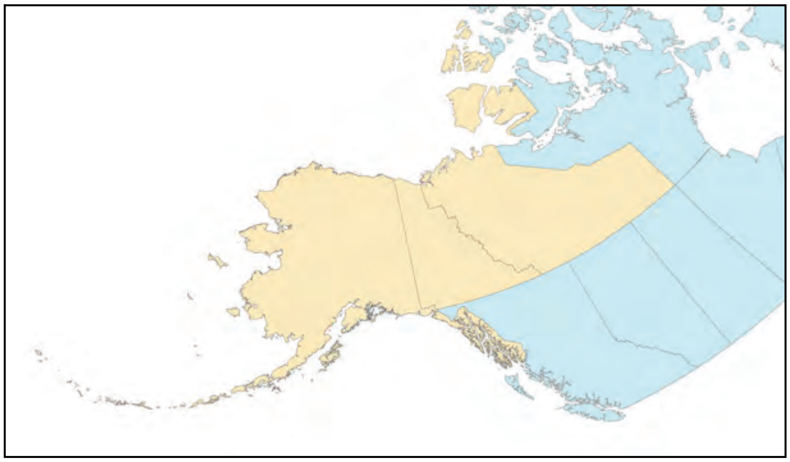
Predicting Future Potential Climate-Biomes

for the Yukon, Northwest Territories, and Alaska



A climate-linked cluster analysis approach to analyzing possible ecological refugia and areas of greatest change

Prepared by the Scenarios Network for Arctic Planning
and the EWHALE lab, University of Alaska Fairbanks

on behalf of

The Nature Conservancy's Canada Program
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Ducks Unlimited Canada
Government Canada
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Executive Summary

The Alaska Climate-Biome Shift Project (AK Cliomes) and the Yukon (YT) and Northwest Territories (NWT) Climate-Biome Shift Project (Ca Cliomes) were collaborative efforts that used progressive clustering methodology, existing land cover classifications, and historical and projected climate data to identify areas of Alaska, the Yukon, and NWT that are likely to undergo the greatest or least ecological pressure, given climate change. Project results and data presented in this report are intended to serve as a framework for research and planning by land managers and other stakeholders with an interest in ecological and socioeconomic sustainability.

"Cliomes" can be considered to be broadly defined regions of temperature and precipitation patterns that reflect assemblages of species and vegetation communities (biomes) that occur or might be expected to occur based on linkages with climate conditions. They are not the same as actual biomes, since actual species shift incorporates significant and variable lag times, as well as factors not directly linked to climate. However, results serve as indicators of potential change and/or stress to ecosystems, and can help guide stakeholders in the management of areas of greatest and lowest resilience to changing climate.

Using climate projection data from SNAP and input from project leaders and participants, we modeled projected changes in statewide climate-biomes (cliomes). The primary data used were SNAP climate models based on downscaled global projections, which provided baseline climate data and future projections. Analysis of these data involved use of the Partitioning Around Medoids (PAM) clustering methodology, which defined regions of similar temperature and precipitation based on a Random Forests™ (Breiman, 2001) generated proximity matrix. Each cluster was used to define one cliome. Thus, for the purposes of this project, clusters are synonymous with cliomes. Further, the Random Forests™ algorithm was used to take the PAM classification and predict the spatial configuration of the cliomes given a changing climate. Alaska and the Yukon were modeled at 2km resolution. These fine-scale data are not available for NWT, so outputs for this territory are at 18.4 km resolution. For all areas, we addressed the inevitable uncertainty of climate projections by analyzing outputs for five different downscaled General Circulation Models (GCMs) as well as for a composite (average) of all five, and for three different greenhouse-gas emissions scenarios (B2, A1B, and A2), as defined for by Nakicenovic et. al. (2001).

The AK Cliomes and Ca Cliomes projects modeled projected shifts in climate-biomes based on current and historical climatic conditions and projected climate change. The eighteen cliomes used in this project were identified using the combined Random Forests™ and PAM clustering algorithms, which are defined by 24 input variables (monthly mean temperature and precipitation) used to create each cluster. They were also assessed via comparisons with four existing land-classification schemes for North America (NALCMS Land cover, AVHRR Land cover, GlobCover 2009, and a combination of the Unified Ecoregions of Alaska described

by Nowacki et al. 2001 and Canadian Ecozones). We used Random Forests™ to model projected spatial shifts in climate-biomes, based on SNAP projections for monthly mean temperature and precipitation for the decades 2001–2009, 2030–2039, 2060–2069, and 2090–2099.

The results of this modeling effort show that profound changes can be expected across the study area, with most regions experiencing at least one cliome shift by the end of the century, and some areas shifting three times. Although results differed according to which GCM was used and which emissions scenario was selected, the general patterns of change were relatively robust. These patterns involved a northward movement of cliomes, with arctic clusters shrinking or disappearing, interior boreal and taiga clusters shifting, and clusters currently found only outside of the study area appearing in Alaska, the Yukon, and the Northwest Territories. Cliomes that are currently typical of the central and southern potions of British Columbia, Alberta, and Saskatchewan are likely to become prevalent in a large percentage of the study area. This can be interpreted as their being a high likelihood for changing precipitation/temperature conditions which may be beneficial to some existing plant and animal species and placing some under high stress.

We analyzed all outputs for resilience (defined as lack of projected cliome shift) and vulnerability (defined as multiple cliome shifts over time). The most resilient regions are projected to be the coastal rainforest of southcentral and southeast Alaska, and the most vulnerable areas are projected to be interior and arctic regions, with the exception of the islands of the NWT. However, these conclusions may be affected by the relative dissimilarity of the coastal rainforest to any other cluster in North America; species change may be less there simply because surrounding cliomes differ so greatly.

The ramifications of these projected changes for land managers and local residents are varied, and depend on the mandates and goals of the organizations and agencies involved. By linking species-specific data and local details of landscape ecology to these projections, land managers can make informed decisions about how to adapt to a changing landscape in an active manner.

Introduction

Understanding the potential effects of climate change on biodiversity and traditional subsistence activities is a challenge faced by federal, state, provincial, Alaska Native, First Nation, and private land managers. Predicting changes in the distribution of renewable resources will help prioritize planning and conservation efforts. One of the most important aspects of such predictions is identifying lands that are most likely to change (dynamic landscapes) and those that are least likely to change (existing and potential refugia). Both of these important categories can then be considered in conjunction with ongoing statewide, national, and international conservation initiatives.

The Alaska Climate-Biome Shift project (AK Cliomes) was implemented in order to carry forward and improve upon some of the preliminary work done as part of the Connecting Alaska Landscapes into the Future project (Connectivity Project) initiated by the US Fish and Wildlife Service in 2008 (Murphy et al. 2010). It was conducted in concert with the separately funded Canadian Climate- Biome Shift project (Ca Cliomes). Where possible, products from the two projects are seamless, representing the transboundary nature of ecological, biophysical, and climatological variables and management of migratory fish and wildlife species

AK Cliomes and Ca Cliomes both centered around the following goals:

1) Develop climate-based land-cover categories (climate-biomes) for Alaska (AK Cliomes) and for the Yukon and Northwest Territories (NWT) (Ca Cliomes), using down-scaled gridded historic climate data available from the Scenarios Network for Alaska and Arctic Planning (SNAP) and cluster analysis methodology

2) Link the resulting climate-biomes to compatible land cover classes or vegetation classifications for North America, based on remote sensing data and the available literature, and define each biome by both climate and ecosystem characteristics.

3) Couple the climate-biomes developed above with the Scenario Network for Alaska and Arctic Planning (SNAP)'s 21st century climate projections (based on Global Circulation Model outputs downscaled to 2km resolution using the PRISM model — see Technical Addendum I), and thereby create predictions for climate-change-induced shifts in climate-biome ranges and locations.

4) Use the above results to identify areas within Alaska (AK Cliomes) and within the Yukon and NWT (Ca Cliomes) that are least likely to change and those most likely to change over the course of this century.

This combined project builds on and makes use of work previously conducted by the University of Alaska Fairbanks (UAF) SNAP program and Ecological Wildlife Habitat Data Analysis for the Land and Seascape Laboratory (EWHALE) lab, with funding and leadership from the US Fish and Wildlife Service (USFWS) and input from a wide range of stakeholders, including The Nature Conservancy (TNC).

The completed climate-biome shift analysis may be used by USFWS, TNC, Ducks Unlimited Canada (DUC), other federal, state and provincial agencies, scientists, scholars, and other partners involved in protected areas, land use, and sustainable land use planning. The intent is that this will contribute to effective proactive habitat management, including sustainable economic activities and waterfowl and wetland conservation in Alaska, the Yukon and the NWT. Climate change is already recognized as an important factor to incorporate in decisions for wildlife conservation at the landscape scale (Western Governors' Association 2008).

Terms and Definitions

The following terms, used throughout the report, are defined as follows:

Adaptation: In this report, adaptation refers to the ability of humans and other species to adjust their behaviors and/or physiology in to meet changing conditions. It does not refer to evolutionary adaptation by natural selection.

Biodiversity: Biodiversity refers to a composite measure of both species' richness (total number of species) and evenness (relative abundance of all species).

Biome: A biome is a broadly defined species assemblage., usually linked to climate and geophysical attributes.

Climate-biome or Cliome: For the purposes of this report, a cliome is a broadly defined region of temperature and precipitation patterns that reflect assemblages of species and vegetation communities (biomes) that occur or might be expected to occur based on linkages with climate conditions.

Climatology: Baseline climate data averaged across a recent time period constitutes a climatology, representing "normal" or historical conditions. SNAP data are downscaled using PRISM climatogies for the years 1961-1990.

Conservation: In this report, we recognize that conservation in the context of a changing environment may not mean maintenance of the status quo, but rather successful adaptation to changing conditions.

Dynamic Landscape: This term refers to an area likely to undergo rapid or extreme change. Dynamic landscapes can be considered the opposite of refugia.

Ecozone: An ecozone is a Canadian region broadly defined by dominant vegetation and geophysical attributes. (see Appendix D).

Potential climate-biome: A potential climate-biome is the biome that best matches projected future climate conditions for a region, based on the linkage between past climate and existing biomes. Potential climate-biomes may differ from actual future climate-biomes for a number of reasons, including differences in soil type and hydrology, or lag time between climate change and seed dispersal and other mechanisms of ecosystem change. Thus, the term "climate-biome" is generally used to underscore this distinction.

Refugia: Refugia are areas in which the potential future climate-biome is projected to be the same as the existing climate-biome through all time steps from 2000 to 2100.

Resilience: In general, resilience is the ability to avoid substantive ecological change despite ongoing perturbations. In this report, cliomes are considered most resilient if they are expected to undergo no shifts over the course of this century.

Vulnerability: For this project, vulnerability is the degree to which a system is susceptible to adverse effects of climate change, including climate variability and extremes. Cliomes that are expected to experience multiple shifts over the course of this century are considered more vulnerable than those expected to undergo fewer shifts.

Background

Connecting Alaska Landscapes into the Future

The Connecting Alaska Landscapes into the Future Project (Connectivity Project), which was initiated in 2008 and completed in 2010, was the precursor to this project. Project results and data presented in the Connectivity Project report are available on line at www.snap.uaf.edu.

The Connectivity Project was a collaborative proof-of-concept effort co-led by Karen Murphy and John Morton from USFWS, Nancy Fresco from the University of Alaska (UA) SNAP, and Falk Huettmann from the UAF EWHALE lab. SNAP is a statewide research group that creates and interprets projections of climate change based on downscaled global models. The EWHALE lab in UAF's Institute of Arctic Biology, Biology and Wildlife Department, specializes in spatial modeling of landscapes and populations for conservation planning and analysis.

The project included a series of three workshops conducted in 2008 and 2009, with participants from Alaska-wide state and federal agencies and non-profit organizations. Using climate projection data from SNAP and input from project leaders and participants, the Connectivity Project modeled projected changes in statewide biomes and potential habitat for four species selected by the group. The primary models used were SNAP climate models originally developed by Dr. John Walsh (Walsh 2008) based on downscaled global time series data, which provided baseline climate data and future projections; Random Forests™, which was used to match current climate-biome relationships with future ones; and Marxan software, which was used for optimizing landscape linkages.

The Connectivity Project, in contrast to AK Cliomes and Ca Cliomes, used pre-defined biome categories based on the literature. These include six Alaskan biomes adapted from the unified ecoregions of Alaska (Nowacki et al. 2001) and six western Canadian ecozones, as defined by Government of Canada. The project used Random Forests™ to model projected spatial shifts in potential biomes for the decades 2000–2009, 2030–2039, 2060–2069, and 2090–2099. In contrast with AK Cliomes, these projections were based on SNAP data for mean temperature and precipitation for June and December only, rather than all twelve months.

The Connectivity Project also employed climate envelope modeling techniques using Random Forests™ to examine potential impacts on four selected species: barren-ground caribou *(Rangifer tarandus granti),* Alaska marmots *(Marmota broweri),* trumpeter swans *(Cygnus buccinator),* and reed canary grass *(Phalaris arundinacea).*

Project Improvements in AK Cliomes / Ca Cliomes

Many of the same participants carried this effort forward in AK Cliomes, including Karen Murphy (USFWS), Nancy Fresco (SNAP) and Falk Huettmann (EWHALE). Michael Lindgren (EWHALE programmer) and Joel Reynolds (USFWS) also played lead roles.

Based on lessons learned in the Connectivity Project, AK Cliomes used a much broader array of data, as well as several fundamentally different techniques. The most important changes included using 30-year or decadal averages of all twelve months of data, rather than just June and December data; eliminating pre-defined biome/ecozone categories in favor of model-defined groupings (clusters); and linking the project with a Canadian version of the same effort, thus extending the scope of the results to western Canada. The benefits of each of these changes will be discussed below.

General Information on Models and Statistical Methods

Historical Climate Trends and Ice Breakup Data

Although historical comparisons and cross-validation with historical climate data were not originally included as part of the project description for either AK Cliomes or Ca Cliomes, project participants decided to add an assessment of whether projected future climate change and associated landscape changes are in line with existing observations of historical trends.

Few consistent data on the measurable effects of changes in climate seasonality are available in a form that could easily be accessed and used, particularly over long time periods. However, annual data have been collected for many decades on ice breakup from the Tanana River in Central Alaska and the Yukon River at Dawson, YT. While these datasets obviously offer only a snapshot of overall trends across the region, spring thaw is a strong indicator of potential biome change, since it correlates not only with warming temperatures, but also with growing season length, winter precipitation, and spring precipitation, and are socially and ecologically significant. (Bonsal and Prowse 2003). Moreover, although the data are from point-sources, river thaw is driven by variables throughout the watershed for each river, meaning that ice breakup is indicative of larger landscape trends (Bonsal et al 2006). Data are available for dates from 1917 to 2011 for the Tanana River and for 1896 to 2011 for the Yukon River.

The results of this analysis (see also Appendix B) show that spring thaw has been trending earlier over the past hundred years in both Alaska and the Yukon (Figure 1) (Nenana 2012; Yukon 2012) This trend is statistically significant in both cases, and is robust for shorter historical periods as well as for the full datasets, although the apparent magnitude of the trend varies according to the time period assessed. For the Tanana River, the trend over the full recorded period averages 0.072 days per year, and for the Yukon, the trend for the full recorded period is 0.058 days per year. For more recent decades, the trend is more extreme, with the Tanana River showing a shift of 0.15 days per year for the past 40 years (1972 to 2011) and the Yukon River showing a shift of 0.11 days per year for the same time period (Figure 2). These shorter-term results must be viewed with some caution, since they are dependent on the selection of starting dates, and also because over relatively short time periods normal interannual variability and the Pacific Decadal Oscillation (PDO) can play a large role. Nonetheless, the implications of this analysis are several. First, the results support the conclusion that ongoing climate change is

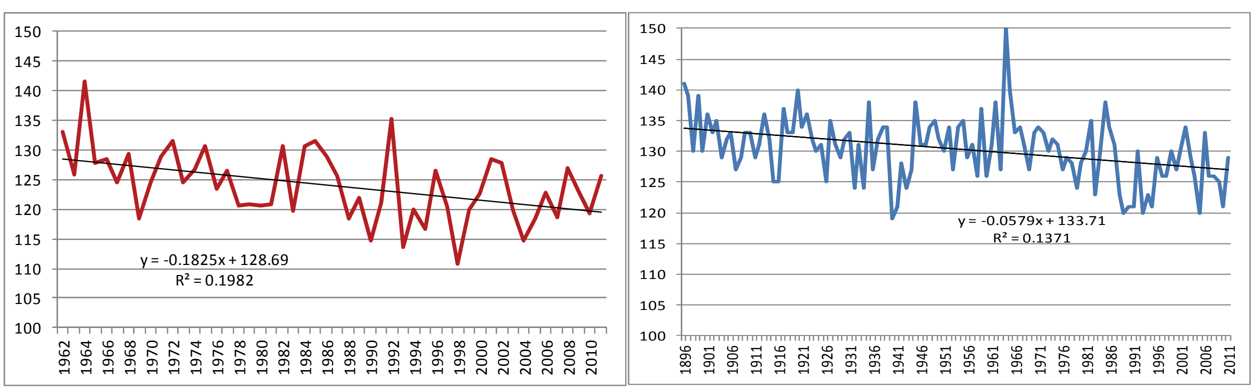

Figure 1 — Ice breakup dates for the Tanana (left) and Yukon (right) Rivers for the full recorded time periods. Days are expressed as ordinal dates. A statistically significant trend toward earlier thaw dates can be found for both rivers. Linear regressions are analyzed fully in Appendix B.

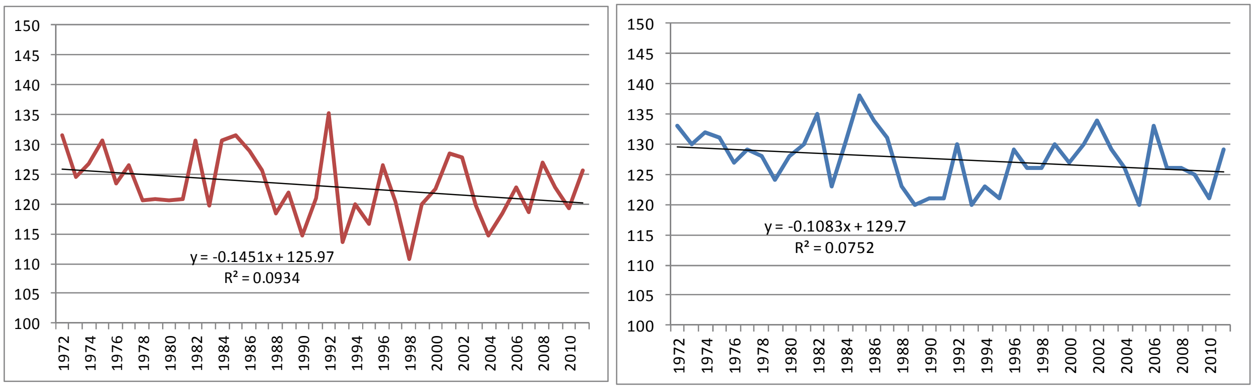

Figure 2 — Ice breakup dates for the Tanana (left) and Yukon (right) Rivers for the past 40 years (1972-2011). The trend toward earlier thaw dates has become more pronounced in recent decades. Days are expressed as ordinal dates.

already causing significant impacts at the landscape level. Second, the data show that the warming trend has become more extreme as the previous century progressed. Finally, these data link local knowledge from local residents with regard to the witnessing of climate change with data that supports these claims.

Cluster Analysis

Cluster analysis is the statistical assignment of a set of observations into subsets (called *clusters*) so that observations in the same cluster are similar in some sense. It is a method of "unsupervised learning" – where all data are compared in a multidimensional space and classifying patterns are found in the data. Clustering is common for statistical data analysis and is used in many fields. A hierarchy of clusters may be represented in a tree structure called a dendrogram. The root of the tree consists of a single cluster containing all observations (Figure 3).

Figure 3 — Example of a dendrogram. Clusters can be created by cutting off this tree at any vertical level, creating (in this case) from one to 29 clusters.

Any valid metric, e.g. linear distance, may be used as a measure of similarity between pairs of observations. The choice of which clusters to merge or split is determined by a linkage criterion, which is a function of the pairwise distances between observations. Cutting the tree at a given height will give a clustering at a selected precision.

For the purposes of the Cliomes projects, we used a clustering method known as Partitioning Around Medoids (PAM). The algorithm PAM first computes representative objects, called *medoids,* where the number of medoids depends on number of clusters desired by the user. A medoid is that object of a cluster whose average dissimilarity to all the objects in the cluster is minimal — in other words, it's the cluster's "center". The dissimilarity matrix (also called distance matrix) describes pairwise distinction between objects — how much each medoid differs from each other medoid.

PAM is usually more robust than the well-known *kmeans* algorithm, because it minimizes a sum of dissimilarities instead of a sum of squared Euclidean distances. As a result, clusters tend to emphasize median values, with minimal influence from outliers. After finding the set of medoids, each object of the data set is assigned to the nearest medoid.

In some ways, clustering is not an ideal way to look at climate data across a landscape, because the input data are by nature continuous. There are no "real" boundaries that demarcatedistinct ecosystems, since biomes almost always blend together at their boundaries. In contrast clustering genetic data to search for markers of particular traits or diseases is likely to offer up results that show true "structure." Nevertheless, landscape management almost always occurs in a manner that recognizes biomes and ecosystems, despite this blurring of boundaries. Shifts from one such system to another is a subject of great interest and concern.

Modeling climate change: SNAP climate models

SNAP climate projections are created from Global Circulation Models (GCMs) selected for the Alaska and Arctic Region from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report Four (AR4). The IPCC used fifteen different GCMs when preparing its Fourth Assessment Report released in 2007. SNAP analyzed how well each model predicted monthly mean values for three different climate variables over four overlapping northern regions for the period from 1958 to 2000. The model selection procedures are described in Walsh et al. (2008). For this project, we used mean (composite) outputs from the five models that provided the most accurate overall results. The selected models, each created by an interdisciplinary team of scientists and modelers, include ECHAM5 (Germany), GFDL2.1 (United States), MIROC3.2 (Japan), HADLEY3 (UK), and CGCM3.1(Canada) (see Technical Addendum 1.)

We relied primarily on model runs based on midrange (A1B) predictions of greenhouse gas emissions, as defined by the IPCC, but also included, for the sake of comparison, 5-model composite outputs using the more pessimistic A2 scenario and the more optimistic B1 scenario. The A2 scenario is now considered likely, given recent climate and emission trends (Nakicenovic et al. 2001, Raupach et al. 2007). For Alaska, the Yukon, and British Colombia

(BC), the GCM results were scaled down from 2.5° latitude/longitude blocks to 2 km resolution, using data from Alaskan weather stations and PRISM (Parameter-elevation Regressions on Independent Slopes Model). PRISM uses point data, a digital elevation model, and other spatial data sets to generate gridded estimates of monthly, yearly, and event-based climatic parameters, such as precipitation, temperature, and dew point (Daly et al. 1998). For NWT, no PRISM data were available, thus, SNAP downscaled data for this territory using the New et al. 2002 CRU CL 2.0 data (Climate Research Unit data, University of East Anglia). These data are available globally at 10 minute spatial resolution (~18.4 km), and are interpolated from a data set of station means for the period centered on 1961 to 1990, taking into account elevation. The CRU CL 2.0 climatology data employ different interpolation algorithms than the PRISM method, and does not utilize data on slope and aspect and proximity to coastlines. The downscaled versions of these data generated by SNAP have been assessed using backcasting, comparison to historical conditions, and have proven to be robust in predicting overall climate trends.

For further information on SNAP data and SNAP models, please see www.snap.uaf.edu.

Modeling climate change: Random Forests™

Random Forests™ (a trademark of Leo Breiman and Adele Cutler licensed exclusively to Salford Systems), is a software package that creates classification trees from large datasets. We employed the Random Forests™ classification algorithm to first create a proximity matrix defining the relationships between the historic temperature and precipitation samples through time, taking an unsupervised approach. These relationships were used to predict future species and biome distribution based on future scenarios of temperature and precipitation regimes. This approach, known as ensemble modeling, takes the average of the outputs of multiple individual models, thus generally providing more robust predictions (Breiman 1998, 2001). More specifically, Random Forests™ run represents an averaged collection of independent, optimized Classification and Regression Trees (CART).

Because its calculations are fast, multivariate, and programmable, Random Forests™ is convenient to use and tends to provide a better fit than linear algorithms and similar nonparamentric classification methods. Random Forests™ deals well with interactions between predictive variables, intrinsically accounting for their relative power, and ranks predictors (Breiman 2001; Hegel et al. 2010). This modeling algorithm also does well when handling "noisy" data, that is, data with high intrinsic variability or missing values (Craig and Huettmann 2008). The model algorithm, which is widely used and well tested, has previously been applied to climate change research and other studies (Climate Change Atlas 2010, Lawler 2001). For further information, see Technical Addendum II.

Important Factors and Models That Were NOT Incorporated

Sea level rise

Over the next century, global sea levels are projected to rise between 0.6–1.9 feet (0.2-0.8 meters), the range of estimates across all the IPCC scenarios (IPCC 2007). However, in some localities (e.g. southeast and southcentral Alaska), the land surface is actually rising as a result of the retreat and loss of glacial ice (isostatic rebound) and, secondarily, as a result of active tectonic deformation. Unfortunately, despite local attempts, there is no sea level rise model available for the study area at this time. Creating a sea level rise model first requires both improved digital elevation models and improved coastline maps. Because coastal areas are likely to experience change associated with ocean waters as well as potential shifts in climate, the results presented in this report should be viewed as conservative representations of change along northern coastlines.

Permafrost change

Permafrost is one of the primary ecosystem drivers for much of Alaska. Researchers, as well as everyday Alaska residents, have been documenting changes in permafrost stability in recent decades. SNAP, in collaboration with Dr. Vladimir Romanovsky and Dr. Sergei Marchenko of the UAF Geophysical Institute, have created a new permafrost map for Alaska, available online at http://permafrost.gi.alaska.edu/content/data-and-maps (GIPL 2012). They have also modeled how permafrost responds to climate changes, including an assessment of permafrost temperatures at varying depths statewide throughout the period spanned by SNAP data. Although this information is not incorporated in our predictive model, we refer to these data in our discussion of model results.

Vegetation change in response to fire

Boreal ALFRESCO (Alaska Frame-based Ecosystem Code) was developed by Dr. Scott Rupp at UAF (Rupp 2007). The model simulates the timing and location of fire disturbance and the timing of vegetation transitions in response to fire. Climate variables are among the key drivers of ALFRESCO. Thus, when SNAP climate projections are used as inputs, ALFRESCO can be used to create projections in changes in fire dynamics with changing climate. ALFRESCO operates on an annual time step, in a landscape composed of 1 × 1 km pixels. The model currently simulates four major subarctic/boreal ecosystem types: upland tundra, black spruce forest, white spruce forest, and deciduous forest. As with permafrost data, ALFRESCO outputs are considered in the discussion of our results. For more information, see http://frames.nacse.org/7000/7132.html

Methods

Cluster analysis

We chose cluster analysis as a means of defining climate-biomes for a number of reasons. These included our desire to be as accurate and unbiased as possible. Clustering creates groups with greatest degree of intra-group and inter-group dissimilarity. It gets around the problem of imperfect mapping of vegetation and ecosystem types, and mapping that uses categories that are either too broad-scale or too fine-scale to best meet the needs of land management at the level of biomes, as opposed to state-wide or province wide management, or stand-level or watershed-level management. It also allows for comparison and/or validation against existing maps of vegetation and ecosystems. Finally, it eliminates the problem of a false line at US/Canada border, where different national classification schemes meet.

Our initial plan was to use an existing vegetation map, such as AHVRR data, to define our biomes. However, preliminary analysis soon demonstrated drawbacks to this approach. It became clear that all available land cover designations are, to an expert user, clearly flawed in one way or another, either through lack of detail (too few categories), uneven detail (some categories finely parsed and others broadly clumped) or through assigning land areas to categories that are incorrect, upon field observation. While these land cover maps are valuable in assessing biomes, we decided they would more effectively be used as a suite of tools for analyzing the characteristics of organically-created clusters. Available land cover maps that we examined are described in Appendix D.

We selected PAM because it is a well-documented method of creating robust clusters with the greatest possible level of intra-cluster similarity, and the greatest possible level of inter-cluster dissimilarity. Each data point was assigned 24 variables, representing mean monthly temperature and mean monthly precipitation for the baseline years 1961-1990. This time period was selected because it was the time span for which gridded historical climate data was uniformly available across the study area, based on IPCC model data, SNAP data, and global climatologies from CRU. Using this method, we were able to create clusters that could be distinguished mathematically, internal to the model; narratively, based on distinctions between means, variances, and ranges of values for all 24 input variables; and ecologically, based on overlap with existing landcover mapping systems. See Appendix C for climate-biome narrative definitions, Appendix D for descriptions of landcover mapping systems, and Appendix E for comparisons of clusters to these systems.

An important step to PAM clustering is to select a distance measure, which will determine how the similarity of two variables (in this case, monthly temperature and precipitation values) is calculated. This will influence the shape of the clusters, as some elements may be close to one another according to one distance and farther away according to another. In our modeling efforts, all 24 variables were given equal weight, and all distances were calculated in 24-dimensional Euclidean space.

Spatial extent

As noted, the AK Cliomes project was conducted in concert with the Ca Cliomes project. Project leaders and participants agreed that both teams – and most future users of our project results – would benefit from linking the two efforts, in order to create one seamless spatial domain and time frame for our analyses. In order to do this, we had to make decisions about the spatial extent to consider.

For several reasons, we needed to place reasonably constrained bounds on the spatial extent of the project. First, we needed to lessen the already considerable computational burden of cluster modeling with so many data points. Greater spatial extent imposes modeling limits and trade-offs, since in PAM clustering every point must be compared to every other point.

Second, since our focus was on predicting the future of climate-biomes in Alaska, the Yukon and NWT, we felt that including Eastern, lakeshore, or Hudson Bay ecosystems might cause erroneous or confusing results. Logically speaking, climate-biomes found in Atlantic Canada are unlike to shift to Pacific Alaska in the course of a century. Likewise, given that climate models show clear warming trends, we concluded that the northernmost ecosystems are unlikely to move south.

We decided to spatially bound the Canadian data that would be included in our cluster analysis using the Canadian system of ecozones (Figure 4). The area that we used for our clustering included the following (Figures 5):

All subregions of these ecozones:

- Pacific Maritime
- Montane Cordillera
- Boreal Cordillera
- Taiga Cordillera
- Taiga Plains
- Boreal Plains
- Prairies
- the portions of the Taiga Shield and the Southern Arctic west of Hudson Bay
- the portion of the Northern Arctic that is part of the Northwest Territories (as opposed to Nunavut).

Figure 4 – Area of Canada selected for cluster analysis. Selected area is lightly shaded, and the unselected area is blue. The red line includes all ecoregions that have any portion within NWT. Limiting total area improves processing capabilities.

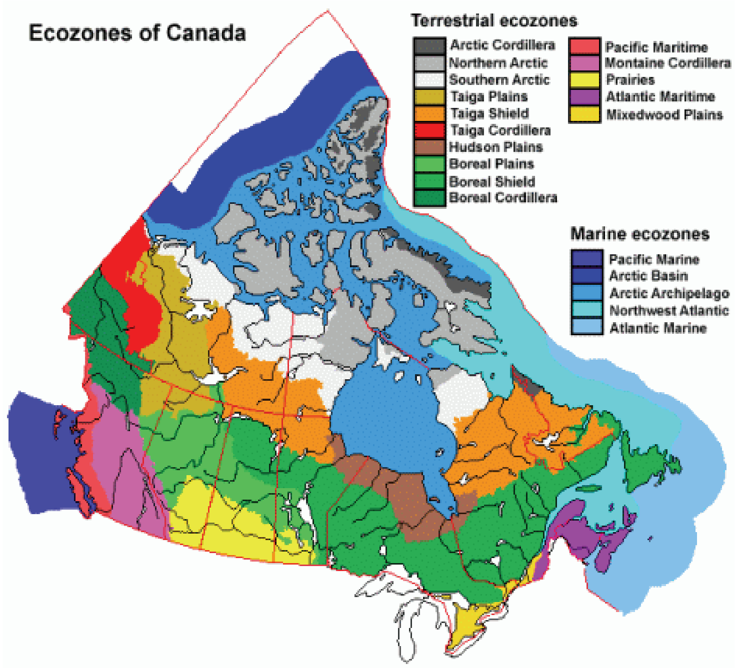

Figure 5 – Ecozones of Canada. We selected a subset of these regions for analysis, based on biomes that might feasibly shift into the focus area (NWT, Yukon, and Alaska).

From the Boreal Shield, we needed to divide by ecoregion (Figure 6). We selected the following ecoregions, eliminating those that seemed likely to be driven by eastern or Hudson Bay climate patterns (Marshall 1999):

- Athabaskan Plain (#87)
- Churchill River Upland (#88)
- Hayes River Upland (#89)
- Lac Suel Upland (#90)
- Lake of the Woods (#91)
- Big Trout Lake (#95)

When added to the full spatial extent of Alaska, the total area is approximately 19 million square kilometers. For Alaska, the Yukon, and BC, these climate data were at 2km resolution. For the remainder of Canada, they were at 10 minutes lat/long resolution, or approximately 18.4 km. In either case, the PAM algorithm selected the data value closest to the large-resolution grid point, thus creating clusters at a uniform scale across the area.

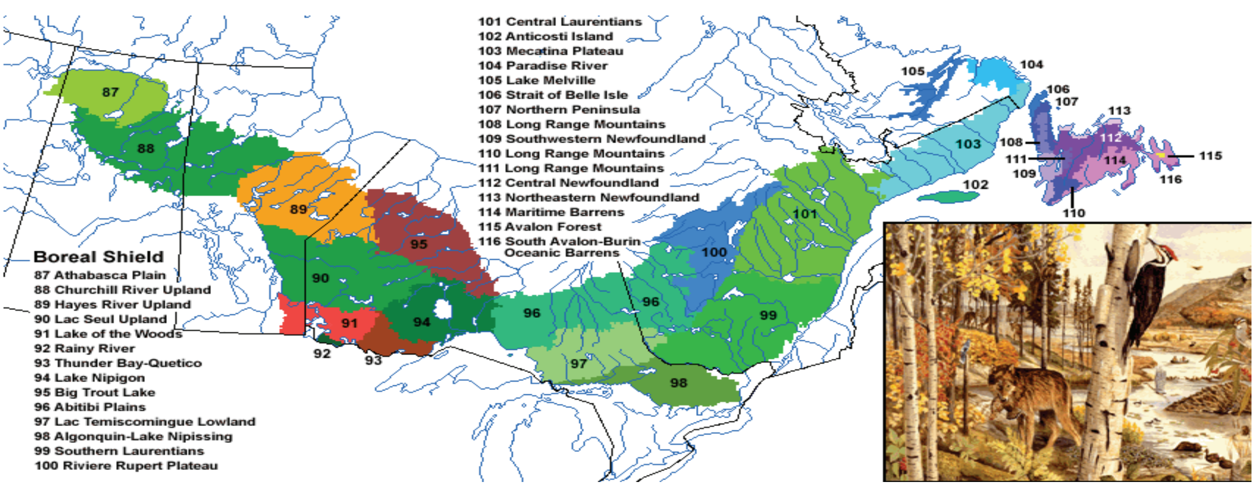

Figure 6 – Ecoregions of the Boreal Shield Ecozone. We selected a subset of these regions for analysis, based on biomes that might feasibly shift into the focus area (NWT, Yukon, and Alaska).

Resolution

There were inherent challenges in selecting a spatial resolution for our cluster modeling, since we did not have baseline climatologies at the same resolution for the entire area. As noted, for Alaska, Yukon, and BC, SNAP uses 1961-1990 climatologies from PRISM, at 2 km, to downscale GCM outputs, while for all other regions of Canada SNAP uses climatologies for the same time period from CRU, at 18.4 km. In clustering these data, both the difference in scale and the difference in gridding algorithms led to artificial incongruities across boundaries. The solution we selected to resolve this difficulty was to cluster across the whole region using CRU data, which is available for the entire area. Once the clustering was complete, we used the finer scale data (2km), where available, to create current and future projections. For areas without available PRISM data, our future projections used CGM data downscaled with CRU data.

Selection of number of clusters

Our cluster analysis, as described above, groups data points according to their similarity to medoids, or "typical" points for each cluster. The data can be mathematically broken into any number of clusters, depending on how many medoids are chosen. Thus, we needed to choose an optimal number of cliomes to define. This choice was based on two major criteria: the degree of detail in biome definition that would be most useful to our end users (land managers and other stakeholders); and the mathematical strength of our clustering. The former is largely qualitative, while the latter is quantitative.

Stakeholders will likely use these results for varying purposes, and at varying scales. However, in all cases, too fine a delineation of cliome categories would likely result in confusion regarding land cover types that are considered functionally similar, in terms of use and management. It would also create difficult questions regarding data uncertainty. The uncertainty engendered by the use of multiple models (five GCMs, CRU, and PRISM) and multiple interpolation strategies, as well as the vagaries of natural variability in weather and topography all reduce confidence in fine cliome gradations. On the other hand, if cliomes are categorized too broadly, then widely dissimilar land cover types are lumped together, and predicted change becomes too coarse to be a useful tool.

Given that the twelve biomes used in the first iteration of this project appeared to meet the needs of end users, and also given the broader spatial scale of this analysis (Alaska, Yukon, and NWT rather than only Alaska) we decided that roughly 10-20 climate-biome categories would prove the most useful. Thirty biomes, while possible, yields a highly complex map (Figure 7) while a map with only five biomes lacks sufficient information (Figure 8).

Within the 10-20 range, it would make sense to choose the most mathematically logical number of categories. In the literature, there are many ways to consider the robustness of clustering results. It should first be noted that in many studies, the breaks between clusters might be expected to be much sharper than the breaks we were likely to find, for several reasons. First, our input data (12 months of precipitation and 12 months of temperature) by their nature show similar patterns across the entire region. For example, January temperatures would be expected to be colder than June temperatures in the Arctic, in the coastal rainforests of southeast Alaska, and in Canada's prairie provinces, although the magnitude of the mean values would of course be different. This similar patterning would be expected to mathematically weaken measures of difference between clusters. Second, most biomes, as identified by landcover type, surface features, and local ecological knowledge, are highly variable within their boundaries, and tend to blur seamlessly with adjoining biomes along their edges. Thus, it would be expected that cliomes boundaries would blur with adjacent cliomes along there edges. As a consequence, many data points used in the PAM analysis would lie along these edges, and be only loosely assigned to either neighboring category. This boundary issue is further discussed below (see Cluster Boundaries).

One commonly accepted metric for selecting cluster number is silhouette analysis. In this method, each data point is assigned a value based on how similar that point is to points in its own cluster compared to points in other clusters (Rousseeuw 1987). Silhouette values above 0.5 are commonly accepted as robust, those between 0.25 and 0.5 are less robust, and those below 0.25 (including negative values) are considered to be marginal or due to mere chance.

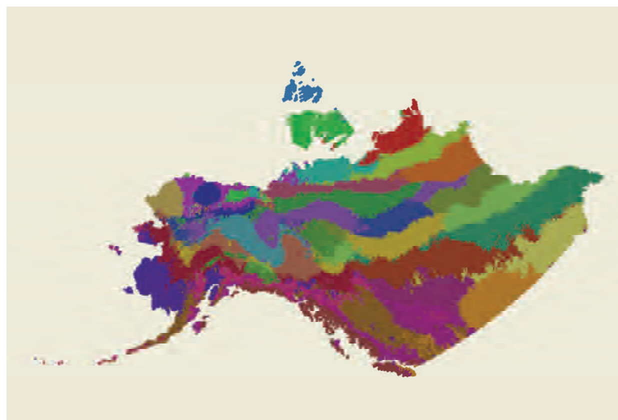

Figure 7 – Sample cluster analysis showing 30 clusters, based on CRU 10′ climatologies. This level of detail was deemed too complex to meet the needs of end users, as well as too fine-scale for the inherent uncertainties of the data.

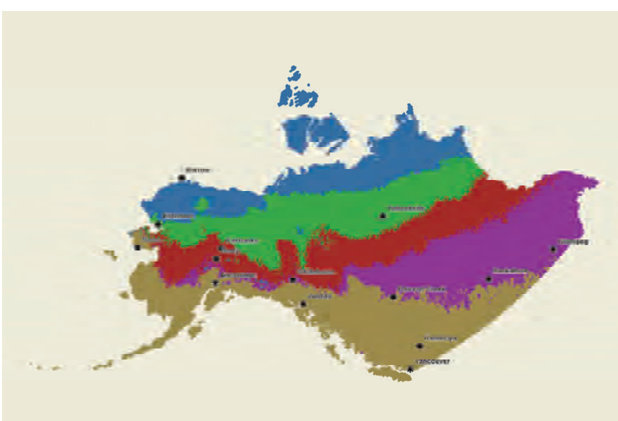

Figure 8 – Sample cluster analysis showing 5 clusters, based on CRU 10′ climatologies. This level of detail was deemed too simplistic to meet the needs of end users.

Maximizing average silhouette values across all points for varying cluster numbers yielded a range of mean values from approximately 0.16 to 0.26 . The highest mean values were for the lowest and highest numbers of clusters (Figure 9), which we eliminated from consideration for qualitative reasons. However, within the selected range (10-20), the greatest mean silhouette width occurred at 11, 17 or 18 clusters, with values of approximately 0.18.

Mean silhouette values of 0.18 are low, when compared to studies of discrete groups, and indicate a lack of substantial structure (i.e. sharp divisions between cliomes). However, such a structure could not be expected in this dataset. Not only does overlap occur at cliome boundaries, but input datasets are heavily auto-correlated. In other words, December and January are likely to be the coldest months, and June and July the hottest months, in all clusters, even though the magnitude of the heat and cold differ. This innate seasonal similarity across all pixels tends to lessen the perceived strength of the modeled clusters without diminishing the usefulness of the outputs.

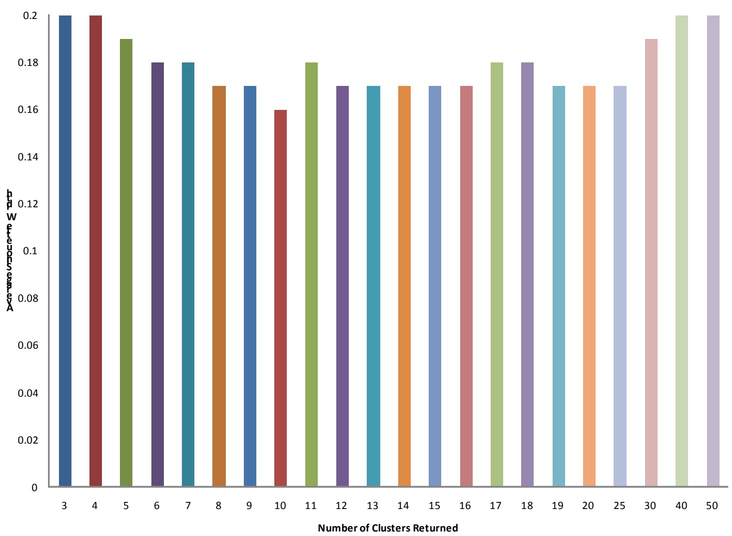

Figure 9 – Mean silhouette width for varying numbers of clusters between 3 and 50. High values in the selected range between 10 and 20 occur at 11, 17, and 18.

Based on the above analysis, we chose to cluster the data into 18 biomes (Figure 10).

Cluster Boundaries

As mentioned above, low certainty regarding cluster assignment is to be expected along cluster boundaries, given the gradient nature of climate, which is mirrored by the fluid nature of vegetative boundaries and biome categorization. In order to deal with this uncertainty, we assessed the average silhouette width of data points spatially (Figure 11).

Selecting climate data

As previously described, SNAP's downscaled climate datasets were used for this project (See Technical Addendum I). In order to provide a manageable and yet diverse set out outputs for analysis, we had to select from three emission scenarios, five models and a composite, and almost 90 years of projected data plus ten-year averages.

After discussion among project leaders, other project advisors and workshop participants, we decided to focus on the same future decades used in the Connectivity Project. Not only did this allow for direct comparison between the project results, it also provided near-future, mid-

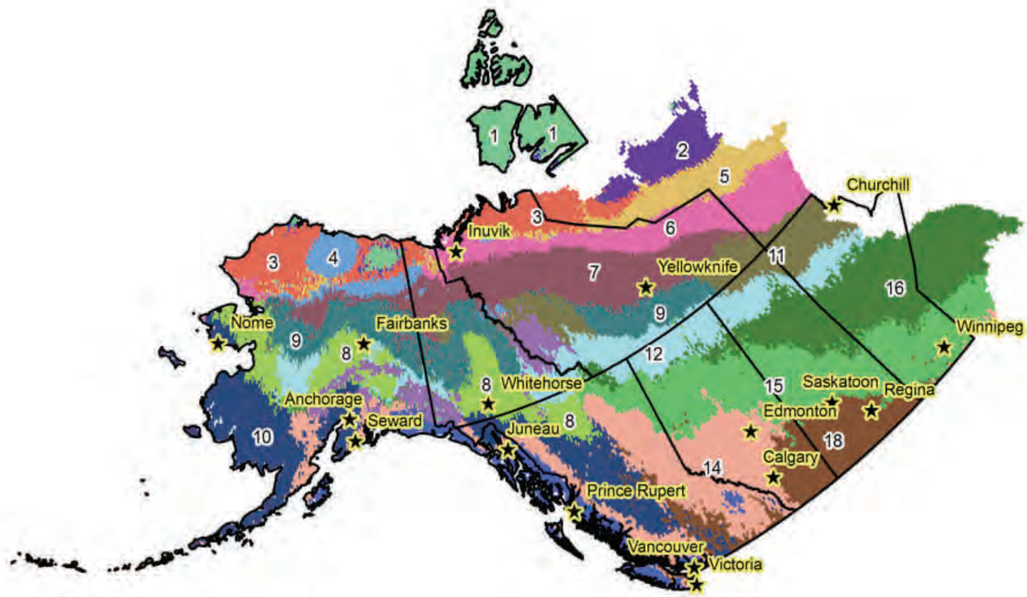

Figure 10 – Eighteen-cluster map for the entire study area. This cluster number was selected in order to maximize both the distinctness of each cluster and the utility to land managers and other stakeholders.

range, and distant projections for use by stakeholders with differing interests and mandates. While this report features the 2000's, 2030's, 2060's, and 2090's, results for the intervening decades were also generated, and are available from SNAP. Although single-year model outputs would likely inject somewhat greater diversity in terms of extreme temperature and precipitation, we

Figure 11 – Cluster certainty based on silhouette width. Darker shades indicate higher certainty (larger silhouette values). Note that certainty is lowest along boundaries.

opted to focus on decadal averages for two reasons. First, SNAP models show no clear indication that year-to-year variability is likely to increase over the course of the decade. In other words, if the average year becomes warmer, the hottest years are likely to become warmer proportionately, meaning that mean values can be used as a surrogate for extreme values. Second, given the long lag-times between climate change and biome shift and the additional lag times between climate change and many of the most crucial biome-driving processes (e.g. permafrost thaw and thermokarst), it is likely that biome shift is driven by averages rather than by extremes.

Choices for emission scenarios available included the A1B (mid-range, somewhat conservative) scenario, as well as the A2 and B1 scenarios. Although we continued to focus on A1B as the primary scenario of interest, we compared our results to those generated with the more severe A2 scenario and the highly conservative B1 scenario, in order to provide a broader range of possible outcomes.

Likewise, although the composite of all five GCMs is likely the most reliable choice for future climate projections, we decided to also look at outputs from each of the five models independently, in order to provide the broadest possible comparison of outcomes.

Projections in RandomForests™

We used the same 24 input variables used in clustering — monthly temperature and precipitation —when creating cliome projections. Using Random Forests™ , we matched these variables for each map grid-cell to the best-fitting cluster, thus assigning every location to a cliome. We first assigned the clusters to the same time period that was used to create them, but at the finest resolution available within the areas of interest (see Technical Addendum II). We then did the same thing for the selected future time periods (2030s, 2060s, and 2090s) for the A1B, A2, and B1 scenarios using the composite model, as well as A1B data for each individual model, all using SNAP climate projections. Thus, we created fine-scale cliome projections for each of these possible futures.

Describing each climate-biome according to its defining climate parameters

Each of the 18 clusters used in this project was defined according to 24 input variables — 12 months of temperature data and 12 months of precipitation. For ease of viewing, Figure 12 combines temperature values seasonally, and Figure 13 uses mean annual precipitation, however finer distinctions can be seen via the full dataset (see Appendix C). As has already been explained, the clusters were created so as to be as distinct from one another as possible, based on these climate parameters. Thus, each can be described according to the climate differences that exist between clusters. These differences are examined and described in great detail in Appendix C. However, to briefly summarize, the clusters can be characterized as follows:

1: The coldest, driest cliome particularly in summer and fall. Very harsh winters, very late springs, almost no summer, and very early falls.

2: Winters as cold as Cliome 1 (-31°C), but slightly more moderate in other seasons with a little more precipitation, although still very dry.

3: Similar to Cliome 2 in summer and fall, but more moderate winters and springs. Dry.

4: Winter and fall similar to Cliome 3, but earlier springs and warmer summers (8°C). Dry, despite slight increases in precipitation.

5: Increased precipitation (243mm). Winters similar to the coldest cliomes (1 and 2) but summer and fall similar to Cliome 4. Spring intermediate, most similar to Cliome 3.

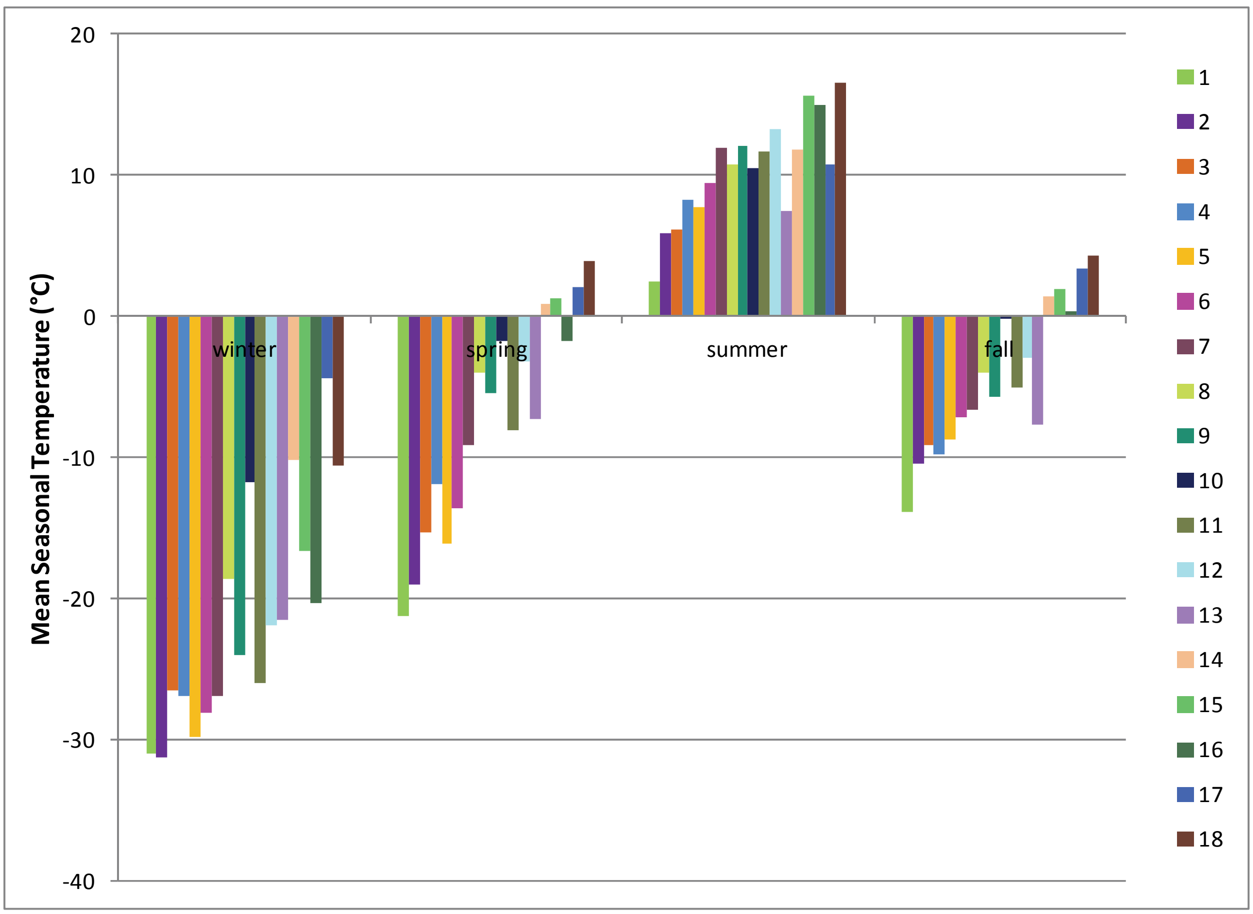

Figure 12 — Mean seasonal temperature by cluster. For the purposes of this graph, seasons are defined as the means of 3-months periods, where winter is December, January, and February, spring is March, April, May, etc.

6: Warmer summer and fall conditions than any preceding cliomes with increased precipitation (272mm).

7: Winters similar to Cliomes 2, 3, and 5, but warmer spring, summer, and fall than all preceding cliomes. Still fairly dry.

8: Markedly higher rainfall-equivalent (355mm) and much more temperature fall, winter, and spring temperatures.

9: Precipitation and summer/fall temperatures similar to Cliome 7, but warmer winters (-24° C) and springs.

10: Much milder winter, spring, and fall conditions and much higher precipitation than all preceding cliomes (561mm), with summers comparable to Cliome 8.

11: Temperatures similar to Cliomes 7 and 9 in summer (12°C). Intermediate between these two in winter and spring, but warmer than both in the fall, with higher precipitation, although drier than Cliome 10.

12: Moderate precipitation similar to Cliome 11 (420mm), but warmer in all seasons.

13: Cool falls and summers similar to Cliome 5, but spring comparable to Cliome 11 (-7°C) and winter similar to Cliome 12. Relatively wet, like Cliome 10.

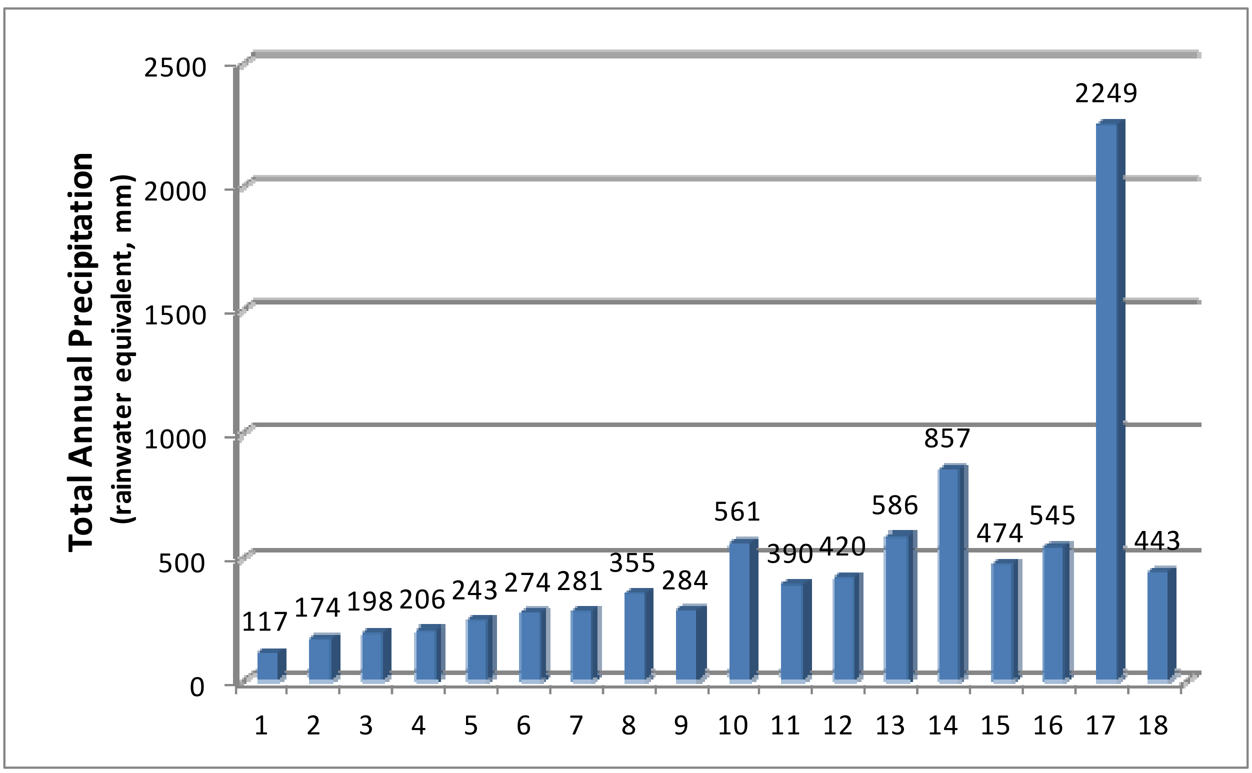

Figure 13 — Precipitation by cluster. Mean annual precipitation varies widely across the clustering area, with Cluster 17 standing out as the wettest.

14: Slightly warmer than Cliome 10 in all seasons, with even higher precipitation (857mm, the second-highest of all 18 cliomes).

15: Early springs, late falls, hot summers (16°C), and moderately cold winters. Moderate precipitation (474mm)

16: Moderately wet, with winters almost as cold as Cluster 13 (-20°C), but spring, fall and summer almost as warm as Cluster 15.

17: By far the wettest of all the clusters. Warmest winters of all clusters (-4°C), with warm spring and fall conditions and moderate summers similar to Clusters 8 and 10.

18: The hottest of all the clusters in spring, summer and fall. Winters similar to Cluster 14. Moderate precipitation.

Assessing similarities to existing land cover classes

In order to make our cluster-derived cliomes as useful as possible to land managers, we needed to define and describe them in a way that is meaningful, given the varied landscape knowledge of potential users. To meet this goal, we defined clusters not only as described above, by the mean values for monthly temperature and precipitation that defined each cluster, but also by comparing them to existing land-cover designations. We matched up clusters with four different classification systems using spatial analysis techniques to assess how congruent or incongruent they were. Thus, each cluster is defined spatially according to its location on a map representing recent conditions (Figure 8); mathematically, according to monthly temperature and precipitation; and qualitatively, according to the multiple available details that are available for four widely accepted land cover mapping systems:

- The North American Land Change Monitoring System (NALCMS)
- Advanced Very High Resolution Radiometer Land Cover (AVHRR) 1995
- GlobCover 2009
- Alaska Biomes (from Nowacki et al. 2001) and Canadian Ecozones (from Environment Canada)

For full details on the sources, creation, and uses of these systems, see Appendix D.

We assessed each of our eighteen cliomes based on the combined characteristics described by these sources. In summary, each cliome can be briefly described as follows, based on its overlap with these pre-defined categories. These definitions should be considered as an augmentation to the climate-derived descriptions already discussed.

1: Northern Arctic sparsely vegetated tundra with up to 25% bare ground and ice, with an extremely short growing season.

2: Cold northern arctic tundra, but primarily vegetated

3: More densely vegetated arctic tundra with up to 40% shrubs but no tree cover
4: Arctic tundra with denser vegetation and more shrub cover including some small trees
5: Dry sparsely vegetated southern arctic tundra
6: Northern boreal/southern arctic shrubland, with an open canopy
7: Northern boreal coniferous woodland, open canopy
8: Dry boreal wooded grasslands — mixed coniferous forests and grasses
9: Mixed boreal forest
10: Boreal forest with coastal influence and intermixed grass and tundra
11: Cold northern boreal forest
12: More densely forested closed-canopy boreal
13: Sparsely vegetated boreal with elevation influences
14: Densely forested southern boreal
15: Southern boreal/aspen parkland
16: Southern boreal, mixed forest
17: Coastal rainforest, wet, more temperate
18: Prairie and grasslands

For full details on the characteristics of each cliome and the comparison between existing land cover designations and cluster-derived cliomes, see Appendix C.

Results

Overview

Projecting cliome shifts over time allows for identification of areas that may be stressed, or undergoing a change process. Areas projected to undergo the least change are likely to be the least stressed, and will thus be classified as likely refugia, whereas areas with the greatest change (more than one shift by the end of the century) would be defined as high-risk or sensitive regions.

Results show marked shifts in cliomes, with the boreal and arctic zones shifting northward and diminishing in size. This trend is consistent with the historical trends seen in the data for river breakup over the course of the previous century. By 2069, projections indicate marked northward shifts and some Canadian cliomes moving in from the east. It is important to note that these shifts represent potential rather than actual biome shift, since in many cases it is unconfirmed that seed dispersal, soil formation, and other functional changes could occur at the same rate as climate change. We know that permafrost (which is climate-linked, but with varying lag times behind changes in air temperature) and other geophysical characteristics (both climate-linked and unrelated to climate) strongly influence species composition (Viereck et al. 1983; Hollingsworth et al. 2006).

Our models indicate that large-scale change is likely by the end of the century. As will be examined and discussed in the following sections, when these changes are assessed within a conservation framework, they will pose new opportunities and challenges for land managers. As discussed previously, results obtained using the mid-range emissions scenario and the five-model average are likely to be robust and relatively conservative, and are the primary focus of our analysis of areas of greatest and least change, and associated discussion of vulnerability, resilience, refugia, and conservation planning. However, in order to show the range of uncertainty implicit in SNAP's models, further results presented below examine outputs for single models and for other emission scenarios.

Baseline historical climate

Based on the assumption that today's ecological systems are as much a product of past climate as of current climate, we include historical climate (i.e., baseline) as part of our analysis. This time period is not only the same one we used to create our clusters, but also the baseline used in the PRISM data that SNAP used to downscale the GCMs (Figure 14).

Note that not all 18 clusters appear in the study area; Cliome 18, characteristic of warm prairie and agricultural land, is absent, and Cliomes 15 and 16 are extremely limited. The arctic islands of NWT (Banks, Victoria, Prince Patrick, Eglinton, Melville, Borden, Brock, and MacKenzie King Islands) are entirely Cliome 1. The arctic coast is primarily Cliome 3, and Cliomes 5 and 6 are also common across the arctic. Cliomes 8, 9, 12, and 13 characterize interior Alaska and Yukon, and most of interior NWT are Cliomes 7, 9, 11, and 12. Cliome 14 is fairly limited.

These baseline maps can be contrasted with maps for more recent time periods as well as with future projections. It can be assumed that the physiological stress to biomes caused by mismatch between prevailing climate conditions and the thermal and moisture tolerances of existing vegetation and species assemblages is not starting now, but rather has been underway for approximately half a century.

Projected change: A1B emissions scenario using the composite GCM data

The results presented in Figures 15-17 all depict a composite (average) of the five Global Circulation Models that SNAP has downscaled for use in climate projections. These models, each created by an interdisciplinary team of scientists and modelers, include ECHAM5 (Germany), GFDL2.1 (United States), MIROC3.2 (Japan), HADLEY3 (UK), and CGCM3.1 (Canada) (see also Technical Addendum 1.)

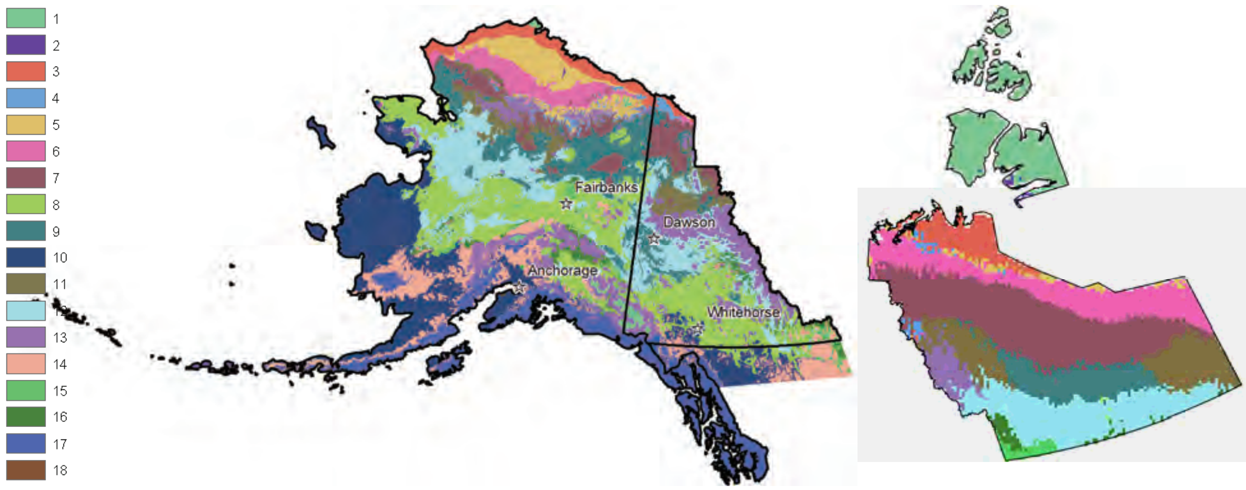

Figure 14 — Modeled cliomes for the historical baseline years, 1961-1990. As in all projected maps, Alaska and the Yukon are shown at 2km resolution based on PRISM downscaling, and the Northwest Territories are shown at 18.4 km resolution based on CRU downscaling.

Five-model A1B results for the time periods 2001-2009, 2030-2039, 2060-2069, and 2090-2099 can be seen in Figure 15. The overall trend is a northward shift in cliomes, with the northernmost cliomes disappearing altogether.

The coldest driest cliomes, 1 and 2, are confined to the NWT, with Cliome 1 all but disappearing by the 2090's, replaced by Cliome 3. In the 2000's, Alaska's arctic coast is primarily Cliome 3, the interior and Yukon arctic are Cliomes 4, 5, and 6, and the NWT (non-island) coast is Cliomes 3 and 6. The shift in the arctic between the 2000's and the 2030's is slight, with the greatest changes being loss of much of Cliome 9 in mountainous arctic regions and decrease in Cliome 7 in the NWT. However, by the 2060's projections show Cliome 3 disappearing except on the islands of the NWT, and by 2090 the change is marked, with Cliomes 4-5 gone, Cliome 6 greatly reduced, and Cliomes 8 (currently characteristic of interior boreal regions of AK and the Yukon), 10 (currently characteristic of western coastal AK, the Seward peninsula, and northern BC), and 18 expanding over the region. Cliome 9, currently found in more mountainous regions, persists in some areas.

Changes in interior regions of AK, Yukon, and NWT are also predicted to be pronounced by the end of this century, with the extent of Cliomes 7, 8, 9, 11 and 12 shifting northward and/or shrinking in favor of Cliomes 14 and 15 (currently found in the southern boreal of AK and BC), and 18. The appearance of Cliome 18 over large areas of southwestern AK and southern Yukon and NWT is particularly startling, since it is currently limited to the hottest most southerly portion of the prairie provinces.

Overall, some cliomes are predicted to become much more prevalent, particularly Cliomes 14 and 18 in Alaska and BC, and Cliomes 8 and 15 in NWT.

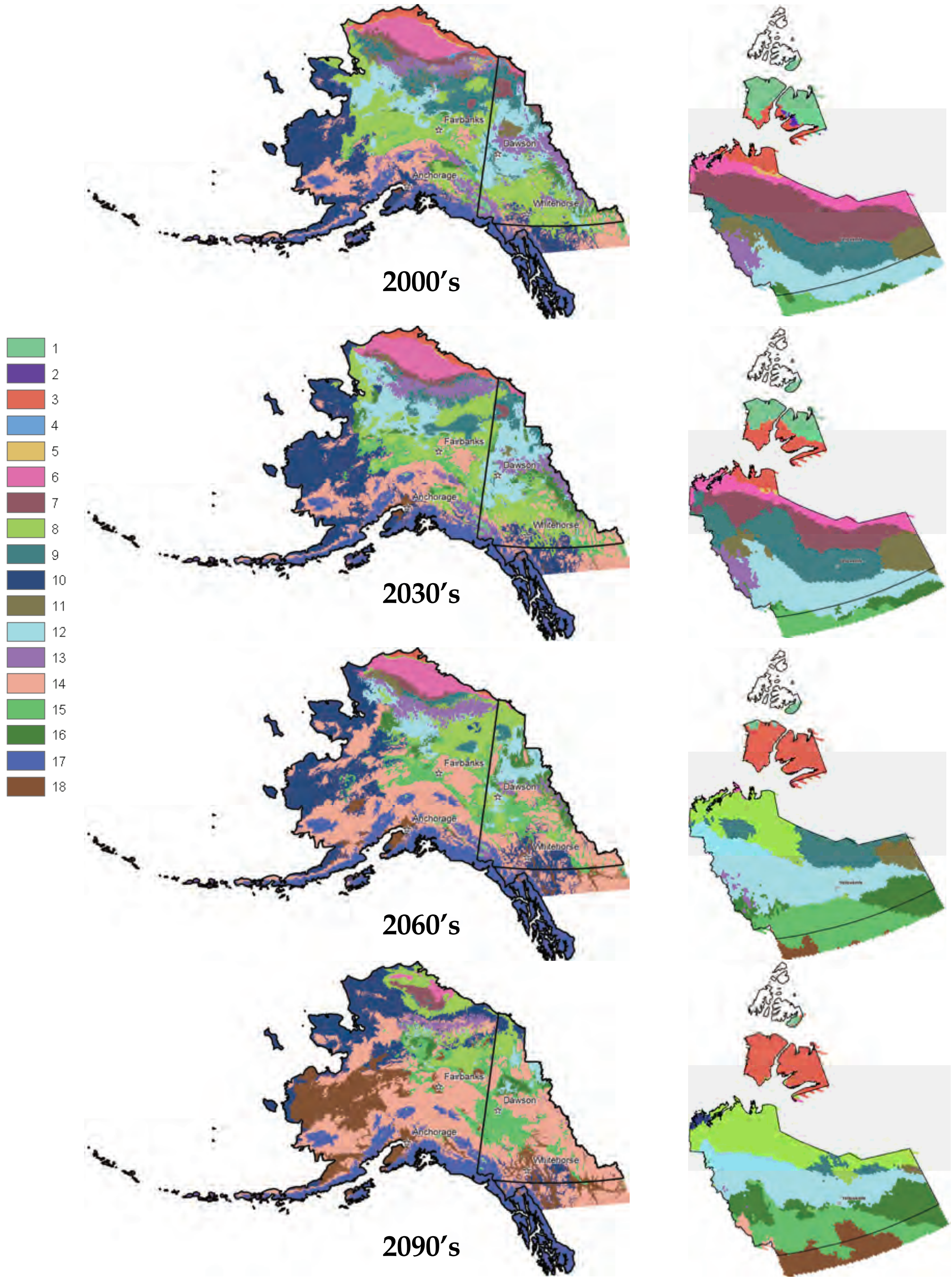

Figure 15 — Projected cliomes for the five-model composite, A1B (mid-range) climate scenario. Alaska and the Yukon are shown at 2km resolution and NWT at 10 minute lat/long resolution .

Less extreme change is predicted in the Aleutians, southcentral AK, and Southwest AK. As will be discussed in more detail later, this may be due to the limited number of cliomes with the high rainfall characteristic of these regions.

Projected change: comparing A1B, A2, and B1 emissions scenarios using composite GCM data

In order to assess the uncertainty associated with assumptions about human behaviors at the global level over coming decades, we examined the differences between future projections for our primary emissions scenario, A1B, and two other scenarios described by the IPCC (see Technical Addendum 1).

The A2 emissions scenario describes a world with higher concentrations of greenhouse gases than the A1B scenario. At the time it was created, it was viewed as a somewhat pessimistic outcome; however, given recent global trends, it may be more likely than the more conservative possibilities (Nakicenovic et al. 2001, Raupach et al. 2007).

Figure 16 shows projections results for the A2 scenario for the same future decades assessed for A1B. Overall, the trends are very similar, with cliomes moving northward over each time step, and the most notable shifts occurring in the latter part of the century, between 2060 and 2090. As compared to the A1B projections, the A2 projections for 2090 show Cliome 8 reaching the islands of the NWT, and a much higher occurrence of Cliome 10 in northern NWT. Differences in the projections for Alaska and the Yukon are more subtle, but also include a higher occurrence of Cliome 10 on the arctic coast.

The B1 emissions scenario is based on a set of more optimistic assumptions about energy sources, energy use, and human population growth. Given our current global trajectory and the lack of unifying governmental agreements regarding emissions controls, it is extremely likely that the greenhouse gas emission levels depicted in this scenario will be overshot. However, B1 projections offer a useful perspective on the most conservative of climate change predictions. Figure 17 shows projected outcomes based on the B1 scenario. As might be expected, less change is predicted than in the A1B or A2 scenarios, although the overall pattern of change is similar. Cliomes are expected to shift northwards, and some cliomes are expected to become far more common while others are reduced or disappear. Less encroachment of Cliome 18 is predicted, as compared to the other two emission scenarios, and the spread of Cliome 14 is also less extreme. However, the trajectory depicted in Figure 17 appears in many ways to be merely a slower version of that seen in Figures 14 and 15; the predictions for the 2090's under the B1 scenario mimic those for the 2060's under the A1B or A2 scenario.

Projected change: comparing among five models

Although the five GCMs SNAP have been shown to be the most reliable for this region,

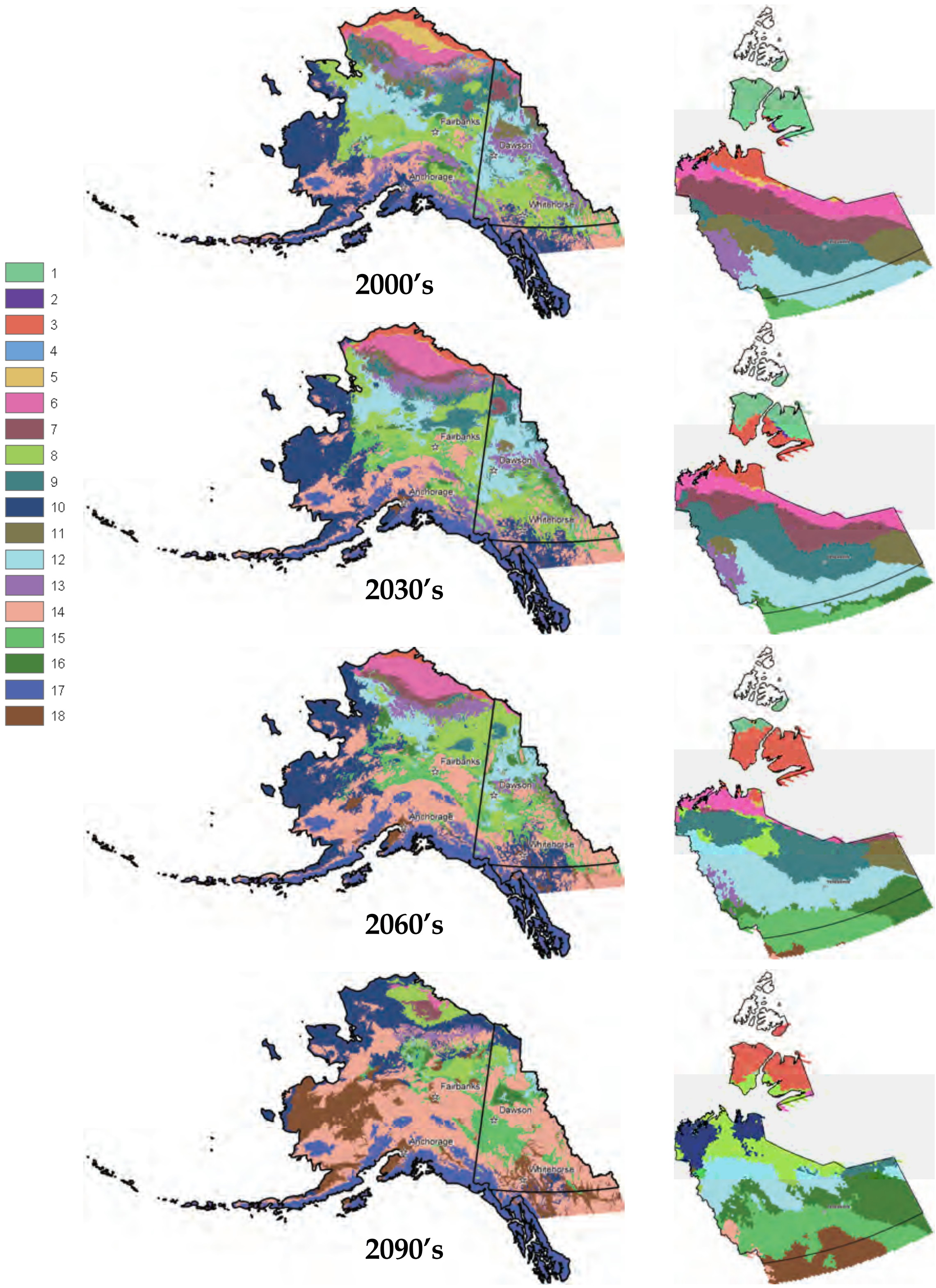

Figure 16 — Projected cliomes for the A2 emissions scenario. This scenario assumes higher concentrations of greenhouse gases, as compared to the A1B scenario.

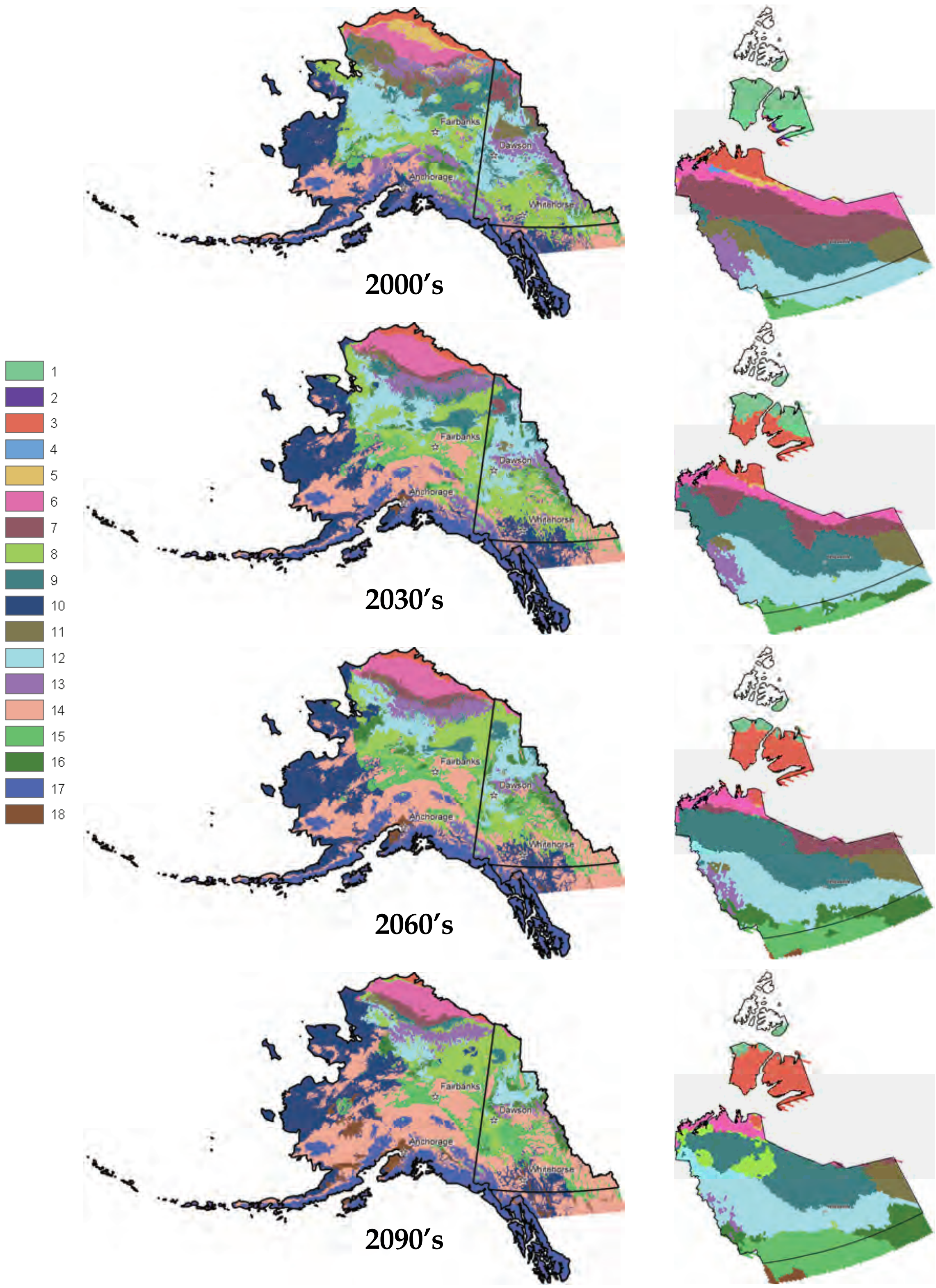

Figure 17 — Projected cliomes for the B1 emissions scenario. This scenario assumes lower concentrations of greenhouse gases, as compared to the A1B scenario.

they are not identical in either their assumptions or their outputs. Comparing among the five models serves as a useful means of gauging uncertainty in the cliome predictions produced for this project. Thus, we created predictions for the A1B emissions scenario for each of the five models independently, as shown in Figure 18.

The outputs from the five models varied in the severity of the change they predicted, particularly for longer time periods (by the end of the century). For the most part, the CCCMA model offered a view of the future with the least change, while the ECHAM5 model predicted the greatest degree of change. However, these trends varied somewhat by region. For example, MIROC predicted the greatest amount of change on the islands of NWT, although ECHAM5 showed greater changes on the northern NWT mainland. GDFL predicted that the central Alaskan arctic would become entirely Cliome 8, while other models showed at least minimal retention of Cliome 3 in that region. GDFL also showed the greatest proliferation of Cliome 14 across the interior of Alaska and the Yukon, where other models showed large regions of Cliomes 8 and 15 in addition to 14. Interestingly, GDFL showed the largest increases of any model in Cliome 18 in NWT, but the most moderate increases in this cliome in Alaska and the Yukon.

Despite the differences between the outputs of the five models, the overall pattern of northward shifts holds true, with changes becoming more pronounced towards the end of the century, and some arctic cliomes disappearing.

Regions of greatest and least change

We assessed the regional resilience and vulnerability of cliomes in the study area by performing spatial analysis to see which pixels were predicted to shift from one cliome to another in each time period — from the 2000's to the 2030's, the 2030's to the 2060's, and the 2060's to the 2090's (Figure 19). Each grid cell had the potential of shifting zero, one, two, or three times. Although it was theoretically possible for a grid cell to shift back to its original cliome, this was unlikely, given the directional nature of the projected climate change. Thus, the number of projected changes in cliome can reasonably be used as a proxy for the degree of ecological pressure due to direct effects of changing climate in a particular region.

It should be kept in mind that this method of calculating resilience and change is approximate and predictive rather than absolute. Uncertainty is introduced at several levels. First, as already discussed, cliome projections vary according to which emission scenario is selected and which model (or model composite) is used. Second, not all cliome shifts represent an equal landscape shift, since some cliomes are more ecologically similar to one another. For example, the vegetation observed in Cliome 1 and Cliome 2 is likely to be similar high arctic species, whereas Cliome 17 and Cliome 18 are likely to have much less in common. These disparities are explored in depth in the Appendices. Third, as shown in Figure 9, cluster designations

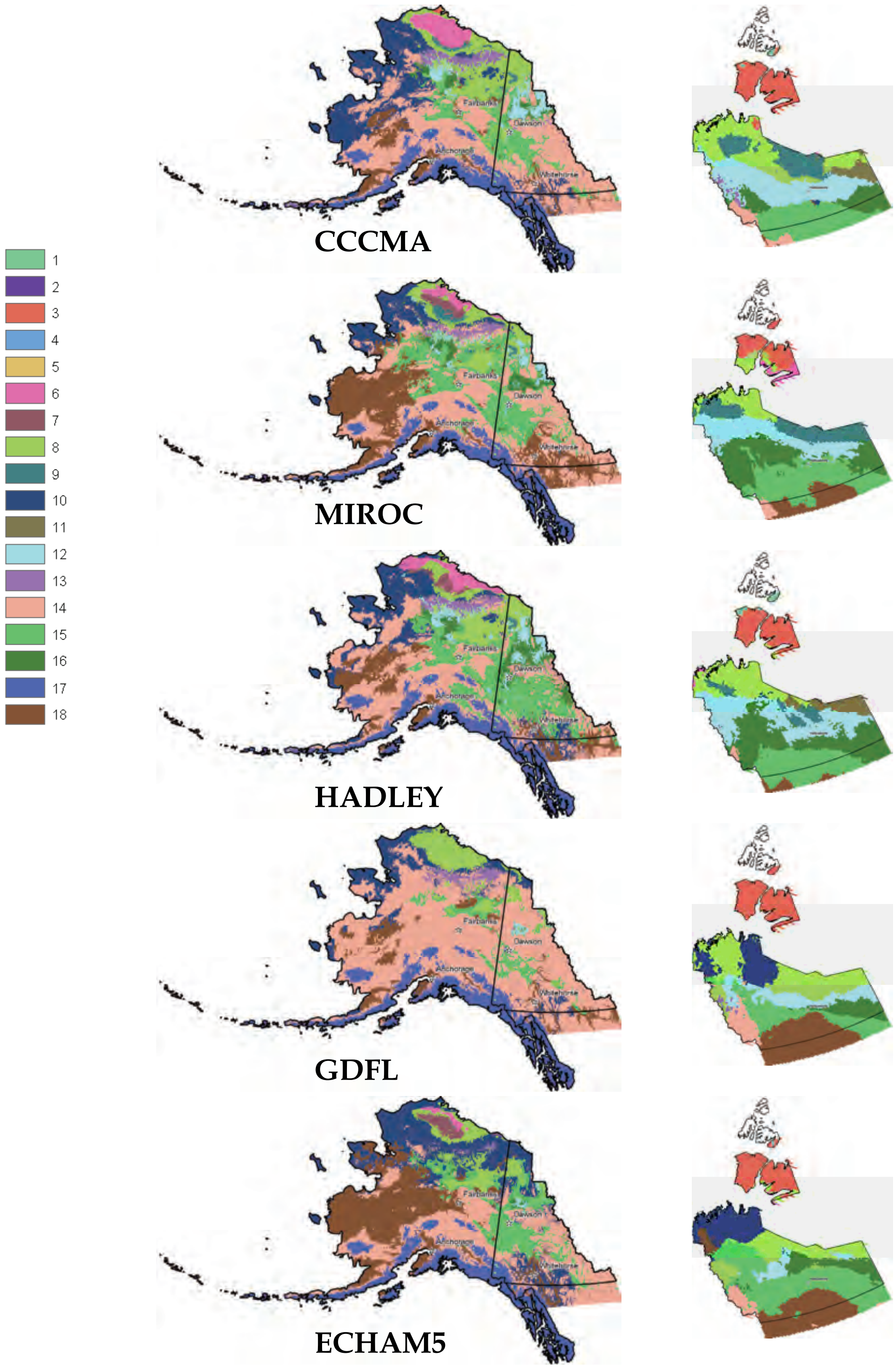

Figure 18 — Projected cliomes for single models. The five GCMs offer differing projections for 2090.

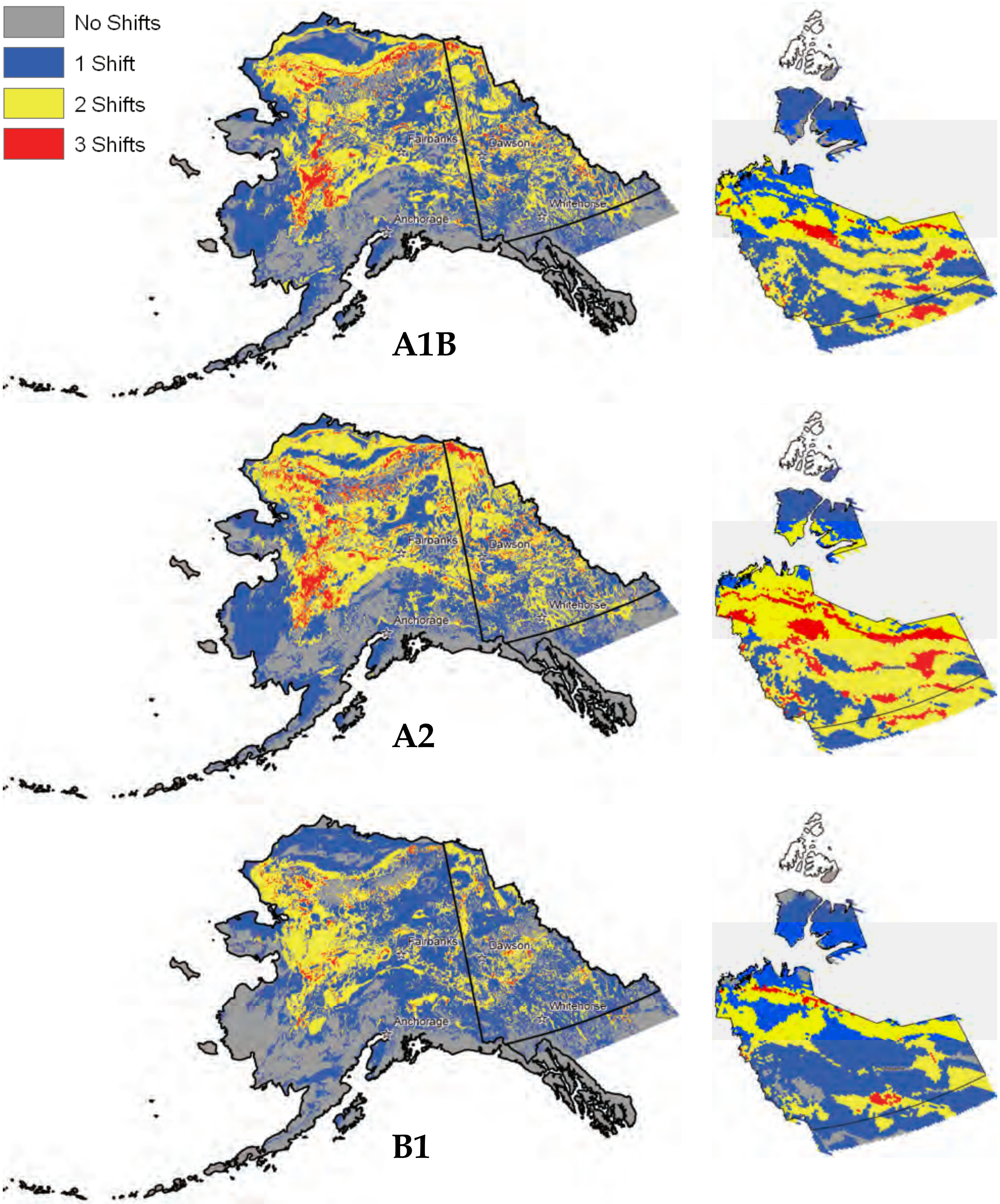

Figure 19 — Projected change and resilience under three emission scenarios. These maps depict the total number of times models predict a shift in cliome between the 2000's and the 2030's, the 2030's and the 2060's, and the 2060's and the 2090's. Note that number of shifts does not necessarily predict the overall magnitude of the projected change.

are more uncertain near cluster boundaries. A shift in these areas can be assumed to be less meaningful than a shift near the "core" of a cluster. Finally, some clusters, particularly Cliome 17, are effectively "locked" on the landscape, not because climate change is not expected in the regions where they occur, but because our clustering region and clustering methodology did not offer an alternate cluster similar enough to capture the expected change.

Nevertheless, assessing the study area according to the number of projected cliome shifts offers relatively robust results. Even if some of the shifts tallied using this method reflect only minor change, as might occur on cluster boundaries or between relatively similar clusters, a triple shift is clearly more significant than a shift of only one — or even zero — cliomes. Moreover, since the predicted cliomes shifts are presented in Figures 14-16, land managers can assess for themselves what changes and what cliomes are under discussion for any particular region, and can reach independent conclusions about what ramifications this may have for land management. This will be explored further in the Discussion section.

In analyzing the ecological change suggested by our models, it is important to note that interpretation of resilience and vulnerability is dependent on not only the number of cliome shifts that are likely to occur over the course of future decades (as shown in Figure 19), but also the ecological disparity and physical discreteness of the cliomes in question. Shifts between cliomes that are noncontiguous on the current landscape and/or highly distinct in their vegetative classification may suggest more important changes or greater ecological stress. Appendices C, D, and E offer land managers the opportunity to explore these issues in detail by comparing the climatic and vegetative characteristics of each cliome.

Results indicate that the regions most vulnerable to ecological shifts under the influence of climate change are likely to be the interior and northern mountainous portions of Alaska; the northern Yukon; and much of the Northwest Territories. Although the A1B and A2 emissions scenarios predict more cliome shift overall, as compared to the more conservative B1 scenario, the patterns hold true across all three. Notably, there are no areas of the NWT predicted to retain their current cliomes.

Figure 20 shows the predicted number of cliome shifts for single-model results. Although each model differs from the others, the patterns of change and resilience across the region remain relatively stable. Little change is expected in the Aleutians, southcentral, and southeast Alaska, including the Alaska Range. Moderate change is predicted in the high peaks of the Alaska Range, the interior foothills of Alaska's arctic, Alaska's west coast, the Yukon Flats, the southern Yukon, and the arctic coast and islands of the NWT. More extreme cliome shifts are predicted in all other areas, including the arctic coast or Alaska and the Yukon, western interior Alaska, much of interior Yukon, and northern and eastern interior NWT.

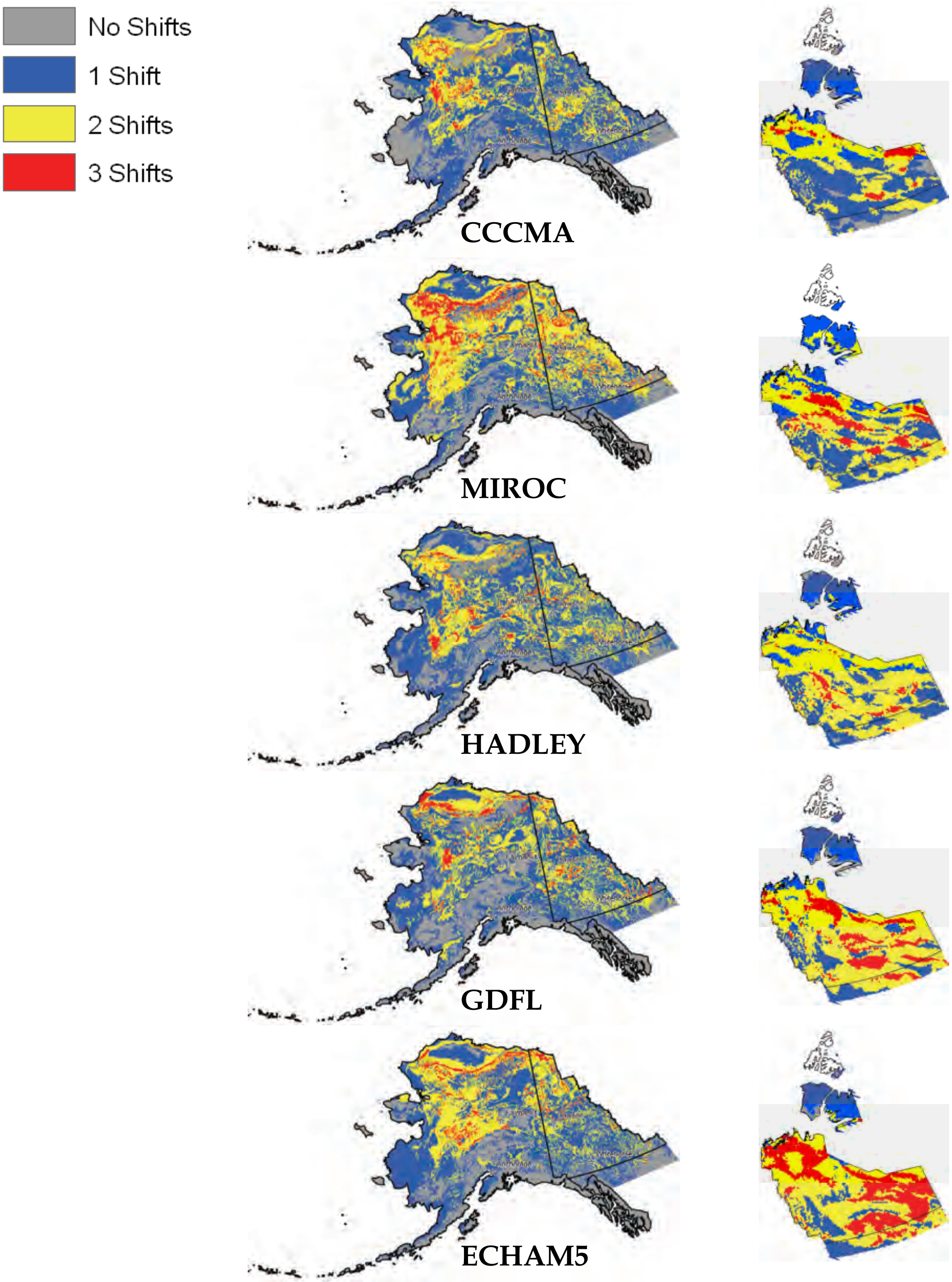

Figure 20 — Projected change and resilience for single models. Maps depict between zero and three shift in cliome between the 2000's, 2030's, 2060's, and 2090's.

Discussion

Interpretation of Uncertainty

By presenting a range of results, including outputs generated using all five GCMs and three different emissions scenarios, we've attempted to demonstrate the range of uncertainty associated with all predictions about future climate and future cliomes. Overall, the predicted trends are robust across all these potential futures, and are consistent with historical trends seen in river breakup data. However, for specific map locations, the story told by the model outputs sometimes differs.

Cliomes vs Biomes — interpreting ecological change

In order to interpret project results fully, this uncertainty must be coupled with the biological and biophysical unknowns associated with biome shift. Even if an area is predicted to change from a tundra -dominated cliome to a forested cliome, or from a mixed shrub environment to dry grassland, such changes are unlikely to happen smoothly and spontaneously, and are certainly not going to happen instantly. Seed dispersal takes time. Changes to underlying soils and permafrost take even longer. In many cases, intermediate stages are likely to occur when climate change dictates the loss of permafrost , a new forest type, or new hydrologic conditions. These intermediate stages — slumping, thermokarst, increased fires — may represent greater landscape change than the simple shift from one cliome to another.

Even in cases when biomes do shift on their own, they almost never do so as cohesive units. Different species have very different abilities to spread and disperse into landscapes that have (climatically) become able to support them, resulting in trophic mismatches. Invasive species may have greater dispersal abilities than native ones. It may become increasingly difficult to even define what an "invasive species" is, given that climate-driven change is likely to force unfamiliar species into new territory across the far north.

Comparisons with existing land cover designations

Although assessing resilience and vulnerability according to the number of cliome changes predicted in the next 90 years offers a clear metric for cross-regional comparison, it is not the only means by which we can ascertain where we may find biological refugia and areas of greatest concern. Comparison of cliomes to existing land-cover designations, as detailed in Appendix E, offers a path toward more complex interpretation of project results. For example, shifts between Cliomes 1, 2, and 3 appear to represent relatively minor vegetative changes, according to most classification systems. Cliomes 4, 5, and 6 are also similar to 1,2, and 3, relatively speaking; they are all sparse or shrubby grass/moss/lichen/tundra environments, according to the land cover designations we examined. However, a shift from any of these to Cliome 8 — as is predicted for much of the arctic in Alaska and the Northwest Territories — represents a more profound change, since this cliome is forested. In some cases the significance of the potential shift is apparent under some vegetation classification systems but not others, which is why we chose not to limit ourselves to one. For example, although the shift of much of western Alaska from Cliome 10 to Cliome 18 might seem slight according to AVHRR, which classifies both these clusters as primarily grassland, it seems more profound when viewed through the lens of NALCMS, which identifies much of Cliome 10 as subpolar shrubland, whereas Cliome 18 is cropland.

In addition to noting resilience of existing cliomes in their current locations, it is important to look at resilience of cliomes overall. In other words, which characteristic clusters of climate variables seem to be disappearing from the landscape, and which are becoming much more common in the study area? Perhaps not surprisingly, the cliomes that are slated to become more common are the warmest ones. Cliomes 16 and 18 are virtually absent in the 2000's, but prevalent in the projections for the 2090's. Cliomes 14 and 15 are predicted to become much more prevalent. The implication is that closed-canopy forests and warm grasslands suitable for agricultural production will become much more common. On the flip side, cliomes 1-7 are expected to shrink dramatically or vanish altogether, except in the arctic islands. These cliomes are all currently characterized by sparse grass/lichen/moss/shrub environments — the tundra that is habitat for a wealth of migratory birds and caribou, among other species. Cliome 13, characteristic of mountainous areas, also seems likely to be greatly reduced.

Implications at the species level

The loss or diminishment of cliomes that currently support a tundra environment does not mean that all tundra will disappear by the end of the century. Likewise, the conversion of western AK and southern NWT to a cliome currently characterized by corn and canola farms does not mean that these regions are going to become a breadbasket for agriculturalists. However, these projected changes do strongly imply that these regions will be stressed, ecologically, and in the process of change. At the species level, this may mean higher susceptibility to diseases and pests, out-competition by species from further south, and heat-shock from more extreme summer temperatures and lessened water availability. Inevitably, some species will be more at risk from these stressors than others. Species such as caribou, which currently and historically have been found across a wide range of cliomes, may prove more adaptable than Beringia relic species such as the Alaska Marmot *(Marmota broweri)* Alaska marmot, which appears to be confined to alpine habitats in the Brooks Ranges and adjacent mountains (Gunderson et al. 2009). Species that can disperse rapidly may prove more resilient and adaptable than those that cannot.

Ultimately, this modeling effort cannot provide specific data about the fate of any one species. It can, however, help inform local residents, land managers, and scientists, who possess location-specific and species-specific knowledge about the behavior of species and species assemblages. We cannot predict what will happen to species of concern if a particular location is predicted to shift from a cliome characterized by moss/grass/lichen tundra to precipitation and temperature conditions supporting shrub tundra in the next 20 years, and then to characteristics displayed by cliomes with spruce forest in the next 30. Those with detailed knowledge of the species in question are necessary to answer this question, because they are equipped to assess how well the species might fare in each of these environments, or how quickly a species might be able to move to a more promising location. When coupled with this knowledge, the relative resilience and vulnerability of a site becomes valuable information. Stakeholders may seek to implement research that evaluates hypothesized responses of species to expected change in habitat based on forecasted climate change.

Implications for Conservation, Research, and Management

Central to the goals of this project was the idea that the products generated from it be useful in guiding the direction of on-the-ground management actions. Meeting this goal depends not only on the proper interpretation of model outputs, but also on the perspective from which management decisions are approached. In the past, local, state, and Federal land managers tasked with conservation directives have generally focused their efforts on maintaining or restoring species abundance and/or diversity, based on some approximation of "historic conditions." However, more recent thinking is challenging this approach (Marris 2011, Cole and Young 2010). In the face of ongoing climate change and other large-scale changes, preservation is no longer a useful benchmark.

Adaptation may now mean managing toward less-certain future conditions, rather than aiming for historical or current conditions (Choi 2007 ; Harris et al. 2006). The Intergovernmental Panel on Climate Change recognizes that adaptation strategies can be anticipatory or reactive. Anticipatory adaptation works with climate change trajectories; reactive adaptation works against climate change, toward historic conditions. The former approach manages the system toward a new climate change-induced equilibrium; the latter abates the impact by trying to maintain the current condition despite climate change (Johnson et al. 2008).

The modeling results in this study advance the dialogue that we need to have within our larger conservation community, at the trans-boundary level. We can begin assessing the relative trade-offs of doing nothing to address climate change or doing something, and whether that something should be reactive or anticipatory in nature.

The identification of cliome refugia offers a significant management opportunity in this region of the world, where historic ecosystems are mostly intact, and refugia can act as population sources for colonization of novel areas. However, given the nature of the modeling, and as previously discussed, those areas defined as refugia (with no projected cliome shifts by 2100) are not necessarily going to face no change in coming decades, and may be at risk if total range distribution would be diminished. Likewise, areas that are expected to shift cliomes two or three times may not be "lost" and should certainly not be written off, from an ecological perspective. Today's refuge for one species may prove to be tomorrow's refuge for another. Wilderness designation under the 1964 Wilderness Act is not predicated on ecological values but instead on perceived wild conditions. Additionally, management intervention to move species in or out of federally designated wilderness may be greatly restricted or prohibited if not deemed necessary to maintain wilderness values or deemed detrimental to use of wilderness as a scientific control for evaluating management intervention (such as species translocation) on other lands.

Of course, this type of shifting causes difficulties at an administrative level. In both the US and Canada, protected areas and conservation lands are relatively "locked in," which means that if a species of concern moves its range, its conservation status may be at risk.

Fortunately, there are also other tools and approaches to strategic land protection including working with Alaska Native or First Nation communities and organizations interested in identifying and designating refugia as special places to sustain traditional ways of life, as well as a myriad of other approaches. In addition, there may be opportunities to protect landscape-level migration corridors through multi-partnered conservation agreements.

There may be opportunities to manage habitats to sustain or create dispersal corridors between biome refugia and sites of future biome establishment, or to protect specific habitat areas or species from anthropogenic stressors to give them time and space to adapt to a changing climate and environment. In that regard, this type of modeling can re-direct our attention to areas that may be at greatest risk.

Appendix A: Additional Reading and References

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