Graduated sampling function for balancing the training data for Random Forest biogeoclimatic projections.

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