Research Plan for Regional Climate Impacts

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About PCIC

The mission of the Pacific Climate Impacts Consortium is to quantify the impacts of climate change and variability on the physical environment in Pacific North America. The Pacific Climate Impacts Consortium is financially supported by BC Ministry of Environment, BC Hydro, BC Ministry of Forests and Range and several regional and community stakeholders. For more information see *http://www.PacificClimate.org*.

Research Plan for Regional Climate Impacts

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Executive Summary

Observational evidence has revealed that Earth's climate is undergoing a major change in response to increasing greenhouse gas emissions. Climate model simulations have indicated that this observed change will increase substantially over the course of the 21st century. While there is great certainty that globally-averaged temperature and precipitation will increase in the future, the climatic response will be locally diverse, especially for precipitation, and will vary by region and with topography. This is particularly true for Pacific North America where climate is strongly influenced by the El Niño/Southern Oscillation, and where complex topography distributes precipitation in ways that are not well simulated by global climate models.

The Pacific Climate Impacts Consortium (PCIC) makes practical information available to government, industry, and the public. PCIC seeks to bridge the gap between the capabilities of global climate research and the need to understand and react to impending climate change. The consortium of researchers and stakeholders is supported by staff with resident expertise in physical sciences that conduct targeted, applied research.

Within this context, the Regional Climate Impacts (RCI) Theme was designed with the objective ***to deliver regional projections of future climate for adapting to impacts on communities, ecosystems, and water resources.***

The RCI Research Plan structures work around the following components:

- User Needs Assessment
- Regional Climate Change
    - downscaling tool development
    - quantifying uncertainty
- Impacts on Communities, Ecosystems and Water Resources
- Products and Services

This research plan and the RCI Theme were prompted by the extraordinary endowment from the BC government that supports the PCIC organization. Consequently, this plan defines and explains the scope of work that PCIC intends to accomplish in support of the BC Climate Action Plan and provincial intentions to adapt to climate change in British Columbia (Climate Action Secretariat, 2008; Climate Action Secretariat, 2010).

1. Introduction

Modern society faces an unprecedented level of risk from climate change. In response to increasing greenhouse gas concentrations, significant warming and a redistribution of precipitation are projected by global climate models (GCMs) for the coming decades (Figure 1). Historical climate trends and projected change strongly depend on topography and other regional characteristics. Furthermore, our ability to assess impacts on local communities and ecosystems, and hence our ability to develop adaptation strategies, depends on climate information on a regional, or even local, scale. Procedures are therefore required to “downscale” the coarse and imperfect GCM output to the smaller scales. The downscaling results must be scientifically sound as well as useful for applications by local experts in socio-economic sectors influenced by climate variability and change (Conference Board of Canada, 2009).

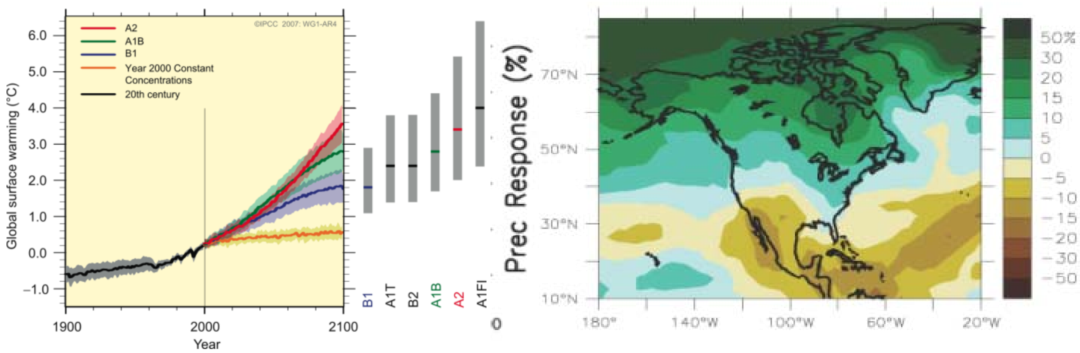

Figure 1: Projected global change. Left: global surface temperature. Right: North America percent change in annual precipitation by 2080-2099 compared with 1980-1999. Source: Figures SPM 5 and 11.12 from IPCC Fourth Assessment Report Working Group I (IPCC, 2007; Solomon et al., 2007).

Producing high-resolution future climate projections is a challenging process. For example, the El Niño/Southern Oscillation (ENSO) signal is large in Pacific North America (PNA) and anthropogenic climate trends are occurring simultaneously alongside natural inter-annual variability. In addition, complex surface topography and proximity to the Pacific Ocean create regional and micro-climates ranging from maritime to alpine. This increases the challenge of downscaling GCM output to a region or locality. However, it is at these local scales where ecosystems and communities are most strongly affected and where credible and useful information is needed most. Therefore, determining the magnitude of climate change in the context of natural variability and quantifying the uncertainties present in estimates of climate impacts are essential elements of the RCI Research Plan.

The Pacific Climate Impacts Consortium (PCIC) consists of individuals and organizations sharing a vision to *stimulate collaboration between government, academe and industry to reduce vulnerability to extreme weather events, climate variability and the threat of global change.* For this purpose PCIC must understand, quantify, and communicate current information on climate change and its impacts within Pacific North America. PCIC forms a bridge between the climate research community and user-stakeholders who need to initiate adaptation measures in response to expectations of climate variability and change. The work of PCIC is focussed on four overlapping themes:

- **Regional Climate Impacts:** climate variability and change, climate change scenarios and downscaling to high resolution,

- **Hydrologic Impacts:** hydrological modelling and climate model diagnostics of changes to the water cycle,
- **Ocean Influences:** storm surge, sea level rise, Pacific storms and seasonal climate prediction,
- **Climate Analysis:** historical data, analysis and extreme weather events.

The first of these themes, Regional Climate Impacts (RCI), is a cornerstone of PCIC and the target of this research plan. Regional change is already occurring and is expected to continue, as shown in Figure 2 (Rodenhuis et al., 2007).

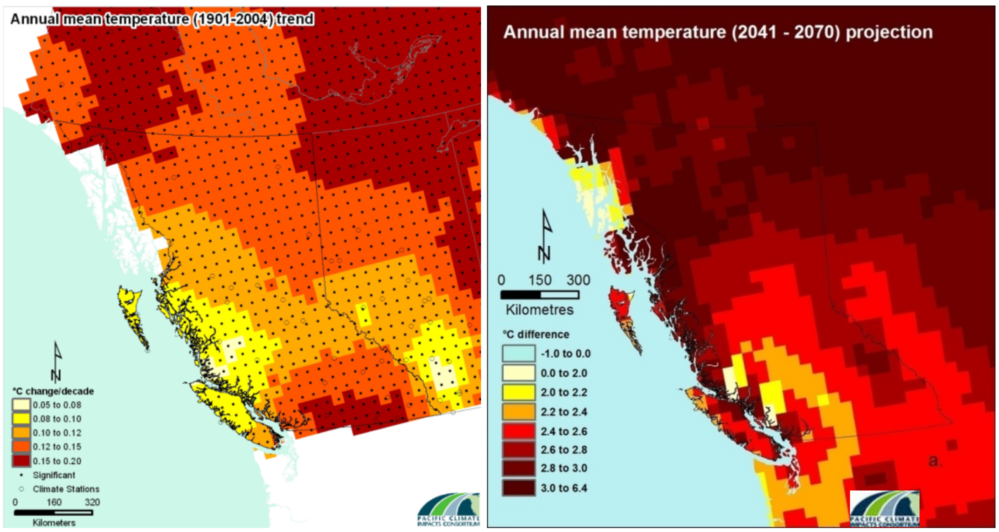

Figure 2: Analysis by PCIC of historical and future annual temperature change in BC. Left: historical trends 1901-2004. Right: example realization of projected future change by 2041-2070 compared with 1961-1990. Data sources: CANGRID historical gridded observations from Environment Canada and CRCM4.1.1 following A2 emissions scenario from Consortium Ouranos (Rodenhuis et al., 2007).

2. Purpose of the Research Plan

The purpose of this plan is to define and structure the Regional Climate Impacts Theme, and to identify priority projects that will transform ideas and concepts into action and accomplishments. This is a plan for projecting future climate conditions along with estimates of uncertainty that will be displayed as climate products for BC and the Pacific North America (PNA) region (Figure 3).

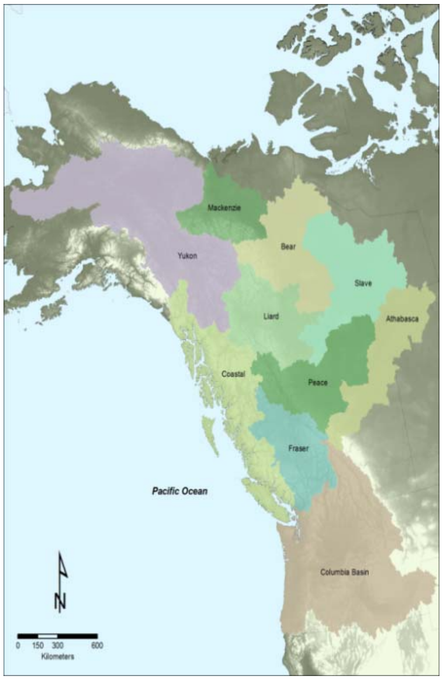

Figure 3: The Pacific North America (PNA) region as defined by the watersheds of British Columbia. The region extends north to Alaska, the Yukon and Northwest Territories, south into the Pacific Northwest of the United States, and eastward into the northern districts of Alberta and Saskatchewan.

The Regional Climate Impacts Theme is motivated by the need to adapt to the impacts of climate change (Climate Action Secretariat, 2008; Climate Action Secretariat, 2010). The structure of the theme is designed in order to deliver information to assist in meeting the adaptation needs of stakeholders in a range of socio-economic sectors:

- Adaptation to global change is a relatively new concept. It requires recursive interaction (Section 3.1) between estimates of climate conditions and user assessments of vulnerability.
- Adaptation is implemented on a local or regional scale; climate change is modelled on a global scale. This mismatch is addressed by downscaling global climate model results to high resolution (Sections 3.2.1 and 3.2.2).
- The management of risk is a central element of adaptation. Future climate projections must be accompanied by quantitative estimates of uncertainty (Section 3.2.3).
- Estimates of future climate conditions are the input to subsequent decision support tools and climate impact models (Section 3.3) that are used by stakeholders in a range of socio-economic sectors including communities, ecosystems, and water resources.

- PCIC helps stakeholders prepare for climate change by providing a suite of products and services (Section 3.4) designed to meet user needs, even as those needs evolve.

2.1. Limitations and Challenges

To achieve the purpose described in the previous section, this research plan must address several limitations and challenges:

1) *Limited historical observations* – Historical observations are essential for the development and verification of downscaling tools. The area of BC is 944,735 km^2, but contains only six observational climate stations which are currently active and have been operating for a minimum of 100 years. There are only 54 reference climate sites in this area, although there are approximately 280 additional sites with daily observations of temperature and precipitation.[i] Also, these sites are distributed unevenly over the province, leaving large areas of northern BC with very limited climate information. Therefore even the present climate is not well-defined and this compromises the ability to use regional estimates of future climate conditions that are computed from low-resolution climate models.

2) *Topography* – The mountainous regions of BC are a unique asset, supporting glaciers, seasonal snowpack, forests, and diverse ecosystems. The climatic conditions associated with this variable terrain are also diverse and can vary radically over a distance of only 1 km or less. The resolution requirements for describing climate and the impacts of climate change are beyond the resolution that defines both the present climate (around 100 km between observations), and future climate projections (15 km at best).

3) *Limitations of climate modelling* – Global Climate Models (GCMs) are based on physical principles describing the conservation of mass, energy and momentum, along with the thermodynamic equation of state (solid, liquid, gas). While all GCMs agree on these physical principles, they do not produce identical results. There are mainly two reasons for this discrepancy:

    - Because of the chaotic nature of atmospheric dynamics single GCM simulations are sensitive to the initial conditions. Even two very similar realizations (e.g., one model on two computers) are bound to diverge after some (usually very short) time. This *natural uncertainty* can be overcome, nevertheless, and the ‘true’ response of the physical system to external forces can be captured by aggregating over either very long or many different realizations (ensembles).
    - Climate feedbacks between constituents of the earth’s climate system such as sea ice, water vapour, CO_2, and microscopic aerosols, have long-term effects. These feedbacks are often governed by small, unresolved processes (such as cloud microphysics) that cannot be simulated using first principles and that may not be completely understood. This lack of knowledge must be parameterized empirically, which is the main source of *model uncertainty*. By using multi-model ensembles this uncertainty can also be quantified.

[i] Personal communication, Pat Wong, Pacific and Yukon Region, Environment Canada (12 January 2010)

In response to increasing greenhouse gas concentrations, results from different GCMs are in general agreement on the largest planetary scales and for long (climatic) time periods. However, significant differences occur at the regional scale and this resolution (grid size of roughly 300 km) is insufficient for resource management of local ecosystems and making decisions on community infrastructure. Consequently, global climate scenarios must be *downscaled* to derive unbiased scenarios at the local scale.

Downscaling methods must find some way to account for extreme topography and the limitations of unevenly distributed and scarce observations. No downscaling technique is optimal for all applications, and may not even be adequate for particular applications. Considerable analysis, experience, and insight are required to select the most suitable method, or group of methods, and to deliver high-resolution climate scenarios at a specific site or for a specific region that are relevant to users and credible to researchers at the same time.

3. Research Plan for Regional Climate Impacts

The objective for the Regional Climate Impacts (RCI) Theme is ***to deliver regional projections of future climate for adapting to impacts on communities, ecosystems, and water resources***.

This research plan is also guided by PCIC's goal to "redirect the intellectual resources of the academic community towards the most critical social and economic needs of our Province and Nation within the environment of Pacific North America" (PCIC, 2009). Finally, the plan for the theme must accommodate the particular geography and characteristics of the communities of Pacific North America.

The research questions that are addressed by the RCI Objective do not grow out of scientific curiosity, but rather out of the specific needs of an identified user. These needs are documented as requirements and addressed by targeted research (PCIC, 2009). All results should be accompanied by quantitative estimates of uncertainty.

Relevance to user needs requires high precision estimates of past and future climate. Credibility within the climate research community requires high standards of scientific accuracy. Although these are naturally in conflict with each other, a commitment to achieving both goals is essential.

To achieve the RCI Objective, this research plan is structured into four components (Figure 4). The activities in each component are motivated by a list of projects that are not only important and achievable, but also depend on the evolution of user needs and their requirements for climate adaptation and risk assessment. The components of the RCI Research Plan are:

- ***User Needs Assessment*** – work with users to determine climate information that is both required (e.g., averages, thresholds, extremes, etc.) and feasible to obtain (i.e., within the constraints of science, data, and resources).
- ***Regional Climate Change*** – improve the spatial and temporal resolution of regional climate projections by developing and verifying downscaling tools through scientific analysis. Provide input to regional impact analyses for PNA along with uncertainty assessments.
- ***Impacts on Communities, Ecosystems, and Water Resources***[i] – in collaboration with extramural experts ("champions"), assess the impacts of climate change and variability on socio-economic sectors, especially on communities, managed natural resources, and ecosystems.
- ***Products and Services*** – deliver products and services to users in the form of data, analyses, reports, and presentations, including tools for analysis and downscaling of future climate projections to regions and local sites.

[i] This portion of the plan includes overlap with other PCIC themes – in particular *Ocean Influences* (coastal infrastructure) and *Hydrologic Impacts* (water resources).

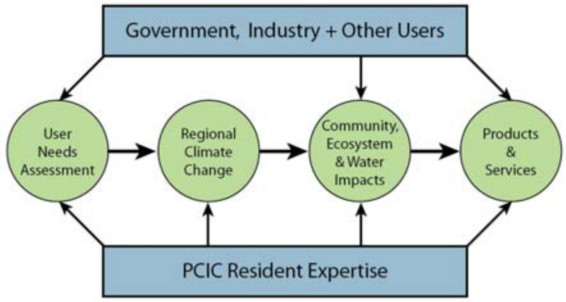

Figure 4: Schematic illustrating stakeholder engagement through each of the RCI components. In collaboration with stakeholders, researchers and other users, PCIC undertakes user needs assessment (Section 3.1). PCIC develops and applies downscaling tools and assesses uncertainty (Section 3.2). PCIC collaborates with champions to assess climate impacts on communities, ecosystems, and water resources (Section 3.3). The resulting products and services (Section 3.4) are then delivered to user stakeholders.

In order to effectively implement a research plan with these components, each must be associated with *user groups*, *research collaborators*, and/or *extramural champions*.

User groups are the climate stakeholders who require future climate conditions in order to make decisions. Users must be identified for an assessment of user needs, and they are the targeted consumer of RCI products and services.

Research collaborators are academic and government researchers who help ensure that PCIC applications are technically sound and credible. Researchers must be identified to support the RCI Theme through research and testing of new methods, development of improved models and methodologies, and inter-comparison of methods and models.

Extramural champions are experts in various socio-economic sectors with whom PCIC staff collaborates to translate future climate conditions into climate impacts on ecosystems, communities and water resources. *Champions* are identified to connect PCIC staff with specific decision support tools and climate impact models without requiring PCIC staff expertise in every socio-economic sector.

Attachment 1 describes the relationships and responsibilities of *user groups*, *research collaborators*, *extramural champions*, and PCIC staff for each component of the RCI plan.

3.1. User Needs Assessment

Objective: to understand and respond to user needs and requirements for adaptation to climate change, climate variability, and extreme events.

Some user needs and requirements for climate information are conventional, or are known from collaborative work already underway by PCIC or other groups (Attachment 2). However, user needs also evolve as experience is gained with first-generation climate products. Therefore a commitment to active collaboration with user stakeholders is essential. Experience with user applications will increase confidence in PCIC products and services.

The first step has already been taken to meet user needs with current PCIC products and services (Section 3.4). These preliminary products need further testing and evaluation. Furthermore, PCIC staff must stay abreast of emerging and evolving needs of climate information users. This requires ongoing communication, learning, and documentation of specific user requirements.

User needs workshops are useful for several reasons: i) users need an understanding of climate change projections, downscaling tools, and uncertainty; ii) PCIC staff will deepen their understanding of the vulnerabilities of each sector and discover adaptation strategies for decision-making (e.g., forestry, ecology, engineering, community infrastructure, etc.); and iii) they contribute to PCIC outreach efforts.

Subsequently, there may be a need to enhance the transfer of climate information to users in training workshops. The development of this concept will depend on the accomplishments of the RCI Research Plan and on the evolution of user needs.

Finally, a familiarity with user needs is vital to all of the components of this plan. For example, the different methodologies of statistical and dynamical downscaling methods need testing to define strengths and weaknesses of approaches for different purposes. The results of the user needs workshops will inform the work of the following Sections 3.2 and 3.3, and will influence and improve the design of new products and services in Section 3.4.

3.1.1. Research Plan - User Needs Assessment

Meeting the objective of this component of the RCI Research Plan requires undertaking new projects and carrying over existing projects as described below.

PCIC will identify users: communities, trade associations, professional societies, resource managers (see Attachments 1, 2, and 3).

Projects:

1) Sponsor user needs workshops directed to selected organizations in different socio-economic sectors. Publish a report on findings, identify methodologies, and initiate targeted research projects. Examples of user sectors (from Attachments 2 and 3) are:
    - Forests
    - Surface transportation
    - Ecosystems
    - Community infrastructure
2) Report annually on user needs for selected sectors from workshops, scheduled presentations, and unscheduled user requests.
3) Assess the need and PCIC capacity to deliver training workshops.

Continuing projects:

4) Assess user needs from presentations at user-driven, scheduled presentations.
5) Assess user needs from user requests for information or critical reviews.

3.2. Regional Climate Change

Objective: to evaluate the effect of global climate change on the regional climate of PNA, and to provide input to regional impact studies, including estimates of uncertainty. This requires an assessment of GCM and RCM climate projections, as well as the development and application of empirical downscaling techniques.

An estimate of future climate impact information at high resolution in time and space *(downscaling)* is needed to transfer projections of future climate conditions from global climate models to the regional or local scales. To this end, several approaches for downscaling (statistical or dynamical) have been developed (Fowler et al., 2007). An understanding of the strengths and weaknesses of each approach is required in order to select the most appropriate methods for use in PNA, and especially for the specific needs of the users. While the statistical and dynamical approaches each have their strengths, this research plan puts the primary focus on statistical downscaling, since it is more economical, flexible and adaptable to user needs.

Beyond downscaling of average conditions, assessment of estimates of future climate *variability* including the extremes (heat waves, floods, droughts, etc.) is required. There is a substantial user requirement for credible estimates of the likelihood of extremes. Precisely what constitutes an extreme *event* is often subjective. A set of climate indices (ETCCDI[i]) that measures climatic extremes in all its diverse aspects has been defined and is now widely used. The RCI Theme will make extensive use of these indices as a performance measure for the various downscaling methods.

No downscaling application is complete without an assessment of uncertainty. This applies especially to the area of PNA, with its complex climate and comparatively sparse observational network. Downscaling results delivered by the RCI Theme will undergo verification on independent data to provide uncertainty estimates. Together with estimates of uncertainty from an ensemble of climate simulations (where available), useful confidence bounds for climate scenarios will be established.

The practical value of downscaling tools and their uncertainty estimates depends on the specific application. Each downscaling tool must produce results in a form that can be communicated easily to a non-specialist, or can be used as input to impacts models and adaptation strategies.

Figure 5 shows the regions of interest for which PCIC will focus its initial downscaling efforts. Major users of PCIC climate information depend on watershed resources, and hence the regions in Figure 5a were chosen to cover the major watersheds. Since individual communities and regional districts also seek climate products relevant to their domains of governance, a second alternative for downscaled products is the 29 regional districts shown in Figure 5b.

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[i] *http://cccma.seos.uvic.ca/ETCCDI*

a) b)

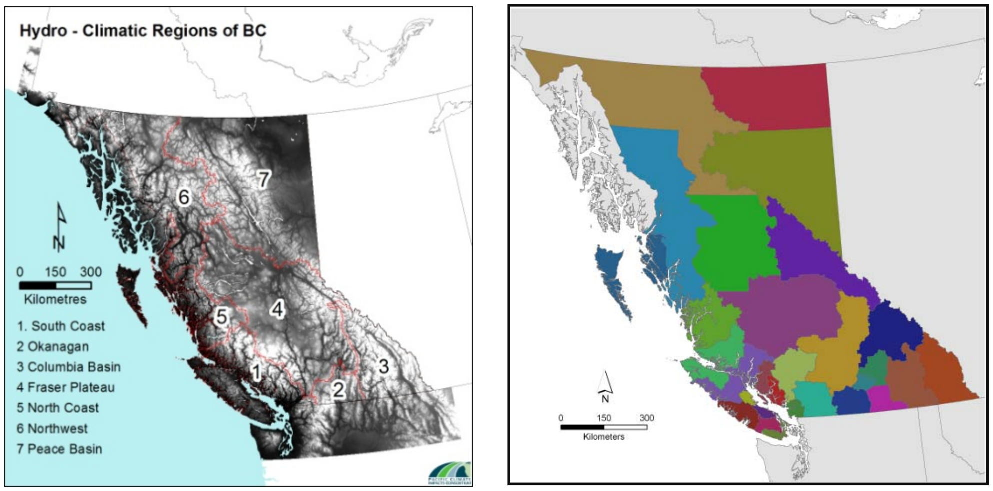

Figure 5: Regional maps showing the initial focus of PCIC downscaling efforts. Left: the seven main hydro-climatic regimes. Right: the 29 regional districts relevant to local community decision-making.

3.2.1. Statistical Downscaling

For a particular area of interest, such as a watershed, the corresponding GCM information usually comes in the form of daily or monthly averages for surrounding grid cells with a typical size of 300 km. Such information is too coarse to be used directly for impact assessment models (Figure 6). For a statistical/empirical approach to overcome this mismatch, it is paramount to have observational data on which to build mathematical relationships between the large scale (synoptic) circulation and the locally recorded weather record.

Spatial and temporal detail: Daily time series of the state of the atmosphere reach back to the 1950s (so-called 'reanalysis products' which use a GCM as a dynamical interpolation tool for station, upper air, and satellite observations). However, local *station* observations required for high-resolution detail in space and time are sparse in the PNA region, particularly in central and northern British Columbia. Several gridded historical datasets are available (Attachment 4), but they all depend upon a sparse network of stations. Consequently, building a solid empirical basis for describing the current BC climate is an essential element of the RCI Theme.

The relative importance of resolution in both space and time depends on the particular impact problem. For example, estimating the climatic impact on river flooding depends on the statistics of extreme precipitation and may require one or two decades of realistic daily precipitation. On the other hand, determining the growth of plant populations from growing-degree days (already an aggregate quantity) requires little more than a few years of daily temperature.

In order to use statistical downscaling to estimate future climate conditions on a regional scale, a two-step process will be used. First, information has to be spatially interpolated from the existing sparse network of climate observations onto the domain of interest. Second, climate must be projected into the future to obtain information consistent with a given scenario of greenhouse gas emissions. Whether the temporal projection or spatial interpolation step is done first depends on the particular user-specified problem. It is important to determine the value, limitations, and mutual consistency of the two paths of downscaling: i) spatial interpolation then temporal projection, or ii) temporal projection then spatial interpolation.

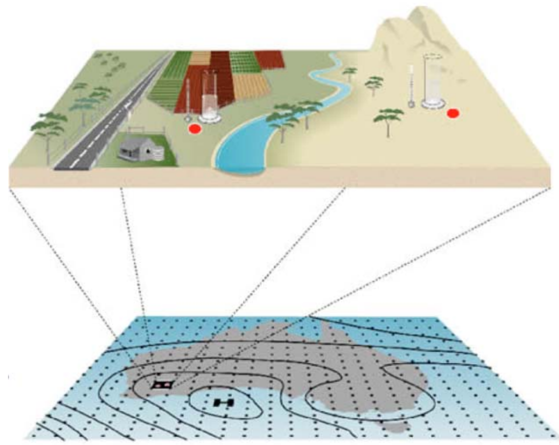

Figure 6: A schematic diagram describing the mismatch of typical GCM scales (lower part) and the generic scales of ecosystems and communities (upper part). Empirical downscaling bridges this gap by building statistical links between both scales based on past observations. Source: Bureau of Meteorology, Australia.

The *delta method* can be applied both spatially and temporally to obtain a very simple first-order approximation of climate change at higher resolution. In this method a high-resolution feature of current climate (either a spatial map or a time series) is modified by adding (e.g., for temperature) or multiplying (e.g. for precipitation) a coarse scale climate anomaly (the "delta"). It should be noted that this approach assumes that variability and extremes are unaffected by climate change, a condition that is not met in general and is highly questionable in complex terrain (Mearns et al., 1997). This method should not be used if variability and extremes are being investigated.

There are many geo-statistical methods for *spatial* interpolation, where information is derived from a sparse network of stations:

- *Thiessen polygons (also known as Voronoi diagrams):* Equivalent to choosing the values from the closest station.
- *Splines:* Collating piecewise polynomial functions (e.g. ANUSPLIN, Hutchinson, 1998a; Hutchinson, 1998b).
- *Kriging:* Optimal weighting of neighbouring stations based on correlation distance which can be used with or without external drivers such as topography (e.g., Cressie, 1993).
- *PRISM:* Hybrid statistical-geographical approach to map climate information at high-resolution (Daly et al., 1994).

Feature-rich climate maps can be produced for any desired spatial resolution using these techniques. For example, digital topographic data in combination with the delta method for temporal projection can yield very high-resolution climate maps for any given GCM scenario. The user may inadvertently assume overly-optimistic confidence in the high precision of the spatial detail in these maps. Therefore, targeted research results need to be accompanied by uncertainty estimates. In addition, Section 3.4 (Products and Services) provides for consultation to assist users with the interpretation of analyses and results.

For the *temporal* projection, where daily or monthly time series are derived in accordance with a given global emissions scenario, the most widely used techniques are:

- *Stochastic weather generators:* Weather events are simulated from random numbers whose statistical properties are conditioned on climate (Kilsby et al., 2007; Richardson, 1981; Semenow and Barrow, 2002).
- *Weather types:* A fixed number of weather types, characteristic of a typical weather situation are selected. The frequency of these types is conditioned on climate (Bardossy and Plate, 1991; Hughes and Guttorp, 1994; Stahl et al., 2008).
- *Regression:* Time series of large-scale circulation fields are directly linked to station time series by means of transfer functions. Function parameters are fitted using least squares methods (Bürger, 1996; Hessami et al., 2008; Salathe et al., 2007; von Storch et al., 1993; Widmann et al., 2003; Wigley et al., 1990; Wilby et al., 1999).

Two examples are shown in Figure 7: spatial interpolation is followed by temporal projection in the upper path, and temporal projection is followed by spatial interpolation in the lower path. In the upper path the PRISM method (Daly et al., 1994) is used to create detailed maps of growing degree-days (GDD) for the present climate using observed records of annual temperature (aggregated from the daily record) and topographic lapse rates. Future GDD maps with the same detail are derived by applying GCM projections using the delta method. In the lower path, the starting point is the same set of station observations for daily temperature. Scenarios of future daily temperature, along with an estimate of the return period for extreme temperature for each of the stations, are derived using Automated Statistical Downscaling (ASD) (Hessami et al., 2008). Maps are then obtained from these station values using ANUSPLIN.

3.2.2. Dynamical Downscaling

Regional climate models (RCMs) provide a complementary approach to the downscaling problem. The primary advantage of RCMs is that the parameter-intensive calibration needed for empirical-statistical models is replaced by dynamical equations that are obtained from fundamental physical principles. Since RCMs are ‘uncalibrated’ regionally they may carry a considerable bias in simulating the present climate from a global scale. Some of this bias is transmitted from the GCM that specifies conditions along the boundary of the RCM domain. Nevertheless, especially in the data sparse northern areas of BC, RCMs can complement or replace the uncertain statistical models.

In cooperation with the Ouranos Consortium and the North American Regional Climate Change Assessment Program[i] (NARCCAP) program, PCIC is prepared to analyse results of several RCMs at a resolution of about 50 km. In addition, one simulation (1975-1995) at high resolution (15 km) has been completed that represents a dynamically consistent realization of the current BC climate and that can be exploited in many ways. For example, it may be used to define a *statistical downscaling* model that represents a computationally inexpensive representation of an RCM that can be driven by other large-scale climate simulations. Furthermore, since the simulation represents an idealized realization of PNA climate, its ‘perfect’ information can be used to test and verify assumptions implicit in the statistical downscaling tools discussed in Section 3.2.1.

[i] http://www.narccap.ucar.edu

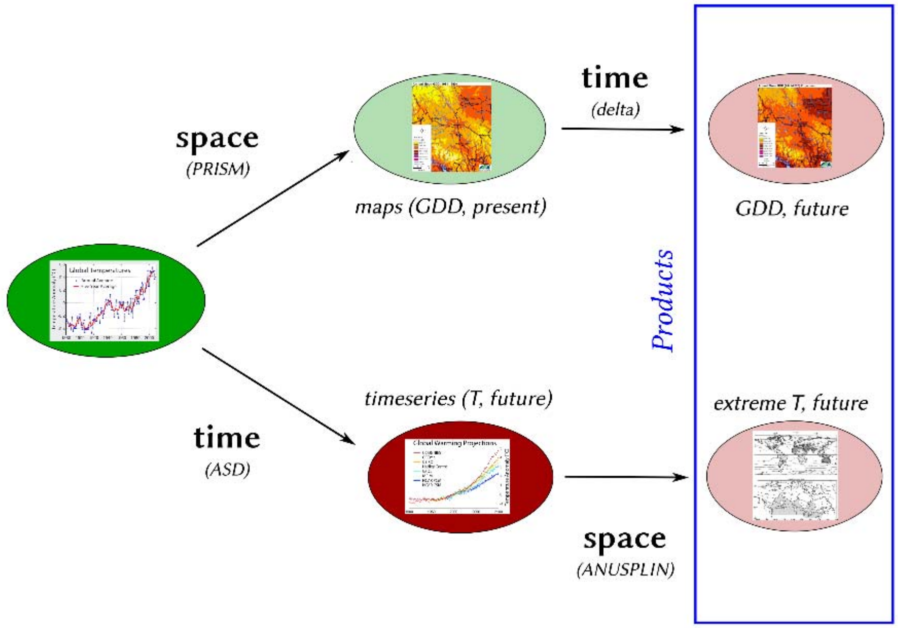

Figure 7: Typical examples of different paths for two target climate variables. Each path starts from a set of observed daily temperature records. Upper path: deriving growing degree days (GDD) for the present using PRISM and for the future using the delta method. Lower path: deriving return periods of extreme temperature for each station, using ASD, and interpolating the result using ANUSPLIN (Section 3.2.1).

3.2.3. Uncertainty Assessment

When descending from larger to smaller scales, each new detail of the downscaling method introduces new uncertainty (such as the standard error for interpolation) that is further transferred or enlarged in subsequent steps. One of the major challenges of the RCI Theme is to maintain a balance between local precision and corresponding uncertainty.

Uncertainty in downscaled future projections is usually a mixture of two components: *natural uncertainty* and *model uncertainty* (Section 2.1). Two types of errors related to these sources of uncertainty must be addressed: sampling errors and systematic errors.

Sampling errors arise from imperfect samples, such as when natural variability is large and the estimated base climate happens to reflect an anomalous state of ENSO. To have a representative sample that captures enough natural variation, it is paramount to include observational data from as many sources as possible. For simulated climates, utilizing ensemble techniques can reduce sampling errors (Solomon et al., 2007). Accordingly, ensembles of simulations will be used as much as possible. This applies to the entire model chain, from GCMs to downscaling and impact models.

When a sample is reasonably representative and some reference state is available, systematic errors (biases), such as from an imperfect model parameterization, are revealed. The bias can be estimated by verifying against the reference, and sometimes removed through bias correction measures. PCIC has resident expertise in the use of downscaled GCMs to convey uncertainty (Bürger et al., 2009; Murdock and Flower, 2009) and in applying bias correction methods (Bennett et al., 2009; Bürger, 1996).

To improve the estimate of RCM uncertainty, the NARCCAP ensemble along with simulations from Ouranos will be assessed in close collaboration with Ouranos, the UVic Climate Lab, and the second theme of PCIC (Hydrologic Impacts). Comparisons of simulations to a set of derived historical gridded datasets (Attachment 4) and station observations will be made with advice from the Canadian Centre for Climate Modelling and Analysis (CCCma) and the Water-Climate Impacts Research Centre. Additionally, an ensemble of high-resolution climate simulations on the Pacific Grid will be conducted using empirical downscaling (Section 3.2.1). A separate *Research Plan for RCM Diagnostics* is being drafted (PCIC, 2010) that will describe the use of RCMs for runoff, snowpack, and other water cycle components.

3.2.4. Research Plan - Regional Climate Change

The projects described below will be undertaken in order to meet the objective of this component of the RCI research plan.

PCIC will confirm, for each of the projects below, that they:

- meet specific user needs that will be identified, and
- involve the required extramural research collaboration.

Projects for downscaling tool development:

1) Conduct statistical downscaling of temperature and precipitation and indices of extremes at seven different *climatic and ecological* sites/areas that cover all of BC using several different methods.
2) Anticipate and support specific requests for downscaling products in support of scientific users and applications.
3) Use high-resolution RCM simulations to assess empirical downscaling tools.

Continuing projects for downscaling tool development:

4) Build resident capacity for several empirical downscaling methodologies: e.g., delta method, PRISM (Daly, 2006), TREEGEN (Stahl et al., 2008), BCSD (Wood et al., 2002), EDS (Bürger, 1996).
5) Support development of ClimateWNA empirical downscaling tool (Wang et al., 2010) and incorporate selected features into the online PCIC Regional Analysis Tool.

Projects for verification and uncertainty assessment:

6) Provide uncertainty analysis of all downscaling products from PCIC (see Project 1, above).
7) Compare the present climate with future conditions as represented by station observations, or RCM simulations, interpolated datasets, statistical downscaling, and/or PRISM. Select several typical climatic and ecological locations in BC.
8) Quantify GCM and RCM uncertainty in the context of natural variability in Pacific North America using model ensembles and selected statistical downscaling.

3.3. Impacts on Communities, Ecosystems, and Water Resources

Objective: in collaboration with extramural "champions" and experts in specific socio-economic sectors[i], produce estimates of climate impacts on communities and ecosystems through collaborative, targeted research.

PCIC's involvement in the assessment of regional climate change, for which substantial in-house expertise exists, was discussed in the previous section. PCIC collaborates with users to assess socio-economic regional climate impacts on communities, managed natural resources and ecosystems.

Adaptation communities and ecosystems will be somewhat integrated. For example, BC Parks, the Environmental Stewardship Division of the BC Ministry of Environment, and the BC Ministry of Forests and Range all have regional units located around the province that work closely with local and regional governments. Also, Official Community Planning and Regional Land Use Planning processes each involve both communities and ecosystems, despite their differences in focus.

Impacts on water resources are also highlighted because water issues have been found to cut across most sectors (Swain, 2007). Impacts on power generation are covered in the Research Plan for Hydrologic Impacts (PCIC, 2007). Future research plans of the Hydrologic Impacts Theme will describe additional hydrological modelling capacity at PCIC for impacts on water resources, including collaborative projects between the two themes.

Ecosystem and community impacts are estimated by utilizing regional climate change projections (Section 3.2) to drive impact models. These models range from direct application of climate parameters to modifications of complex operational decision tools. Most users possess operational models or decision tools that determine optimum settings or guide management decisions for the operation of their industry. These tools often contain climate variables implicitly, or must be restructured to respond to climate change scenarios (Dickenson, 2009). The use of climate impact models or decision support tools requires knowledge of user needs (Section 3.1) and collaboration with an extramural "champion" expert in the designated sector. As an example, storm water management requires specialized climate information developed from downscaling of climate variables. In this case precipitation intensities on a timeframe of minutes to hours are needed (e.g., Murdock et al., 2007a). Selecting and developing operational support tools for use in climate adaptation requires a commitment to collaboration and exchange of knowledge between PCIC staff, users, champions, and researchers (Attachment 1).

The following examples are useful for describing the scope of the work to be conducted in this activity. PCIC will establish priorities and additional projects based on the results of User Needs Workshops (Section 3.1).

- *Extreme precipitation:* Changes to precipitation extremes are important for assessing many potential ecological and infrastructure impacts (e.g. storm water management and decision-making tools[ii], flood, drought, and landslide risk assessment).
- *Future heating and cooling demand*: Projections are required for developers, communities, utilities, and governments to estimate future energy requirements. Changes to heating and cooling requirements need to be considered from the scale of individual buildings to regional energy planning (Crawley, 2007; Robinson et al., 2008).

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[i] Section 3.3 includes overlap with other PCIC themes – in particular *Ocean Influences* (coastal infrastructure) and *Hydrologic Impacts* (water resources).
[ii] e.g. BC Water Balance Model *http://www.waterbalance.ca*

- *Landslide risk:* Landslide risk depends on several environmental and land-use triggers (Jakob and Weatherly, 2003). The influence of climate is complex and depends on location. Along the BC coast, landslide risk is most related to prolonged and high intensity rainfall (Jakob and Lambert, 2009). Increased rock avalanches in north-western BC may be more associated with increasing temperatures causing glacier retreat and de-buttressing of slopes (particularly during freeze/thaw cycles). In north-eastern BC, increased landslides appear to be related to permafrost melt (Geertsema et al., 2007).
- *Water quality*: Changes in the amount and timing of streamflow are being investigated under PCIC's Hydrological Impacts Theme. Water quality is affected by changes in both the amount of water as well as the stream temperature (Davies and Mazumder, 2003).
- *Transportation:* Design criteria for transportation infrastructure, such as culvert size and bitumen content of roads, depend on climate. Climate information has normally been used indirectly. Projections of temperature and precipitation extremes are now required to adapt transportation infrastructure design criteria for climate change (Mills et al., 2007).

3.3.1. Research Plan - Impacts on Communities, Ecosystems, and Water Resources

Each of the projects in this section will usually depend on both a research collaborator and an extramural champion.

PCIC will identify, for each project described below:

- *Champions* or experts in the sector that is impacted by climate. In collaboration with these champions, PCIC provides climate information that users need for adaptation to climate change;
- *Research collaborators* in the sector, or an expert on climate adaptation models for which climate information is needed.

Projects:

1) Respond to user needs identified in Section 3.1 by setting up projects and identifying champions and collaborators.
2) Analyze heating and cooling demand, and return periods of rainfall extremes for building design.
3) Extend the analysis of tree species suitability to additional species: consider the effects of genetics, pest outbreaks and wildfire; estimate future habitat suitability for additional types of species, wetlands, or ecosystem/habitat classification.

Continuing projects:

4) Projections of extreme winds and wind climatology from GCMs and RCMs.
5) Extremes of temperature and precipitation with return periods for transportation infrastructure.
6) Streamflow and water temperature for water quality.

7) Provide supporting services to users of the online Regional Analysis Tool (RAT) and provide additional historical and future climate information to consortium members and extramural researchers on a project-specific basis.

3.4. Products and Services

Objective: to provide future climate projections with estimates of uncertainty that can be applied by users and climate stakeholders. These results will drive decision support tools and climate adaptation models that are needed in each socio-economic sector for operational decisions, planning, and the development of policy.

The delivery of products and services is of primary importance. It is through products and services that the work described in the preceding sections supports the development of policy, planning and operational decisions for adaptation to climate change. The type of products and services delivered for a particular project will be determined through consultation with users, both in the needs assessment phase (Section 3.1) and on an ongoing basis as projects evolve. In addition to user-defined products and services, PCIC staff will continue to build upon existing resident expertise and further expand upon activities such as:

Regional Analysis Tool

The PCIC Regional Analysis Tool[i] is an interface to derive estimates of future climate projections from individual GCMs and ensembles. Features included are box plots and scatter plots to display the range of values and implied uncertainty present in future projections. Figures may be easily created for selected regions. The tool is designed to assist regional impacts researchers (e.g., foresters, biologists, ecologists, and hydrologists) in choosing a range of projections for subsequent analysis of climate impacts.

Regional Planning Tool

A regional planning tool[ii] has been developed in conjunction with community planners in order to provide a separate interface to the data underlying the Regional Analysis Tool. A less complex and cluttered interface was created by removing features that are not required for planning (such as hundreds of choices for individual GCM experiments). Emphasis will be placed on assisting with the interpretation of results. This tool provides regional results and was designed with a planning audience in mind, including engineers, architects, developers, municipal and regional district staff, and elected officials.

Presentations and training

The increasing demand for future climate impact information increases the need for workshops and seminars to stimulate the development of user requirements for climate information and adaptation to climate change. PCIC presents selected results at workshops organized by the user community. These are distinct from presentations to the scientific community to ensure robustness of results. There is an opportunity to deliver training workshops on the use of downscaling tools and interpretation of future climate projections, if needed.

i *http://www.PacificClimate.org/tools/regionalanalysis/*
ii *http://www.Plan2Adapt.ca*

Regional climate change impacts reports

Several assessments of historical climate, variability, trends and future projections on a regional basis in British Columbia have already been initiated. (Dawson et al., 2008; Murdock and Bennett, 2007; Murdock et al., 2007b; Murdock et al., 2009; Picketts et al., 2009; Sandford et al., 2007; Werner and Murdock, 2008). Each report depends on identification of an extramural *champion* to collaborate in the assessment, and thus provides an opportunity for two-way knowledge transfer including both stakeholder capacity-building and also improved understanding of user needs by PCIC.

Extramural publications

Historical trends and future projections analysed within the RCI Theme are provided in reports as described above. Specialized results are also sometimes needed by organizations that are developing climate adaptation plans. For example, in 2008 trends and projections were provided by PCIC to six BC government publications along with interpreted materials. Critical reviews of the extramural use of these results improve understanding of user needs and increase the quality and utility of PCIC services.

3.4.1. Research Plan - Products and Services

The projects below describe activities for delivering products and services to users.

PCIC will identify needs (Section 3.1) that will be met by, and users that will benefit from, each product and service.

Projects:

1) Create an on-line interface for improving and modifying the user needs documents from extramural input after the completion of each element of Project 1 of Section 3.1.1. This interface is also a forum for frequently asked questions, online discussions, and available products and services. Finally, it provides an opportunity for users to initiate new projects within PCIC.
2) Prepare an on-line atlas of downscaling results and regional climate impacts for specified (future) periods and for designated areas in BC. Utilize the output from projects 1 and 6 of Section 3.1.1.
3) In collaboration with users, utilize their operations models, risk-based decision support tools and/or climate adaptation models to demonstrate the value of downscaling tools and scenarios for estimating impacts on communities, ecosystems, and water resources.
4) Design a proposal to extend the beta-version of the regional planning tool[i].
5) Upgrade the Regional Analysis Tool and search for improvements in quality as well as new features. For example: i) add uncertainty information to downscaling products; ii) improve resolution with additional RCM projections from NARCCAP; iii) improve climatology and trends with additional historical datasets; iv) add information on climate variability.

i http://www.Plan2Adapt.ca

Continuing projects:

6) Produce technical project reports and journal articles for peer-review.
    - Publish reports on regional climate trends, variability, future projections, and climate impacts. These reports are used for subsequent development of strategic decisions and policies by regional users.
    - Publish papers in peer-reviewed journals in conjunction with research collaborators in order to ensure high technical standards and credibility within the research community.
7) Maintain a current database of GCM and RCM projections from IPCC, CCCma, NARCCAP and Ouranos. Access the data for use by PCIC, research collaborators, champions, and users.

4. Example: Climate Change and BC Forests

In this section an example of a completed project is provided as a means of illustrating the products and services PCIC can deliver in response to user needs. The project began before the RCI structure was developed (in fact, it was the first multi-year project undertaken at PCIC).

To understand climate change impacts on ecosystem services[i] an approach is needed that considers both the whole system as well as individual components (Austin et al., 2008; BC Ministry of Forests and Range, 2008). One step is to consider the effect of climate on individual species. As species respond in different ways, conservation of ecosystems that resemble the past may not be possible and ecosystem classifications based on the past may not be adequate to describe the future (Pojar, 2009). Conservation may thus move to a focus on ecosystem function and integrity, away from a focus on species. Projections of changes to individual species ranges and habitat types remain valuable to regional land-use planning that considers climate change in combination with local ecological knowledge (Pojar, 2009).

User Needs Assessment began with joint proposals to the Forest Science Program of the BC Ministry of Forests, developed with a team of impacts researchers from the BC Ministry of Forests and Range, Natural Resources Canada's Canadian Forest Service, the University of Victoria, the University of British Columbia, and the University of Alberta. The objectives of this applied project were to improve databases of historical and future climate for use in forest health research, and to apply them to climate impacts on two tree species and related forest pests. User and researcher involvement was enhanced by a workshop (Abbott et al., 2008; Flower and Murdock, 2008) and maintained by team meetings throughout the project.

The project made use of the ClimateBC empirical ***downscaling tool*** that drapes GCM projections over PRISM 4 km climatology with further interpolation and an elevation correction on temperature (Wang et al., 2006). When the project began, AR4 GCM projections were not incorporated into ClimateBC. The capacity was developed to use any AR4 GCM with ClimateBC, an improvement that is being incorporated into the next version (ClimateWNA).

A set of 10 projections from GCMs were selected to provide ***scenarios*** that represent most of the possible future conditions of temperature and precipitation values represented by the complete set of ~140 AR4 projections across BC (Figure 8).

Several methods of 'climate envelope' modelling of the ***ecological impacts*** of tree species suitability and forest pest risk were assessed (Murdock and Flower, 2009). ***Community impacts*** were investigated by using results of tree species and pest suitability in a preliminary bio-economic model. In conjunction with improvements in climate-based seed transfer (O'Neill et al., 2008) the results provide guidance for selecting tree species that may be better adapted to the future climate. Species suitability projections are preliminary. Differences in methods for deriving the impacts on species and related factors, such as competition and soils, are uncertain and factors such as extremes and inter-annual variability were not considered. Further advancements, such as incorporating additional risks from wildfire, will depend on PCIC resident expertise in ecology as well as collaboration with foresters, hydrologists, entomologists, biologists, and agrologists.

The tree species suitability impact models developed were subject to ***verification*** against independent datasets of tree species locations. For pest outbreaks, only one dataset was available. Impact model ***uncertainty*** was partially addressed in this case by comparing results from two independent methods of determining future risk of pest outbreak. Climate model and emissions scenario uncertainty were each investigated using two different ensembles of 10 future projections. This allowed for the presentation of results in terms of model agreement

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[i] E.g., the purification of water and air, pest and disease control, recreational experiences, and the provision of energy, fuel, and food

(Figure 9) and for comparison of results from low and high greenhouse gas emissions scenarios (Murdock and Flower, 2009).

Products and services delivered by the project included several datasets for further forest health impacts work, a set of high-resolution scenarios, as well as final results: future tree species suitability and pest risk projections and preliminary bio-economic impact model results. Results have been made available through a project report, extension notes, a journal publication (in preparation), several presentations to researchers and users, and regional impact assessment reports.

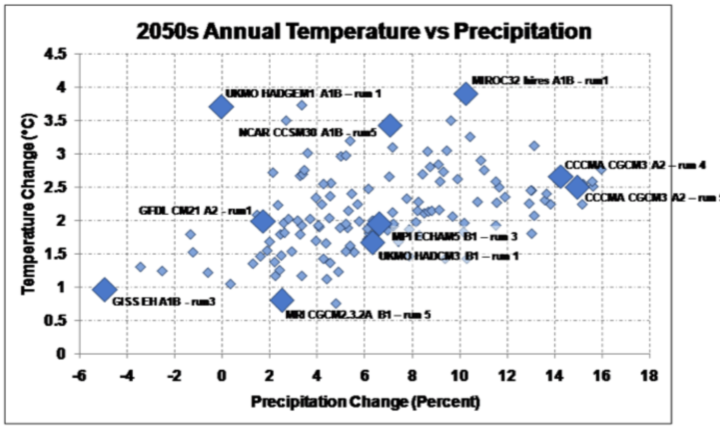

Figure 8: Scatterplot of 2050s annual temperature and precipitation averaged over BC for all ~140 GCM projections from AR4 compared to the ensemble of ten projections used to represent the range (indicated by larger diamonds).

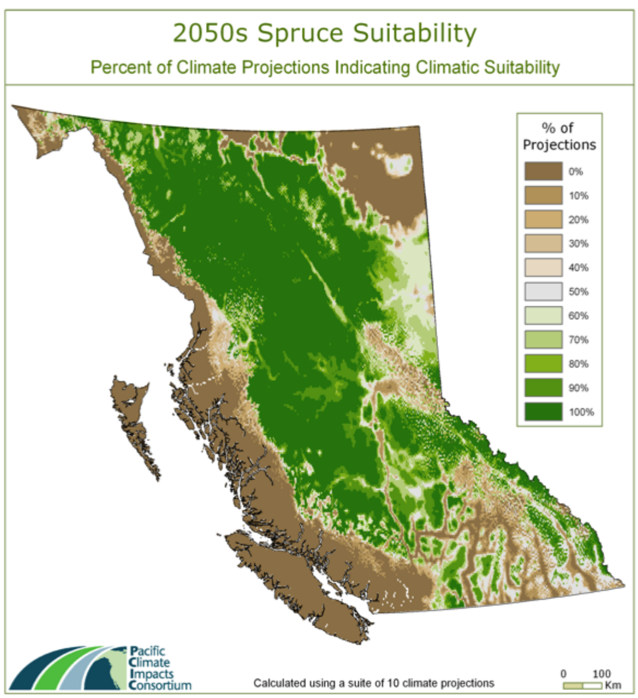

Figure 9: Percent of empirically downscaled GCM projections that indicate climate suitable for spruce by 2050s. Dark green (brown) indicates agreement between models that climate is (not) suitable (Murdock and Flower, 2009).

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List of Attachments

Attachment 1: Roles of PCIC, Users, Champions, Researchers

	PCIC staff	User Groups	Extramural Champions	Research Collaborators
3.1 User needs to understand and document user needs and requirements for adaptation to climate variability and change, including extreme events	Understand and respond to user needs	Provide adaptation information requests ("wish lists") to PCIC	Assess and catalogue user needs; communicate user needs to PCIC	Advise PCIC on scientific constraints on meeting user needs
3.2 Regional climate change to evaluate the effect of global climate change on regional climate conditions in BC and Pacific North America	Prepare ensembles of GCM and RCM climate scenarios Apply and develop downscaling tools Assess uncertainty and verify tools/methods	Use climate scenarios and downscaling tools Feedback on improvements	Disseminate and apply downscaling tools	Develop dynamical downscaling Develop, test, and compare statistical downscaling
3.3 Impacts on communities, ecosystems, and water resources in collaboration with extramural champions or experts in specific socio-economic sectors, produce estimates of climate impacts on communities and ecosystems through collaborative, targeted research	Apply regional climate projections to climate impacts models in collaboration with extramural champions	Use climate scenarios Feedback on improvements	Provide expertise in operational decisions, decision tools, or adaptation models Provide guidance on use of impacts models	Develop impacts models and compare methods
3.4 Products and services to provide future climate projections with estimates of uncertainty that can be applied by users and climate stakeholders	Produce maps, analyses, and interpretation of regional and community climate impacts Deliver results through reports and online tools	Apply results to planning, decision making, and policy	Disseminate PCIC results Collaborate on joint reports Apply results to decision support tools	Carry out vulnerability assessments Interpret climate projections

Attachment 2: Climate Information Needs

Adaptation needs by sector – January 2010

- Forestry: climate suitability of trees, pest outbreak risk, hydrological impacts, wildfire
- Agriculture: growing conditions, ecosystem services, range shifts of plants and animals, pest outbreaks
- Energy: heating/cooling/ventilation requirements, adapted green buildings, power generation and transmission, wind
- Health: heat waves, humidex, vector-borne disease, water quality
- Infrastructure: storm water runoff, flood risk (from changes in runoff amount, timing, sea-level rise, storm surge, and ice-jams), wind, dam capacity
- Fish: thermal effects on migration and spawning, marine food web, ocean acidification
- Transportation: return periods for landslides on roads, avalanche risk, freeze-thaw events, snow on ice, freezing rain, ice-jam flooding
- Tourism: snow amount, reliability, seasonal changes
- Conservation of ecosystem integrity: species suitability, habitat suitability

Climate information requests of users engaged in PCIC projects – January 2010

Columbia Basin

- Extreme wind
- Snow pack and spring runoff
- Wildfire increase
- Impacts on fish population
- Flooding of major waterways
- Frost-free days and growing season
- Climate variability and change
- Evapotranspiration
- Guidance on use projections
- Comparing station to gridded data

Cariboo-Chilcotin

- Snow pack
- March and April mean temperature, January minimum temperature
- Precipitation March, April, August, May to September
- Frost-free days and growing season
- BEC zones and tree suitability

City of Vancouver

- Extreme precipitation
- Extreme wind

Prince George

- Future changes to ENSO
- Winds - past, future, extremes
- Sunshine hours - energy opportunity
- Streamflow
- Monitoring and modelling lightning
- Freeze-thaw cycles
- Inversion analysis
- Precipitation extremes and snow

Dawson City

- Permafrost changes
- Flooding potential and ice jams
- Streamflow in future – Yukon River
- Caribou migration/population

BC Government

- See BC Climate Action Secretariat Adapting to Climate Change: Research and Information Needs (September 2009)

Attachment 3: Types of Collaborators

Users and champions by sector include:

- foresters, land-use managers, farmers
- engineers, hydrologists, power generation and transmission experts
- educators (outreach, extension, training) for professional organizations and the general public
- integrated assessment, environmental assessment, risk management professionals
- decision-makers in industry, finance, private sector, government (First Nations, federal, provincial, regional district, municipal), conservation organizations
- planners, municipal and regional district staff, architects, landscape architects, consultants

Research collaborators include those who study:

- the climate system and climate modelling
- physical impacts on forestry, ecology, hydrology, agriculture, etc.
- socio-economic impacts including policy and integrated assessment

Attachment 4: Historical Gridded Datasets for Pacific North America

Dataset	Reference	Frequency	Resolution	Years
WORLDCLIM	(Hijmans et al., 2005)	50-year climatology	1 km	1951-2000
PRISM - Canada	(Daly et al., 1994)	30-year climatology	4 km	1961-1990
PRISM - US	(Daly et al., 2002)	monthly	800 m	1890-2007
CANGRID	(Zhang et al., 2000)	monthly	50 km	1901-2006
ClimateBC	(Wang et al., 2006)	monthly, 30-year climatology	400 m	1901-2006
ClimatePP	(Mbogga et al., 2008)	monthly, 30-year climatology	400 m	1901-2006
CRU	(Mitchell and Jones, 2005)	monthly	0.5° (~50 km)	1901-2001
UDEL	http://climate.geog.udel.edu/~climate/	monthly	0.5° (~50 km)	1900-2006
GPCC	http://gpcc.dwd.de	monthly	2.5° (~250 km)	1951-2000
VIC-UW, VIC-UW2, VIC-PCIC, VIC-PCIC2	http://www.hydro.washington.edu/Lettenmaier/Data/gridded/ http://www.PacificClimate.org/	daily	1/8° (~12 km), 1/16°(~6 km), 1/16° (~6 km), 1/16°(~6 km)	1949-2000, 1915-2006, 1950-2006, 1915-2006
ANUSPLIN	(McKenney et al., 2006)	daily	10 km	1901-2000
TCM	(Atkinson, 2002)	daily	GTOPO30 (~1 km)	1957-2001
CPC	http://www.cpc.noaa.gov/products/precip/realtime/retro.shtml	daily	1/4° (~25 km)	1948-1998
NCEP*, NCEP2*	(Kalnay et al., 1996; Kistler et al., 2001)	daily	T62 (~210 km)	1948-present, 1979-present
ERA-40*	(Uppala et al., 2005)	daily	2.5° (~250 km)	1957-2002
NARR*	(Mesinger et al., 2005)	3-hourly	~32 km	1979-2006
RAMS*	(Ainslie and Jackson, 2009)	daily		

* Reanalysis