Final Report

FFESC project 014

High Resolution Spatial Climate Data for Climate Change Research in BC

Prepared by

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Project goal: Easy access to high quality historic and climate change data for impact assessments and development of adaptation strategies.

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Executive Summary

Climate data are necessary for many aspects of planning resource use and protection of public safety and infrastructure. Data such as historical time series and return periods of extreme weather events are required. How climate change will affect these climate measures also needs to be considered. Although large climate data bases are available, they are not readily accessible by non-specialist users, may not be at an appropriate temporal or spatial resolution, consistent format, or have the appropriate climate variables. Project 014 was designed to address many of these issues. In doing this we had to consider the immediate needs of Future Forest Ecosystem Science Council projects as well as future needs of scientists, resource managers, policy makers, and community stake holders. There were five components to our work: produce guidelines for applying climate change data; update the high spatial resolution climate software package ClimateWNA; evaluate techniques to provide information on changes in extreme temperature and precipitation events under climate change; determine how climate change time series data can be used to assess inter-annual variability in future conditions; communicate results.

The purpose of the guidelines component was to assist users of climate change data in the selection of future projections of climate change for application in impact, vulnerability and adaptation analyses. The focus of the guidelines is British Columbia (BC) but much of the content is applicable to applying regional climate change scenarios anywhere. A draft of the guidelines was released in early 2010 and final version published in 2011 on the Pacific Climate Impacts Consortium's (PCIC) web site. There are a large number of projections of future climates available as a result of different greenhouse gas emissions pathways and differences in resolution, formulation and initializing climate conditions of the climate models. The report recommends subsets of these projections for use depending on the purpose of the analysis. Sources for climate change data and examples of using the data are described. The report has received substantial use and positive feedback.

The updated version of the stand-alone high spatial resolution software package, ClimateWNA, was released, peer reviewed and a journal article published. ClimateWNA is a stand-alone software package that generates high-resolution monthly climate data for individual locations. Temperature and precipitation data and related variables for historic (1901-2009) and climate change projections (2020s, 2050s and 2080s) are available. ClimateWNA's domain is western North America from 100°W longitude to the Pacific Ocean and from 20 to 80°N latitude. An extensive effort was made to evaluate the accuracy of ClimateWNA for predicting historic monthly data. Predictions of monthly temperature and precipitation were compared to measured data from 3353 weather stations over its domain. Standard error was less than 0.8°C on monthly temperature and less than 10 mm on monthly precipitation. New equations were developed to predict derived variables such as degree days and frost free period on a monthly basis. This was required because ClimateWNA covers a much larger range of climates than its predecessor ClimateBC. Monthly reference evaporation and climatic moisture deficit were also added to the output. A selection of climate change projections from the Intergovernmental Panel on Climate Change's 4th assessment were incorporated into the package and other projections can be easily added when available. We contributed to the production of a new set of temperature and precipitation

normals that are the base data for the software through a cooperative effort with Oregon State University and the Pacific Climate Impacts Consortium (PCIC).

ClimateWNA is an important tool for climate change research in BC. It is being extensively applied in resource management research to provide data to visualize impacts of climate change and for the development of adaptation plans. In particular, its stand-alone mode of operation on a personal computer provides a tool to put the user in control. It provides researchers and resource managers with easy access to large, complex climate data bases. A simple graphical user-interface allows interactive queries, generation of time series, and multi-location processing. A web-based version is also available.

Our work has set the stage for the development over the coming years for quantifying how climate change may affect extreme climatic events in BC. Measured climate data for six Environment Canada weather stations and NCEP reanalysis of historic upper atmosphere data were used to calculate 29 measures of extreme temperature and precipitation (Climdex). Climdex has been adopted by the World Climate Research Programme as a standard for indices of extremes and includes such measures as maximum 1-day precipitation and maximum temperature. A peer-reviewed paper was published on the accuracy of five downscaling methodologies to determine the historic range of climate extremes. A subset of the indices was well predicted and the data demands on the modelling techniques are high. Research was conducted to compare the downscaling techniques on an ensemble of six global climate model projections for the 2050s. Extreme warm events and precipitation events became more frequent. However, the downscaling method has a strong influence on the prediction highlighting the need for extensive verification of methodologies under current climatic conditions. An article on this work has been submitted to a scientific journal.

A related project to the testing of methods for downscaling of extremes provided projections of a drought index and a wildfire index. Historic daily data for six weather stations in southeastern BC and one in Alberta and NCEP reanalysis data were used to calibrate the expanded downscaling method and predict the indices. Six climate change scenarios were downscaled and indices calculated for the 2050s and 2080s periods. The estimates of drought are accompanied by large uncertainties which originate from a number of sources, such as biases in the precipitation climatologies. Only one station in southeastern BC showed an increase in measures of drought because it was the only one that did not have an increase in precipitation accompanying the warming. It is recommended that downscaling of monthly rather than daily data be evaluated as this may be a more robust way to estimate drought indices and more climate projections can be used.

We evaluated the use of climate change time series data to assess inter-annual variability in future conditions. Monthly climate projections (as anomalies from 1961-90) for a suite of 8 global climate models for 2011 to 2100 were obtained from the Canadian Climate Change Scenarios Network. These data were combined with historic data for specific weather stations to create time series from 1901 to 2100. Degree days above 5°C, reference evaporation and climatic moisture deficit were calculated. Not all global climate models had the full suite of variables necessary and this required further assumptions and modelling. Uncertainty in the prediction of historic weather data using ClimateWNA means that care needs to be taken in extending weather station data back to the early

1900s for use in evaporation estimates. Further work on time series analysis will be based on the climate projections produce for Intergovernmental Panel on Climate Change's 5th Assessment.

Communication of results was an important component of our project. We successfully addressed the need to provide information (data and consultation) for the Future Forest Ecosystem Science Council research community. This information also aided PCIC's contribution to the Regional Adaptation Collaborative project in the east Kootneys that directly involved local communities. We published in the scientific literature and presented at scientific conferences in Canada and internationally. Numerous presentations were made to government personnel, students, consultants, community stakeholders and industry. We incorporated information into web-based tools to facilitate dissemination. ClimateWNA and work at PCIC has enabled improvements to the Plan2Adapt web site. This site provides visualization of projected future climates to aid in community planning and resource management and for informing the general public about climate change. PCIC's regional analysis tool, designed for sophisticated users, has also benefited from our work.

The project was able to leverage substantial resources through partnering with PCIC. Other government agencies and corporations have similar needs to our project and provided funding to PCIC that allowed us to achieve results well beyond the resources our project could contribute. Similarly, the project's success has been enhanced though our collaboration with personnel at the Centre for Forest Gene Conservation at the University of British Columbia and the Department of Renewable Resources at the University of Alberta in Edmonton. Although we were not able to complete all proposed activities, this has not prevented our success in meeting the project goal of "improved quality of and access to climate change data for impact assessments and development of adaptation strategies". There is still much work to be done and project 014 has provided a solid basis to continue.

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Introduction

Climate data are necessary for many aspects of planning resource use and protection of public safety and infrastructure. Data such as historical time series and return periods of extreme weather events are required. How climate change will affect these climate measures also needs to be considered. There is a need to match scales of the climate data with that of resource databases and this means that there is often a need to have high spatial as well as temporal resolution. Although large climate data bases are available, they are not readily accessible by non-specialist users, may not be at an appropriate resolution, consistent format, or have a comprehensive set of relevant climate variables. A number of efforts have been made to provide web-based tools that visualize historic and projected climate change, and software packages to query large climate databases. Examples include the WorldClim program (Hijmans et al. 2005), the ClimateBC software package (Wang et al. 2006), the Climex model (Sutherst et al. 2007), NRCAN Climate Change Scenarios (McKenney et al. 2011, Price et al. 2011), the PRISM Climate Group (Daly et al. 2008), and the Climate Wizard web-tools (Girvetz et al. 2009).

The current project focuses on providing readily accessible historic climate data and climate change projections at a high spatial resolution for use in British Columbia (BC). However, in doing this we recognize that climate data outside of BC's boundaries are required by users. For example, the range of many plant species extends over a large part of western North America and thus the climate data base should cover the full range to allow a complete description of species climatic envelopes. Also climate change may produce climates in BC that are analogous with climates in the northern United States. As well as providing climate data, there was a requirement to provide guidance to other Future Forest Ecosystem Science Council (FFESC) projects on using climate change projections. This project builds on previous work developing spatial climate data for BC (Wang et al 2006, Rodenhuis et al. 2009) and downscaling of climate extremes (Burger et al. 2010) through three objectives (called phases in the project proposal), i.e.:

Objective 1: Provide improvements in data access and number of scenarios to aid initial implementation of FFESC projects – November and December 2009

- Development of draft user guidelines for applying climate change scenarios.
- Official release of ClimateWNA stand alone spatial climate data software package.

Objective 2: Increase the options and sophistication of climate change data to address on-going needs of FFESC projects and others – January to December 2010

- Improvements to PCIC Regional Analysis Tool for data viewing and data delivery.
- Increase the range of gridded data available in PCIC Regional Analysis Tool.
- Subject ClimateWNA to peer review through submission of article to scientific journal
- Begin downscaling work to provide indices of extremes of climate, including evaluating selected methodologies.
- Development of degree-day equations for monthly values for use in plan2adapt web site.
- Extension activities, e.g., conferences, seminars

Objective 3: Further improve options, sophistication and access of data for climate change analysis to meet future needs of scientists, resource managers, policy makers, and community stake holders - January to December 2011.

- Continue downscaling work on indices of extremes of climate, including evaluating selected methodologies
- Evaluate application of climate change time series
- New PRISM data base for BC
- Assess feasibility of adding solar radiation layer to ClimateWNA
- Upgrades to ClimateWNA such as monthly derived variables as output
- Journal publication on ClimateWNA
- Publish user guidelines for applying climate change scenarios.
- Journal article submitted on downscaling of indices of extremes
- Extension activities, e.g., conferences, seminars, publications

This report describes how we achieved these objectives under five chapter headings. Brief descriptions of the work are presented. Details are available in published reports and journal articles. Some changes were made to the timing of the project components to meet the realities of the amount of work involved and the personnel available. For example, we moved some items from objective 1 to 2; options other than in the proposal were explored, e.g., applications added to PCIC's plan2adapt web site; and work is ongoing as part of a larger project, e.g., development of a new PRISM base climate.

A number of people were responsible for the research reported here. The project was overseen by Dave Spittlehouse (MFLNRO), Tongli Wang (UBC) did much of the programming and statistical analysis for ClimateWNA, and Trevor Murdock (PCIC) coordinated the work on downscaling.

User Guidelines for Applying Climate Change Scenarios

The purpose of the guidelines was to assist users of climate change data in the selection of projections of climate change for application in impact, vulnerability and adaptation analyses. The focus was on British Columbia but much of the content is applicable to using regional climate change scenarios anywhere. It builds upon the Intergovernmental Panel on Climate Change (IPCC) guidelines for use of scenarios (IPCC-TGICA 2007). The report focuses on scenarios from the IPCC Fourth Assessment Report and describes tools for data access that are readily available in BC. The need for recommended sets of scenarios for use in climate change studies in BC was initiated by needs of the Future Forests and Ecosystems Scientific Council research program and the British Columbia Regional Adaptation Collaborative. The full report (Murdock and Spittlehouse 2011) is available on the PCIC web site[1].

A climate projection is produced for each scenario - one run of one climate model with one emission pathway. There are a large number of projections of future climates available as a result of different greenhouse gas emissions pathways and differences in resolution, formulation and initializing

[1] www.PacificClimate.org

climate conditions of the climate models (Figure 1). The report recommends subsets of these projections depending on the purpose of the analysis. Mean changes in temperature and precipitation are described for each of them. Three model/emission scenario combinations are recommended as a minimal set to use for climate change studies, based on providing a range of future climates over most of British Columbia: HadGEM A1B run 1 (hot / dry), CGCM3 A2 run 4 (warm / very wet), and HadCM3 B1 run 1 (cool / wet)[2].

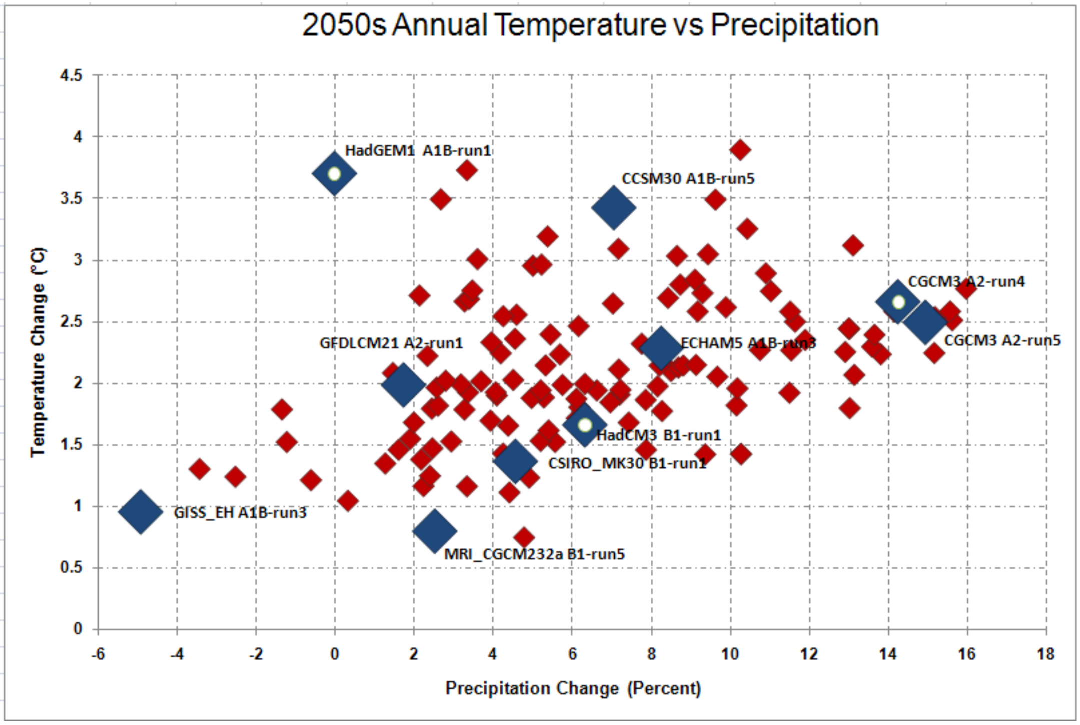

Figure 1: Range of change in mean annual air temperature and precipitation by 2050s for British Columbia. Data are projections from 18 models and the A2, A1B and B1 emissions scenarios (red and blue diamonds). The 10 blue diamonds indicate a recommended set of projections for use in climate change studies that span a wide range of future climates. The blue diamonds with white dots indicate a minimum of three scenarios for use. Model identifiers are explained in Appendix I and the emission scenarios in Appendix II. (From Murdock and Spittlehouse 2011.)

Selecting climate change scenarios should be done in concert with an understanding of how they will be used. Some applications require evaluation of the impact of specific emissions trajectories while others might consider the impact of highest and lowest changes in climate. Sensitivity analysis uses selected changes to climate variables to illustrate the sensitivity of a system, e.g., species range or stream flow, to a change in specific variables, e.g., annual temperature, summer precipitation. Time series analysis requires monthly or daily data for a number of years and is useful for doing risk analysis. Examples of using global climate model output to meet each of these tasks are included in the report.

[2] "Had" indicates models from the Hadley Centre, UK, while CGCM3 is the Canadian GCM. The terms A1B, A2 and B1 refer to greenhouse gas emission scenarios, and run indicates one of the simulations done by the model for this scenario. (See Appendix I and II.)

Current global climate model output is often at too coarse a scale to provide sufficient local detail on climate and on extreme events. Downscaling tools to address these differences in spatial scales are illustrated in the report. These include empirical tools such as the ClimateWNA software package (see below) and statistical downscaling. Scenarios of future monthly or daily time series and occurrence of extreme events are required for some impact analyses, and methods of generating such data are described. Sources for obtaining scenario data as well as visual images of the degree of projected climate change for western North America and regions of British Columbia are listed. Examples are presented based on PCIC's Regional Analysis Tool[3] and Plan2Adapt[4] web sites.

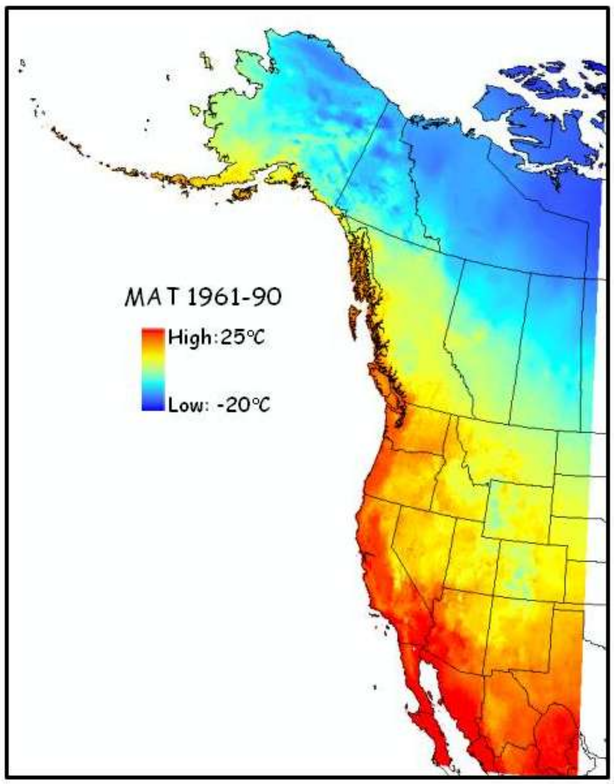

Figure 2: Domain of ClimateWNA showing the mean annual temperature (MAT °C) for the 1961-90 normals. ClimateWNA was used to generate the data that were then input into a geographic information system to produce the map.

ClimateWNA

ClimateWNA is a stand-alone software package that generates high-resolution monthly climate data for individual locations by downscaling through a combination of bilinear interpolation and elevation adjustment. ClimateWNA's domain is western North America from 100°W longitude to the Pacific Ocean and from 20 to 80°N latitude (Figure 2). It is based on previous packages for BC (Wang et

[3] www.PacificClimate.org/tools/regionalanalysis/
[4] www.Plan2Adapt.ca

al. 2006) and western Canada (Mbogga et al. 2009). Work was done to evaluate accuracy of ClimateWNA predictions of local climate and consistency with predictions from ClimateBC. A selection of climate change projections from IPCC's 4th Assessment were incorporated into the ClimateWNA package. Other projections are available from the PCIC web site[5]. A peer reviewed-paper was published in early 2012 (Wang et al. 2012) and a note publicizing it and activities of PCIC was published in the winter 2011/12 issue of the BCAgrologist (Appendix III). The availability of ClimateWNA was also noted in the FORREX Watershed Management Newsletter announcements. ClimateWNA is available free of charge[5]. A web version restricted to single locations is also available[6].

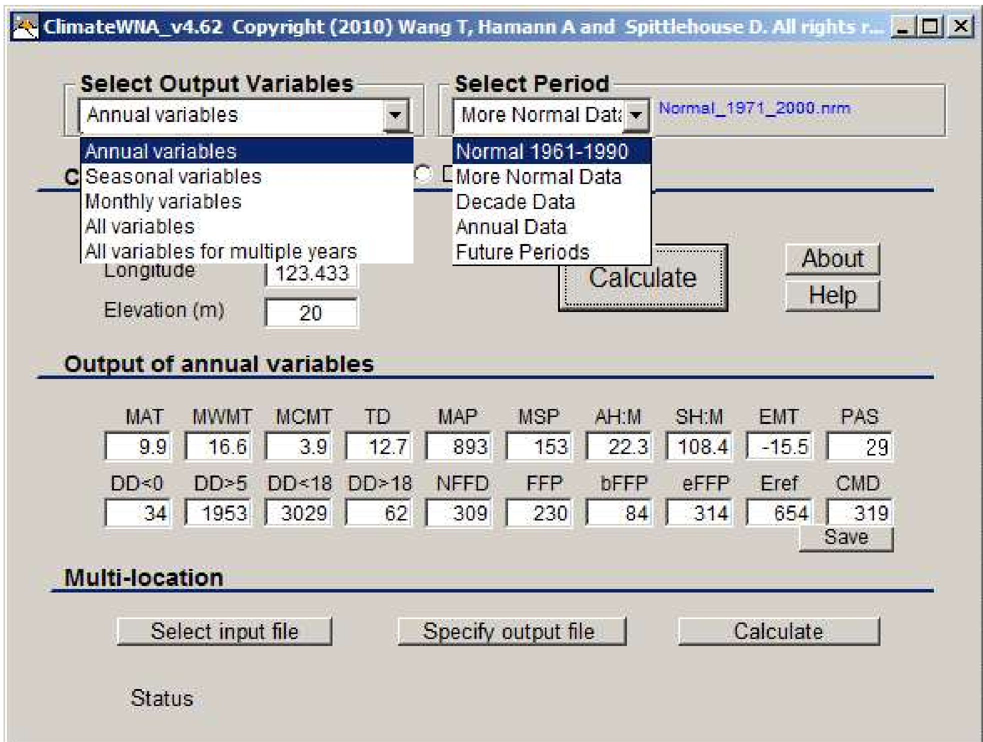

Figure 3: Screen shot of ClimateWNA control panel showing some of the options and variables that are available.

ClimateWNA's stand-alone mode of operation on a personal computer provides a tool to put the user in control. It provides researchers and resource managers with easy access to large, complex climate data bases. A simple graphical user-interface (Figure 3) allows interactive queries, generation of time series, and multi-location processing. A web-based version is also available. ClimateWNA's predecessor, ClimateBC, has been used in over 100 scientific publications (excluding self-citation) in the past 5 years. Publications are now appearing that use ClimateWNA. Both packages are used by consultants in western Canada for environmental impact assessments in mining and hydrology where estimates of historical and projections of future precipitation are required. Climate informed resource

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[5] www.genetics.forestry.ubc.ca/cfcg/ClimateWNA/ClimateWNA.html and extra climate change projections at www.PacificClimate.org/tools/climatewna/

[6] http://www.genetics.forestry.ubc.ca/cfcg/ClimateWNA_web

management applications that have used our software include the delineation of forest seed planning zones (Hamann et al. 2011), mapping forest site index (Coops et al. 2011), assessing pest outbreaks (Campbell et al. 2007), ecosystem classification (Delong et al. 2010) and habitat conservation (Rose and Burton 2011).The software is also changing the way people design field experiments and analyzing data in ecology, genecology and natural resource management in BC (Wang et al. 2012).

Evaluation of ClimateWNA

ClimateWNA predictions for locations are determined from a data set of monthly temperature and precipitation data on a grid of 2.5 arc minutes (approximately 4 km). The baseline data (1961-90 normals) were generated using PRISM (Daly et al. 2002, 2008) and ANUSPLIN (e.g., McKenney et al. 2011) interpolation methods. Each grid cell has a mean elevation and the monthly data are values for the cell. Bilinear interpolation and elevation adjustment are used to determine the climate at specific locations (latitude, longitude and elevation) within the cell. Historic climate and climate change projections are determined using the delta method. These data are represented in ClimateWNA as a grid (1° latitude x 1° longitude) of the absolute difference in temperature, or percentage difference in the precipitation referenced to the 1961-90 normals. The actual historic or projected data temperatures are obtained by adding the difference for the period of interest to the base line temperature; precipitation is the baseline value increased or decreased by the percentage difference for the period of interest to the base line. Anomaly grids are interpolated using bilinear interpolation in run time to remove step artefacts at grid boundaries. Consequently, the accuracy of the downscaled climate data depends on the accuracy of the baseline data.

It is important to determine the reliability of this spatial interpolation. Wang et al. (2012) compared ClimateWNA prediction with measurements from 3353 Environment Canada and US weather service stations. Standard error was less than 0.8°C on monthly temperature and less than 10 mm on monthly precipitation. Jarosh et al. (2010) and Cannon et al. (2012) obtained excellent agreement between downscaled data from the NCEP reanalysis data (Mesinger et al. 2006) and ClimateBC predictions at weather stations. It is difficult to assess the statistical accuracy of climate surfaces for areas that lack station coverage, such as high montane and arctic environments. Moore et al. (2012) used spatially distributed temperature and precipitation data from ClimateBC to run a monthly water balance model for watershed on Vancouver Island. They found that annual runoff compared to stream gauge data was predicted with modest accuracy - mean absolute error was 25.4% of the gauged value, and 52% of the streams had errors less than 20%. How much of this error is due to the assumptions in their simplified water balance model or the spatial data is unknown.

Work was done to assess whether ClimateWNA predictions for BC's climate were the same as those from ClimateBC. This is important to allow consistency between previous and future analyses. There should be excellent agreement because the BC component of ClimateWNA is based on ClimateBC, but there was a need to link to the larger scale and to provide equations to calculate derived variables that work for a wider climatic domain. Also, part of NE BC used ANUSPLINed data rather than PRISM. The latter adjustment resulted in cooler minimum temperatures in some areas and warmer in others. This influenced the derived variables such degree days below 0°C. The improved algorithms for frost free period (FFP) resulted in an increase in FFP for all locations and had the largest effect on locations with short frost free periods. Frost free period started earlier and ended later. There was also an increase in the calculated fraction of precipitation as snow (PAS) (Spittlehouse 2011).

We checked the quality of the temperature and precipitation grids for the IPCC's 4th Assessment Report (AR4) scenarios that are used in ClimateWNA. They were also compared to the prediction of IPCC's Third Assessment Report (TAR) for 4 variables and 19 locations throughout western North America. The agreement in the range and median between PCIC's collation of 128 runs from AR4 and Hamannlab's ensemble of 63 runs from AR4 is excellent (Figure 4). AR4 managed some reduction in spread for temperature (red v. pink, top panel) compared to TAR, while the precipitation predictions show a tendency to be wetter (red v. pink, bottom panels).

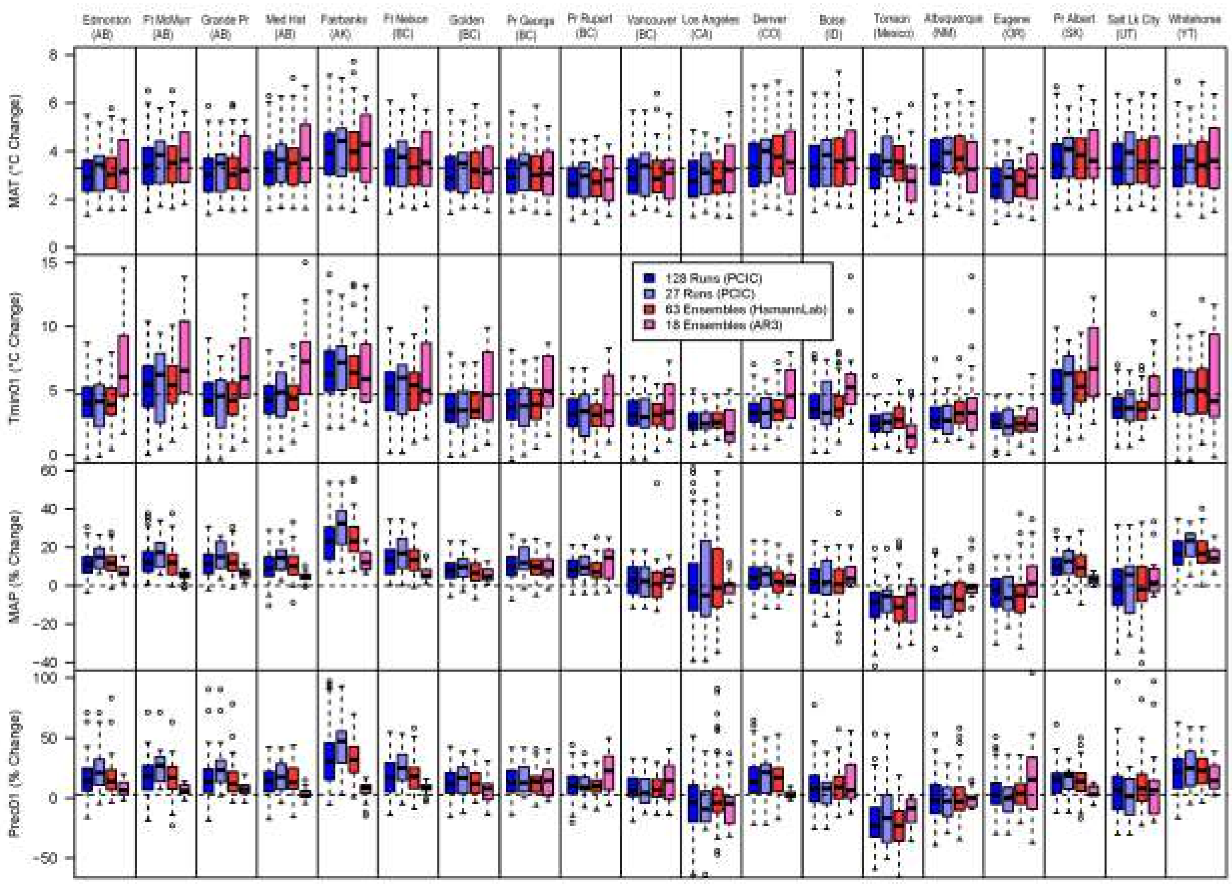

Figure 4: Box plots of the range and median of temperature and precipitation scenarios for individual runs and ensembles for 4 variables and 19 locations throughout western North America from PCIC's collation of 128 runs and Hamannlab's ensemble of 63 runs from AR4. (Source: Dr. Andreas Hamann, Univ. Alberta, Edmonton, AB).

It is not possible to evaluate the accuracy for the interpolation of climate change projections. It is possible that climate change may fundamentally alter local weather patterns at small scales (Fowler et al. 2007, Daly et al. 2009), and such changes are obviously not accounted for with the delta approach, or most statistical downscaling methods. The main objectives of the delta approach are to remove the errors in the GCM data associated with their baseline data and to avoid large step-artifacts at tile boundaries. This does not “improve” the GCM projected changes at the local scale.

Calculation of derived variables on a monthly basis

ClimateBC and ClimateWNA provide annual values of a number of derived variables, e.g., degree days, which are usually calculated on daily basis, but are determined from the monthly temperature data. Provision of monthly values of degree days, precipitation as snow, reference evaporation and climatic moisture deficit would benefit users of the software and also PCIC’s plan2adapt web site. All of these variables except degree days are already calculated on monthly basis and can readily be added to the output of ClimateWNA or to the web site. The algorithms for degree days (<0°C, >5°C, <18°C, >18°C) were modified to allow for the fact that there can be some degree days in months where the mean temperature is below the base temperature and months that are up to three degrees above have days below the base temperature. Wang et al. (2006, 2012) use a correction factor on the annual totals to compensate for these discrepancies. However, they have to be avoided when providing monthly totals.

Caveats

ClimateWNA is used to generate high-resolution climate data for study areas in complex mountainous landscapes, where climate conditions and ecological communities can change at scales of a few hundred meters. While temperature gradients along mountain slopes are well characterized, we should note that all interpolated climate surfaces of this dataset are ultimately based on standard weather stations. Consequently, microclimate driven by vegetation, water bodies or small scale topography such as aspect, slope, and frost pockets are not captured.

Investigating adding a solar radiation layer in ClimateWNA

There are various methods to estimate incident solar radiation using the clear-sky values and the mean daily temperature range. The challenge is to find adequate solar radiation data to calibrate the models. There are data from a sparse network of measurements of solar radiation and sunshine hours in BC that was maintained by Environment Canada, plus a few remote research locations. Some preliminary work was done using monthly normals and the coefficients applied to generate monthly time series data. However, the coefficients are not universal, varying with geographic location and elevation. There are also problems with published winter solar radiation normals data for snowy environments, through sunshine hour data appear “correct”. Regional solar climatology and satellite measurements (Schroder et al. 2009) may provide guidance on spatially extending the point data.

Development of a new PRISM climatology

The reference grids of monthly climate data for the 1961-1990 normal period for the Canadian component of ClimateWNA were generated by the Parameter Regression of Independent Slopes Model (PRISM) (Daly et al. 2002, 2008) in the early 2000s. Interpolation routines have been improved since the original base layer was produced. Also, a project is underway to increase the number of weather stations available in BC to aid spatial climate modelling (Anslow 2012). FFESC project 014 partnered with the CRMP project, thus leveraging resources and funding of at least three times our contribution. The province of BC's Climate Related Monitoring Program (CRMP) and the PCIC's Climate Analysis and Monitoring (CAM) theme address the need for reference climate data and interpreting recent seasonal weather. Faron Anslow at PCIC is working directly with the PRISM Climate Group to form the station normals which will be used for climate mapping. He provided the following update:

CRMP and CAM have made substantial progress toward the development of a new PRISM based climatology for British Columbia. The first half of 2011 was dedicated to collecting CRMP data and pooling it into what is to be termed the Provincial Climate Data Set (PCDS). This activity focused on ingesting data from participating ministries and two private corporations who monitor weather and climate (Rio Tinto AlCan and BC Hydro). Data ingestion brought the disparate observed variables, observation frequencies, and data quality reporting into a common database. At present, the database contains information from more than 6400 historical and active stations in the province and a total of more than 300 million observations of many meteorological variables. To begin the transfer of knowledge from the PRISM Climate Group at Oregon State University to PCIC, two visits to Oregon State were made in summer 2011. These visits included instruction on the use of the PRISM software as well as an introduction to the data quality control procedures used by the PRISM group for the formation of monthly climatologies for the 1971-2000 climate normals. In recent months, near real-time ingestion of data from Environment Canada is being implemented to allow for automatic extension of the temporal coverage of the database enabling the eventual computation of the 1981-2010 climate normals and PRISM climate maps. It is foreseen that initial PRISM maps will be generated by summer 2012. At that time, the climate normals will be made available online as will the entirety of the PCDS through a web-based data portal.

On-going work

Upgrades to ClimateWNA continue with the inclusion of monthly output of derived variables such as degree days and reference evaporation is almost done. The latest historic climate grids of change in temperature and precipitation for individual years produced by the Climate Research Unit, UK (Mitchell and Jones 2005, Jones et al. 2012) are being incorporated. Work will start soon on adding a humidity variable and solar radiation. Once the new PRISM grids have been evaluated and approved, files of gridded monthly temperature and precipitation data will be generated for incorporation into the spatial climate interpolation software. The PRISM data in ClimateWNA and ClimateBC are at 2.5 arc minutes, approximately a 4 km grid. The new PRISM will be at about 800 m, a 16 fold increase in size of the data base. Incorporating this resolution, using downscaling, allowing use of regional climate model projections and the projections from the 5th Assessment (Taylor et al 2012) require a revision of the program and reassessment of the whole package to address increased resolution of the data and size of data files. Preparation is underway to make ClimateBC and ClimateWNA ready for the upgrade. Web-based applications will also be modified.

Downscaling to Determine Extreme Climatic Events at the Local Scale

Evaluation of empirical downscaling techniques

Current global climate model output is at too coarse a scale to provide sufficient local detail on extreme events. Empirical-statistical downscaling is one way to bridge the gap between these scales. Empirical downscaling starts with a statistical analysis of present climatic conditions for an area, as represented by large-scale, e.g., NCEP reanalysis data (Mesinger et al. 2006), and local observations, e. g. station data. From this analysis a statistical model is derived that transforms the large-scale information (predictors) to the local scales (predictands). The model is comprised of a set of numerical tools (such as quantile mapping or linear regression) whose parameters (such as fitting coefficients, means, and variances) represent the climate of the location in question. It is assumed that the predictor-predictand relation remains valid so that future projections of local climate can be derived from the larger scale climate fields. The research evaluated the performance of five methods - Automated regression-based Statistical Downscaling (ASD), Bias Correction Spatial Disaggregation (BCSD), Expanded Downscaling (XDS), Quantile Regression Neural Networks (QRNN), and TreeGen (TG) - on 29 indices of extreme events such as maximum 1-day precipitation and maximum temperature (Climdex[7] , European project STARDEX[8]). Climdex has been adopted as a standard for extremes by the World Climate Research Programme[9]. These indices are relevant to a broad range of impact analysis needs.

The methods were evaluated at six locations from the coastal, mountainous, and Taiga region of BC. All methods are calibrated with data prior to 1991, and tested against the two decades from 1991 to 2010 (Bürger et al. 2012a). Each prediction of a Climdex index had to pass a three-step testing procedure to establish a given method as reliable for that index. The first step analyzed the sensitivity of a method to actual index anomalies, by correlating observed and NCEP-downscaled annual index values. Whether the distribution of an index corresponds to observations is then evaluated. Finally, this latter test was applied to a downscaled climate simulation. This gives a total of 486 single and 162 combined tests. The temperature related indices passed about twice as many tests as the precipitation indices, and more complex indices that involve consecutive days passed none of the combined tests. With respect to regions, there is some tendency of better performance at the coastal and mountain-top stations. With respect to methods, XDS performed best on average with 19% (48%) of passed combined (single) tests, followed by BCSD and QRNN with 10% (45%) and 10% (31%), respectively, ASD with 6% (23%), and TG with 4% (21%) of passed tests.

The validated models were applied to climate change projections (Bürger et al. 2012b). Projections of future climate were obtained from six GCMs from IPCC's 4th Assessment selected based on the availability of predictor fields - the main limiting factor being daily upper level fields. The corresponding simulations for present and future were downscaled using six methods. The analysis was based on Climdex changes between the periods 1981 to 2000 for present and 2046 to 2065 for future climate. The extreme warm events and precipitation events become more frequent. However, the

[7] http://www.climdex.org
[8] http://www.cru.uea.ac.uk/projects/stardex
[9] http://www.clivar.org/organization/extremes

downscaling method has a strong influence on the prediction highlighting the need for extensive verification of methodologies under current climatic conditions.

Projections of drought and fire severity in SE BC

Water provides a wide range of services to society. It is important for agricultural production, forest growth and disturbance, human recreation, aquatic habitat, as a source of potable water for human consumption and energy production. There are concerns about future water availability under a changing climate due to changes in precipitation regimes and increases in evaporative demand. Wildfire is a major source of ecosystem disturbance and property damage in British Columbia. It is thought that the frequency and intensity of fire could increase under future warmer and drier conditions.

A related project to the downscaling of extremes under climate change provided projections of a drought index and a wildfire index. This project is an example of how FFESC funding was able to leverage funding and technical support from other sources. Daily weather data from six locations in southeastern BC and one in Alberta and NCEP reanalysis data (Mesinger et al. 2006) were used to calibrate the expanded downscaling (XDS) method. Two GCMs (CGCM3 and ECHAM5) and three emission scenarios (A2, A1B, B1) were used to provide the projected climatologies (van der Kamp et al 2011). The study area, downscaling technique, and GCMs were chosen based on a combination of data/method availability and expected robustness.

Using XDS and NCEP reanalysis data the study found that while predictions of historical temperature were accurate, precipitation and wind speed were not as well simulated. The drought code (DC) (Lawson and Armitage 2008), which relies only on temperature and precipitation (thus avoiding the errors in downscaled wind speeds) was used to provide an indication of future fire weather severity. The standard precipitation index (SPI) (Guttman 1999) was used as an indication of anomalous precipitation. By definition the SPI has a mean of zero and is positive (negative) for periods of above-average (below-average) precipitation.

Based on an ensemble of future climatologies provided by the models, there was no obvious, region-wide projected change in the fire weather or drought severity. The models project a drying in the summer in southern BC but this is restricted to July and August while March through June tends to be wetter. This is consistent with a recent analysis by Haughian et al. (2012). The only significant case of projected drying is for the late summer in Castlegar with negative SPI anomalies (Figure 5) positive DC anomalies (Figure 6). Results for Castlegar demonstrate the complimentary information contained within the DC and SPI. There is no increase in precipitation at the station and no significant change in SPI values. However, Castlegar shows positive anomalies in DC values, because there was no increase in precipitation to counter-act the temperature increases. Kelowna and Penticton are the only stations to show any decreases (increases) in the DC (SPI).

As is often the case with climate change projections in general, the estimates in drought projections are accompanied by large uncertainties which originate from a number of sources. For instance, there is an obvious lack of stations around the centre of the study area. Also, the effects of overwintering or changes in the initialization date on the DC values were not included. Apart from these issues, a primary source of uncertainty in the projections presented both here and in other studies lies in

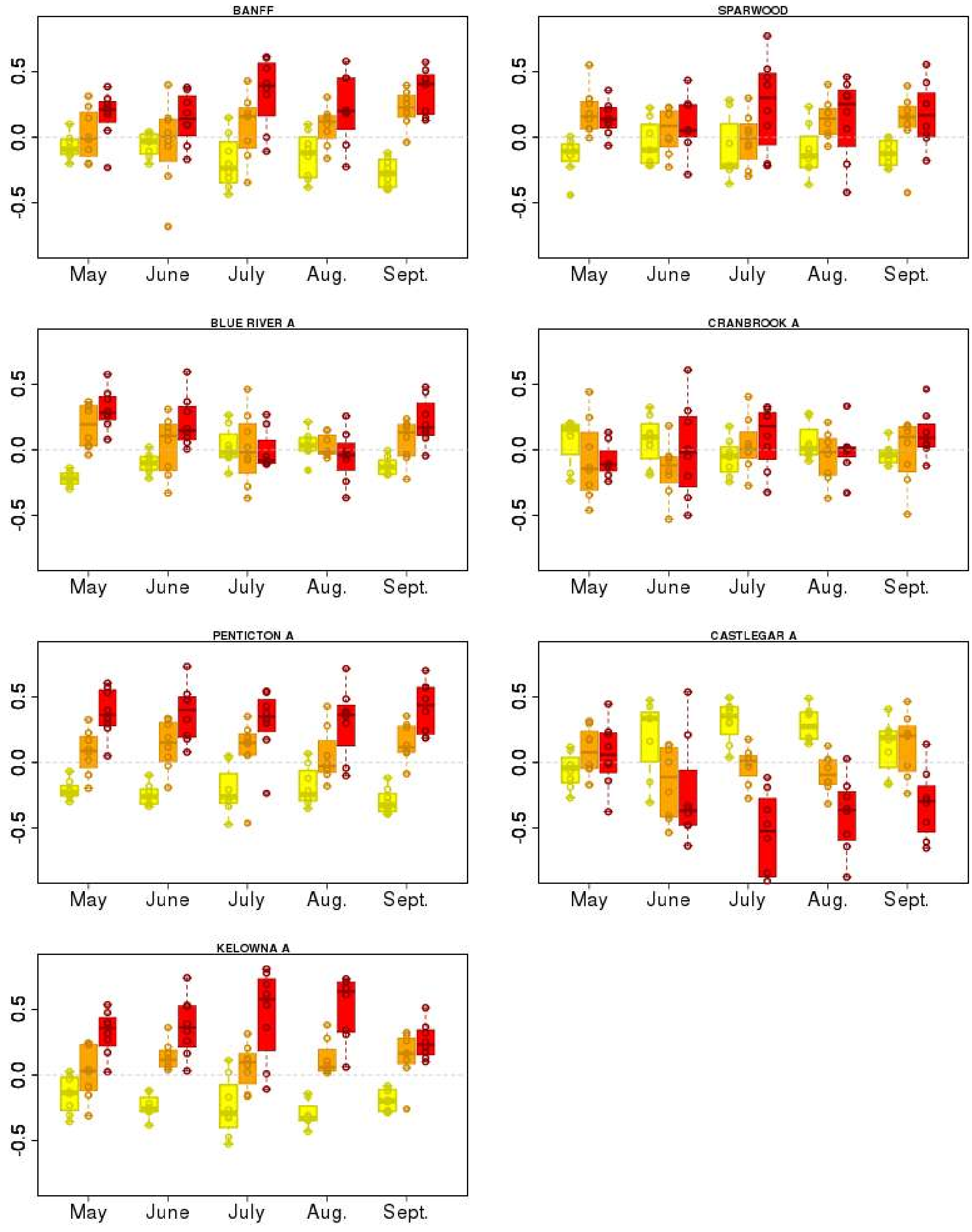

Figure 5: Monthly mean standard precipitation indices (SPI) for May to August obtained from the ensemble of GCMs, scenarios and runs for seven locations. Values are for the historical data (*yellow*), the 2050s climates (*orange*) and the 2080s climates (*red*). The boxes have three lines, the 25th percentile, the median value and the 75th percentile. Error bars indicate the 95% percentile for the distribution of values across all scenarios, models, and runs. (From van der Kamp et al. 2011.)

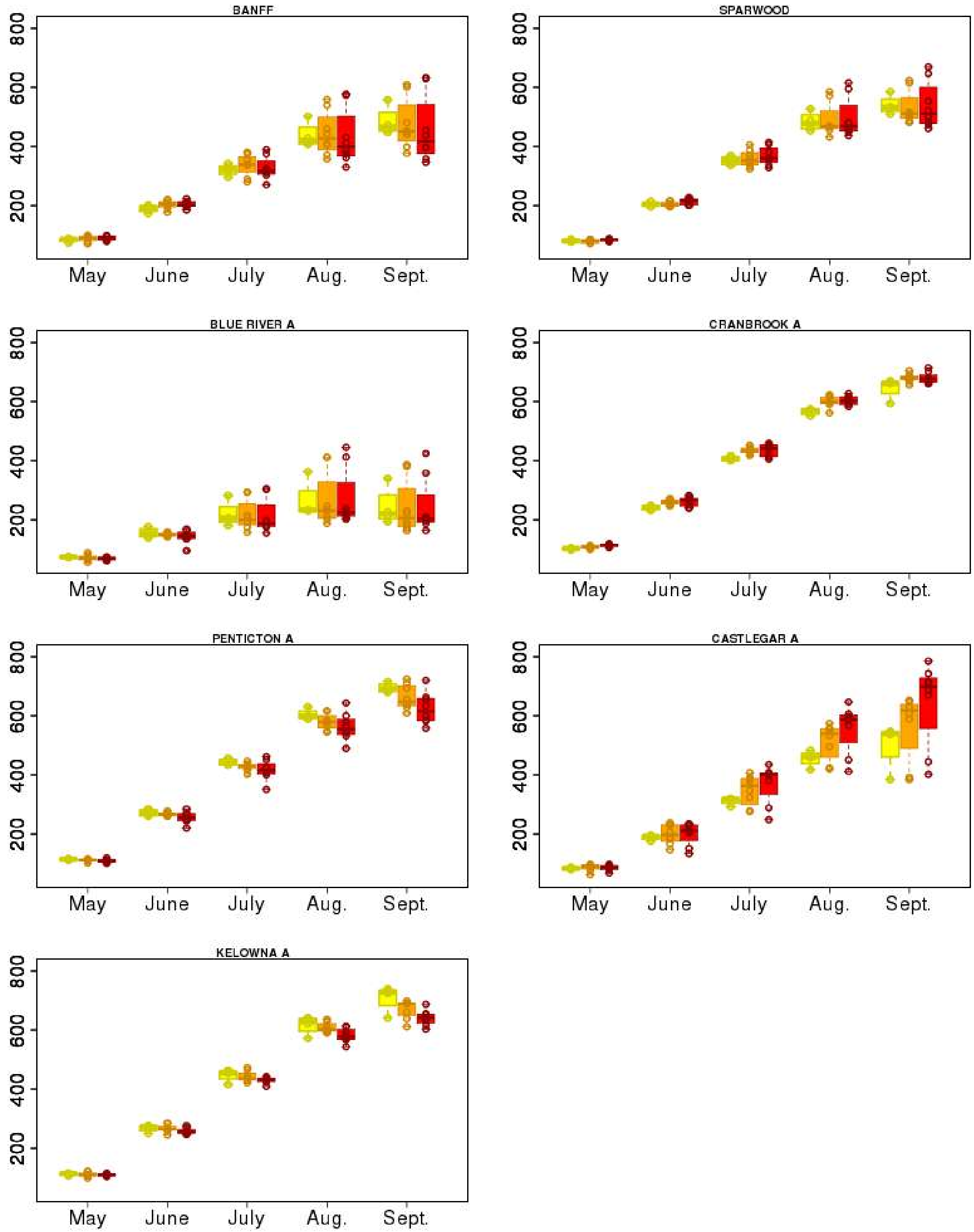

Figure 6: Monthly mean drought code (DC) for May to August obtained from the ensemble of GCMs, scenarios and runs for seven locations. Values are for the historical data (*yellow*), the 2050s climates (*orange*) and the 2080s climates (*red*). The boxes have three lines, the 25th percentile, the median value and the 75th percentile. Error bars indicate the 95% percentile for the distribution of values across all scenarios, models, and runs. (From van der Kamp et al. 2011.)

the issues surrounding precipitation projections. The large biases in the precipitation climatologies are of concern when calculating the DC because these differences will “accumulate” in the DC throughout the summer due to its long drying lag-time. Indeed, additional analysis suggests that a persistent precipitation bias will lead to an even larger bias in the historical downscaled late-summer DC as compared to the DC calculated from observations. Consequently, future work should consider the possibility of downscaling a monthly version of the DC developed by Girardin and Wotton (2009). This would allow for a more simplified downscaling approach for monthly temperature and precipitation using a larger suite of GCMs for which monthly data are more readily available. Alternatively, the monthly DC could be downscaled directly, avoiding the errors and uncertainties of the intermediate step. We can then determine if there is any benefit to using the more sophisticated daily XDS technique outlined here.

Downscaling with weather generators

The downscaling project is also evaluating the use of weather generators to statistically describe monthly or daily weather data such as temperature and precipitation. The statistical information (probability distributions, means etc.) can be adjusted based on changes in mean conditions indicated by GCMs and used to create a time series of weather data under a changing climate. A number of software packages, e.g., LarsWG5 (Semenov 2008) and BioSim (Régière and St. Amant (2007), are available for free and have been extensively used in climate change studies, particularly in Europe. Results from this analysis are presented in (Bürger et al. 2012b).

Time Series Analysis

Time series data are required to evaluate how future inter-annual variations in weather may impact resources. They are also necessary to place the future in the context of the past because our use of resources and design of structures is often based on the probability of occurrence past conditions. The focus in this study was evaluating monthly time series of climate change projections to estimate changes in thermal units, atmospheric evaporative demand and climatic moisture deficit. The initial test location was Victoria International Airport, in part because of the availability of a suite of historic weather data including solar radiation. The work is being extended to other locations in BC.

Measured temperature and precipitation data were obtained from the Environment Canada’s National Climate Data and Information Archive[10]. Sunshine hours or solar radiation were supplied through information request to Environment Canada and via their paper archive (annual climate summaries). Data for the chosen location prior to the station’s existence were obtained from ClimateWNA interpolation of historic temperature and precipitation anomaly fields (Wang et al. 2012) and by regression from the Victoria Gonzales weather station (sunshine hours).

Climate change data were obtained from the Canadian Climate Change Scenarios Network[11] (CCCSN) for the grid box encompassing Victoria airport. Climate change projections were from the 4th

[10] http://climate.weatheroffice.gc.ca/climateData/canada_e.html
[11] http://cccsn.ec.gc.ca

Assessment report and were chosen to span the range of future climates as recommended in Murdock and Spittlehouse (2011). Mean annual air temperature and precipitation changes by 2050s range from 1 to 3.5 C° and -5 to 15%, respectively. The full suite of required monthly weather data was only available for one GCM. Only two GCMs had maximum and minimum temperature data. Consequently, the missing data had to be calculated from other variables, or the use of climatology. Tests were performed to evaluate the effect of estimating the missing data. The CCCSN site has data for individual model runs for some projections, and averages of a number of runs for others.

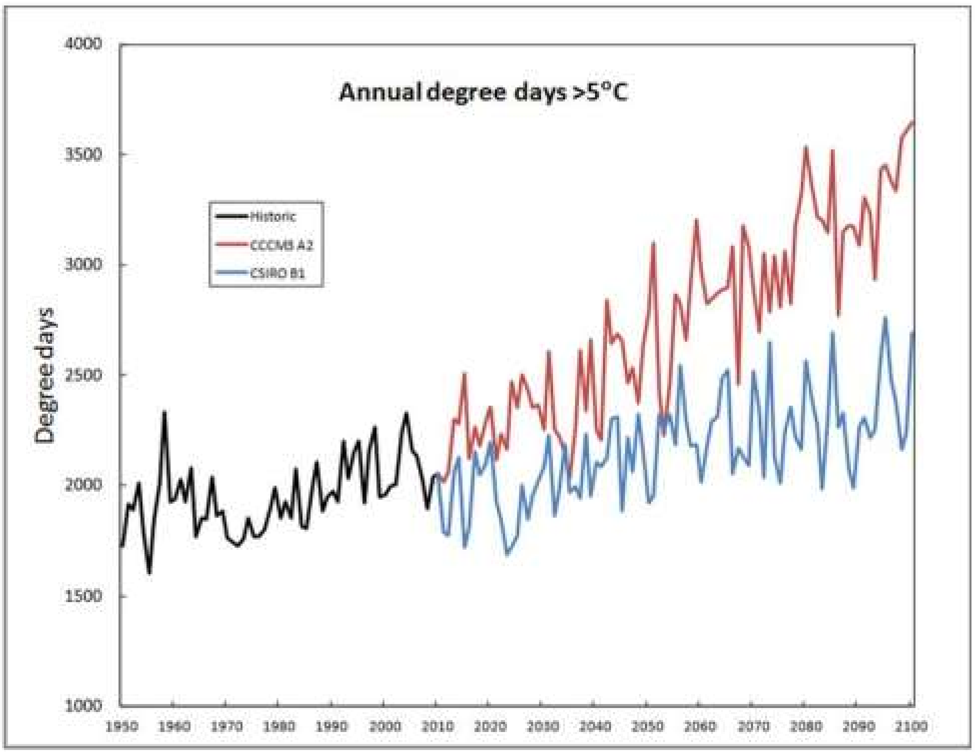

Figure 7: Annual degree days above 5°C for 1948-2010 (black line) and 2011-2100 climate projections from the CCCM3 A2 (red line) and CSIRO B1 (green line) scenarios for Victoria International airport.

Degree days above 5°C (DD5) were calculated on a monthly basis using the modified equations described in Appendix IV. Figure 7 shows the annual total of the DD5 for the historic period (1948-2010) and two climate projections for 2011-2100. The warmer climate of the CCCM3 A2 scenario resulted in more degree days than the cooler CSIRO B1 scenario. (See Appendix I and II for explanation of scenario symbols.) It should be noted that these time series show the trend and range of interannual variability and should not be interpreted as indicating the weather condition that would occur in a specific year. The CCCM3 A2 projection indicates a warmer climate over the next 20 years than CSIRO even though changes in greenhouse gas concentrations would not be that much different for these two emission scenarios for this period. This illustrates the differences that can occur in projections due to variations in GCM formulation, resolution and starting climatology. DD5 for the 1948-2010 period are 1950±160, and by 2050s (2041-2070) are 2750±270 for the CCCM3 scenario and 2215±170 for CSIRO scenario.

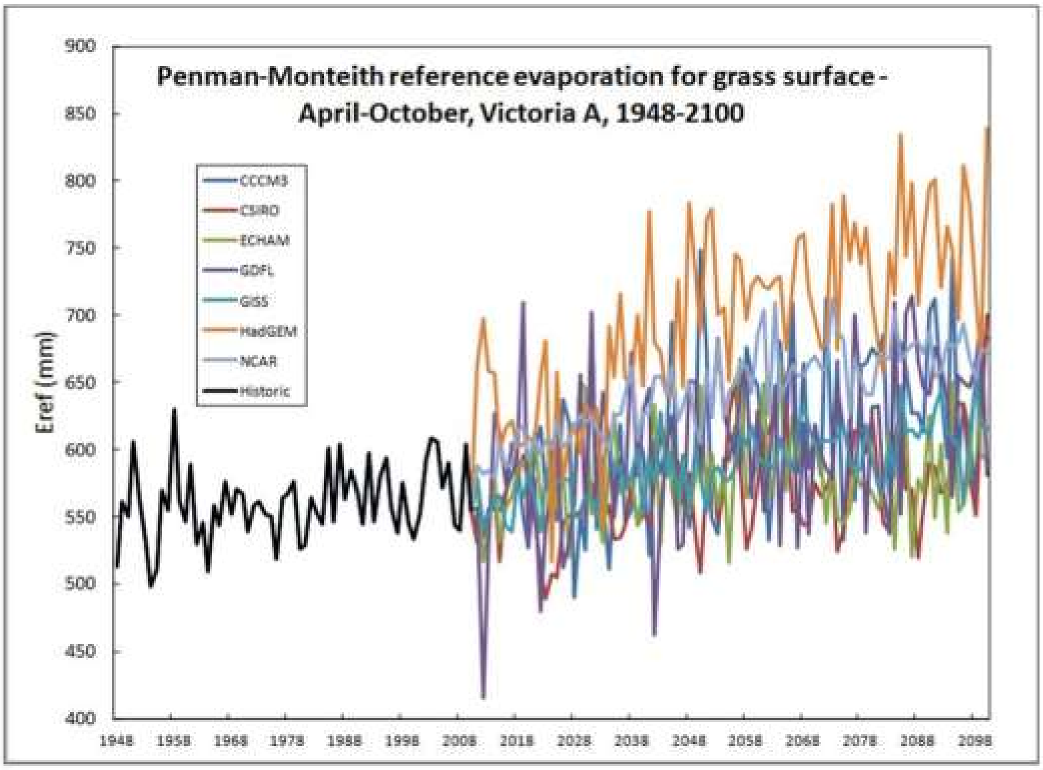

Figure 8: April to October reference evaporation (Eref mm) for 1948-2010 (black line) calculated from measured weather data and from 2011 to 2100 calculated from 7 GCMs (coloured lines).

Reference evaporation was calculated using the Penman-Monteith equation and a modified form of the Hargreaves equation. The former requires solar radiation, maximum and minimum air temperature, humidity and wind speed. Hargreaves requires only maximum and minimum temperature and was validated against the Penman-Monteith equation for use in ClimateWNA (Wang et al. 2012). The reference evaporation has a mean of 560±27 mm for the 1948 to 2010 period. All the projected climates show an increase in atmospheric evaporative demand with the amount of projected warming. The HadGEM scenario has the greatest warming and the evaporative demand was 718±41 mm by 2050s, CCCM3 scenario simulated 612±56 mm for evaporation in the 2050s. The smallest increase was from CSIRO scenario at 580±36 mm by the 2050s. The respective evaporative demands for each scenario by 2080s were 744, 641 and 586 mm, which parallels the projected increases in air temperature.

The reference evaporative demand needs to be adjusted when applied to specific vegetation types (Allen et al. 1998). An option is the use of evaporation equations with coefficients specific to forests. In this case, the Penman-Monteith equation and a vapour deficit equation that can be applied using only maximum and minimum air temperature (Tan and Black 1976, Hogg 1997). The vapour deficit approach performed well. Consequently, either equation could be incorporated into a simple monthly water balance model along with soil information to estimate evaporation, moisture stress and drainage. A similar procedure using a different evaporation model was applied by Moore et al. (2012).

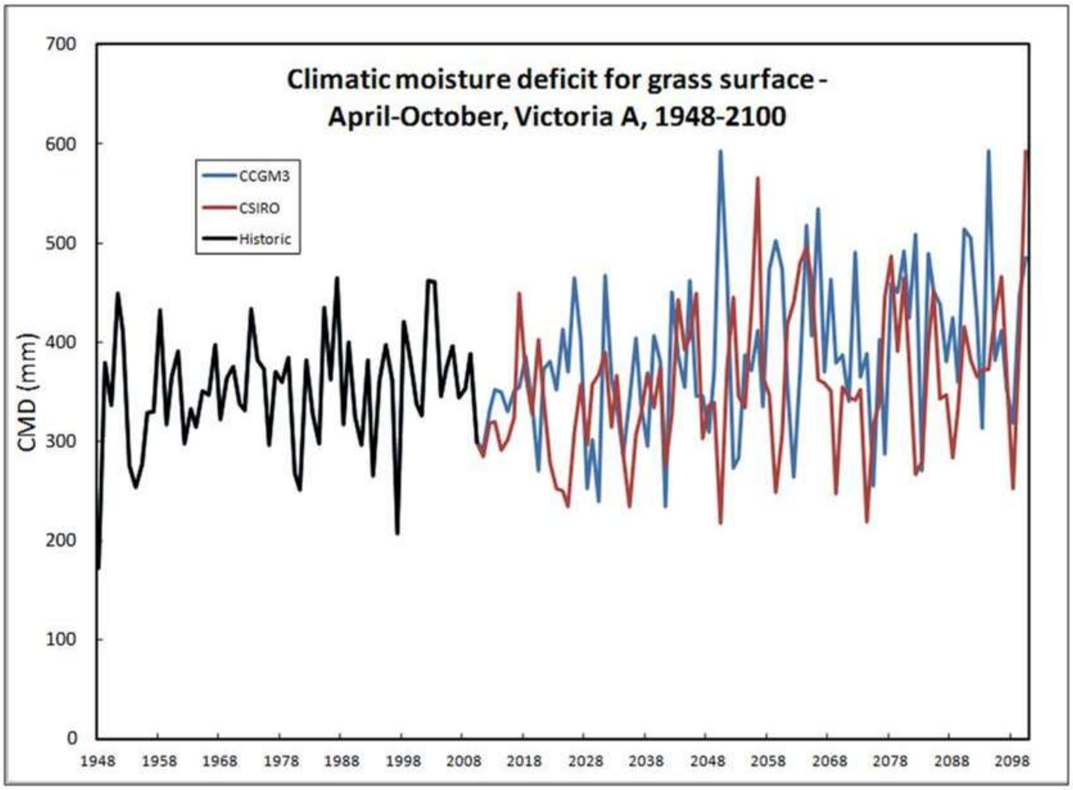

Figure 9: April to October climatic moisture deficit (CMD mm) for 1948-2010 (black line) calculated from measured weather data and from 2011 to 2100 calculated from 2 GCMs (coloured lines).

The climatic moisture deficit (CMD) combines the effect of changing evaporative demand with the changes in precipitation. If the monthly evaporative demand is greater than the precipitation, the monthly CMD equals the difference, otherwise it is zero. The historic period and all projections have an excess of precipitation for November through March. Consequently, CMD is presented only for the April to October period (Figure 9) and only two scenarios shown for clarity. These two scenarios show similar trend in the CDM even though they have quite large differences in warming (Figure 7) and evaporation (Figure 8). This is because CMD is a dependent on changes in evaporative demand and precipitation. The average CMD for the historic period is 350±59 mm, while for the 2005s CCCm3 gives 396±84 mm and CSIRO 374±76 mm. In some projections, e.g., ECHAM, the increase in precipitation offsets the increase in evaporative demand and the CMD shows a decrease (360 mm in 2050s and 340 mm by 2080s for ECHAM). The projections with a decrease in precipitation and greatest warming show the largest increase in CMD, e,g., HadGEM (546 mm by 2050s and 570 mm by 2080s).

Conclusions

The climate change projections show a greater inter-annual variability in weather variables, degree days, evaporative demand and climatic moisture deficit than the historic record, at least for those climates that are not averages of a number of model runs. This may be an artifact of the GCMs because the 1961-90 period from the GCMs (individual runs) showed a higher variability than the measured data. However, the increased variability is much smaller than the range of variability between projections.

Excellent agreement was obtained between reference evaporation calculated with the full suite of weather variables and a reduced set. The Hargreaves equation provided reliable estimates of evaporative demand and appears suitable for use with a reduced suite of weather data. The analysis indicates that the GCM time series data can be combined with historic data to determine a time series in reference evaporation. The lack of a full suite of historic data for the location of interest, or for the GCM projection did not seriously hamper application. GCM data can be used in conjunction with ClimateWNA, the latter being used to generate historic monthly temperature data and to provide the 1961-90 baseline on which to apply the GCM anomalies. There were difficulties in using ClimateWNA predictions to extend the weather station measurements of temperature. This relates to the limits to the accuracy of the Mitchell and Jones (2005) CRU anomaly fields of historic data and ClimateWNA's interpolation of the data. Although predicted temperatures are within the error estimates reported by Wang et al. (2012) and Mbogga et al. (2009), the way the data are used in the evaporation calculation can magnify the error. Consequently, it is recommended that a comparison of overlapping measured historic data and ClimateWNA prediction of temperature and precipitation be done where possible and the predicted data adjusted accordingly.

Projections of change produce for IPCC's 5th Assessment (Taylor et al. 2012) are becoming available. They used a different, though somewhat equivalent, set of future emission scenarios, than the 4th Assessment projections used here. Also they were produced using GCMs with higher resolution and physical complexity. It is unlikely that the range in projected changes in climate will be much different from those of the 4th Assessment. However, more data and variables will be available and any further time series analysis work should be based on the new projections.

Communication of Results

ClimateWNA

- ClimateWNA v4.62 is the latest release. It covers historical annual data up to 2009 and climate change scenarios based on IPCC's 4th Assessment. It is available at: http://www.genetics.forestry.ubc.ca/cfcg/ClimateWNA/ClimateWNA.html
  Extra climate change projections are available at: www.PacificClimate.org/tools/climatewna/
- A web version of ClimateWNA has a functionality equivalent to ClimateWNA v4.62 except it is limited to processing one location at a time is available at: http://www.genetics.forestry.ubc.ca/cfcg/ClimateWNA_web/

Web-based climate change information

- The Pacific Climate Impacts Consortium's Plan2Adapt provides visualization of projected future climates to aid in community planning and for informing the general public about climate change. Data and applications were added to the site as a result of work performed by this

project. Project members also participated in a workshop to aid the development of climate change impacts pages for resource management.
http://pacificclimate.org/tools-and-data/plan2adapt

- Gridded data are available via the Pacific Climate Impacts Consortium Regional Analysis Tool. This interactive web site allows selection of all or part of BC, visualization of data, comparison of global climate model output and access to data. The web site is: www.PacificClimate.org/tools/regionalanalysis/

Publications

Bürger, G., S.R. Sobie, A.J. Cannon, A.T. Werner, T.Q. Murdock. 2012b. Downscaling extremes - an intercomparison of multiple statistical methods for future climate. J. Climate (In review).

Bürger, G., T.Q. Murdock, A.T. Werner, S.R. Sobie, A.J. Cannon. 2012a. Downscaling extremes - an intercomparison of multiple statistical methods for present climate. J. Climate http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-11-00408.1

Hamann, A, T. Wang, D.L. Spittlehouse and T.Q. Murdock. 2012 A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bull. Am. Met Soc. (submitted).

Murdock, T.Q., and D.L. Spittlehouse. 2011. Selecting and using climate change scenarios for British Columbia. Pacific Climate Impacts Consortium, Univ. Victoria, Victoria, 35 pp. http://www.pacificclimate.org/resources/publications

Spittlehouse, D.L. 2012. Climate change information for British Columbia. BC Inst. Agrologists Newsletter Winter 2011/12, 1 pp. (Appendix III).

Wang, T., A. Hamann, D.L. Spittlehouse, and T.Q. Murdock. 2012. ClimateWNA -- High-Resolution Spatial Climate Data for Western North America. J. Appl. Meteorol. Climatol. 51: 16-29. http://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-11-043.1

Contributions to: Pike et al. 2010. Climate Change Effects on Watershed Processes in British Columbia, Chapter 19. In: Pike, R.G., et al. (Eds.), Compendium of forest hydrology and geomorphology in British Columbia. B.C. Min. Forests and Range, For. Sci. Prog., Victoria, B.C. and FORREX Forest Research Extension in Natural Resources, Kamloops, B.C. Land Management Handbook 66, pp 699-747. http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm

Presentations

There have been over 25 presentations (oral and posters) in British Columbia and at national and international locations (Appendix V). Audiences included scientists at conferences (Canadian Meteorological and Oceanographic Soc, Canadian Geophysical Union, American Geophysical Union), government personnel (Agriculture and Agri-Food Canada & Environment Canada, BC Min. Transportation and Infrastructure, Min Forest Lands and Natural Resource Ops., City of Victoria), students (U Victoria, UBC), consultants, community stakeholders and industry. Information is also being used in the development of Module 2 of the "Climate Insights" course, Pacific Institute for Climate Solutions, Univ. Victoria, Victoria.

Deviations from the Project Plan

Adding new climate change layers to HectaresBC has been delayed. We decide to wait until the new PRISM layer is available so that we can update the current climate layer as well us the climate change projections from the 5th Assessment.

We had proposed to link ClimateWNA temperature and precipitation grids, a digital elevation model to calculate of potential solar radiation on slopes and a regional solar climatology in a GIS to improve estimates of small topographic effects on climate. This project was put on hold due to the provincial government reorganization of personnel that resulted in the loss of a team member with the requisite GIS skills. There was no one available to join the team and take on this task, which is quite ambitious.

Conclusions

Although we were not able to complete all proposed activities, this has not prevented our success in meeting the project goal of “easy access to high quality historic and climate change data for impact assessments and development of adaptation strategies”. There is still work to be done and this is happening even though project 014 is complete. The guide to selecting and using climate change scenarios is available at PCIC’s web site and we continue to answer queries on this topic as well as make presentations to a wide range of audiences. Work continues to add information to the Plan2Adapt web site. Research on producing indices of climate extremes under climate change continues. A new data base of climate normals (PRISM) that provides the basis for ClimateWNA and ClimateBC will be available by mid 2012 and software is being readied for the inclusion of these data. Global climate model projections produced for Intergovernmental Panel on Climate Change’s 5th Assessment report will be included as they become available. We are also adding an updated historic temperature and precipitation anomaly database. In the meantime, versions of ClimateWNA and ClimateBC with monthly output of derived variables will be released this spring along with updated web-based versions.

Literature cited

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith, 1998: Crop evapotranspiration – guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper FAO56, U.N. Food and Agriculture Organization, Rome.

Anslow, F. 2012. Research Plan for 2012-2016, Climate Analysis and Monitoring, Pacific Climate Impacts Consortium, Univ. Victoria, Victoria. http://www.pcic.uvic.ca/resources/publications

Bronaugh, D and T.R. Murdock. 2010. Developing improved degree-day equations. Pacific Climate Impacts Consortium, Univ. Victoria, Victoria, BC, 29pp.

Bürger, G., J. Hiebert, H. Eckstrand, and T. Murdock 2010. Climate change assessment for the Coquihalla Highway. Pacific Climate Impacts Consortium, Univ. Victoria, Victoria.

Bürger, G., T.Q. Murdock, A.T. Werner, S.R. Sobie, A.J. Cannon. 2012a. Downscaling extremes - an intercomparison of multiple statistical methods for present climate. J. Climate, doi:10.1175/JCLI-D-11-00408.1.

Bürger, G., S.R. Sobie, A.J. Cannon, A.T. Werner, T.Q. Murdock. 2012b. Downscaling extremes - an intercomparison of multiple statistical methods for furture climate. J. Climate (In review).

Campbell E.M., R.I. Alfaro and B. Hawkes, 2007. Spatial distribution of mountain pine beetle outbreaks in relation to climate and stand characteristics: A dendroecological analysis. J. Integr. Plant Biol. 49, 168−178.

Cannon, A.J., D. Neilsen and B. Taylor. 2012. Lapse Rate Adjustments of Gridded Surface Temperature Normals in an Area of Complex Terrain: Atmospheric Reanalysis versus Statistical Up-Sampling. Atmosphere-Ocean 50:9-16. DOI: 10.1080/07055900.2011.649035

Coops, N.C., R. Gaulton, and R.H. Waring, 2011: Mapping site indices for five Pacific Northwest conifers using a physiologically based model. J. Appl. Vegetation Sci. 14, 268-276.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, and J. Curtis. 2008. Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. Int. J. Climatol., 28, 2031-2064.

Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. Clim. Res., 22, 99-113.

Daly, C., D.R. Conklin, and M.H. Unsworth. 2009. Local atmospheric decoupling in complex topography alters climate change impacts. Int. J. Climatol. 30: 1857-1864.

DeLong, S.C., H. Griesbauer, W. Mackenzie, and V. Foord, 2010: Corroboration of Biogeoclimatic Ecosystem Classification climate zonation by spatially modelled climate data. BC J. Ecosystems and Management 10:49–64.

Fowler, H.J., S. Blenkinsop and C. Tebaldi. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol. 27:1547–1578.

Girardin, M. and B. Wotton. 2009. Summer moisture and wildfire risks across Canada. J. Appl. Meteorol. Climatol. 48: 517-533.

Girvetz, E. H., C. Zganjar, G. T. Raber, E. P. Maurer, P. Kareiva, and J. J. Lawler. 2009. Applied Climate-Change Analysis: The Climate Wizard Tool. PloS ONE, 4, e8320.doc 10.1371/journal.pone.0008320.

Guttman, N. 1999. Accepting the standardized precipitation index: A calculation algorithm. J. Am. Water Resour. Assoc. 35: 311-322.

Hamann, A., Gylander, T. and P. Chen, 2011: Developing seed zones and transfer guidelines with multivariate regression trees. Tree Genetics & Genomes 7: 399–408.

Haughian, S.R., P.J. Burton, S. W. Taylor, & C. L. Curry. 2012. Expected effects of climate change on forest disturbance regimes in British Columbia. BC Journal of Ecosystems and Management 13:1–24.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25:1965-1978.

Hogg, E.H. 1997. Temporal scaling of moisture and the forest-grassland boundary in western Canada. Agric. For. Meteorol. 84:115-122.

IPCC. 2007. Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 18 pp.

IPCC-TGICA. 2007. General guidelines on the use of scenario data for climate impact and adaptation assessment. Version 2. Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, 66 pp. http://www.ipcc-data.org/guidelines/TGICA_guidance_sdciaa_v2_final.pdf

Jarosch, A.H., F.S. Anslow, and G.K.C. Clarke. 2010. High-resolution precipitation and temperature downscaling for glacier models. Climate Dynamics, DOI 10.1007/s00382-010-0949-1.

Jones, P. D., D. H. Lister, T. J. Osborn, C. Harpham, M. Salmon, and C. P. Morice. 2012. Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010. J. Geophys. Res., 117, D05127, doi:10.1029/2011JD017139.

Lawson, B. and O. Armitage. 2008. Weather Guide for the Canadian Forest Fire Danger Rating System. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. nofc.cfs.nrcan.gc.ca /bookstore_pdfs/29152.pdf

Mbogga, M., A. Hamann, and T. Wang. 2009. Historical and projected climate data for natural resource management in western Canada. Agric. For. Meteorol. 149:881-890.

McKenney, D.W., M.F. Hutchinson, P. Papadopol, K. Lawrence, J. Pedlar, K. Campbell, E. Milewska, R.F. Hopkinson, D. Price, and T. Owen. 2011. Customized Spatial Climate Models for North America. Bull. Am. Met. Soc. 92:1611-1622.

Mesinger, F. and 18 others. 2006. North American Regional Reanalysis. Bull. Am. Meteorol. Soc. 87:343–360

Mitchell, T. D., and P. D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol., 25:693-712.

Moore, R.D., J.W. Trubilowicz, and J.M. Buttle. 2012. Prediction of streamflow regime and annual runoff for ungauged basins using a distributed monthly water balance model. J. Am. Water Resour. Assoc. 1-11. DOI: 10.1111 ⁄ j.1752-1688.2011.00595.x

Murdock, T.Q., and D.L. Spittlehouse. 2011. Selecting and using climate change scenarios for British Columbia. Pacific Climate Impacts Consortium, Univ. Victoria, Victoria, 35 pp. http://www.pacificclimate.org/resources/publications

Price, D.T., D.W. McKenney, L.A. Joyce, R.M. Siltanen, P. Papadopol, and K. Lawrence. 2011. High-resolution interpolation of climate scenarios for Canada derived from general circulation model simulations. Inf. Rep. NOR-X-421, Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB.

Régnière, J. & R. St-Amant. 2007. Stochastic simulation of daily air temperature and precipitation from monthly normals in North America north of Mexico. Int J Biometeorol. 51:415-430.

Rodenhuis, D., K. Bennett, A.T. Werner, T.Q. Murdock, and D. Bronaugh, 2009: Hydro-climatology and Future Climate Impacts in British Columbia. Revised 2009, Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC. http://www.pacificclimate.org/resources/publications

Rose, N.-A. and P.J. Burton, 2011: Persistent climate corridors: The identification of climate refugia in British Columbia’s Central Interior for the selection of candidate areas for conservation. BC J. Ecosystems Manage. 12, 101–117.

Schroeder, T.A., R. Hember, N.C. Coops and S. Liang. 2009. Validation of solar radiation surfaces from MODIS and reanalysis data over topographically complex terrain. J. Appl. Meteorol. Climatol. 48: 2441–2458.

Semenov, M.A. 2008. Simulation of weather extreme events by stochastic weather generator. Climate Research, 35:203-212.

Spittlehouse, D.L. 2011. Comparison of annul derived variables calculated in ClimateBC and ClimateWNA. BC Min. Forest Lands and Natural Resource Operations, Victoria, BC, 4pp.

Sutherst, R.W., G. F. Maywald and A. S. Bourne. 2007. Including species interactions in risk assessments for global change. Global Change Biol., 13:1–17.

Tan, C.S. and T.A. Black. 1976. Factors affecting the canopy resistance of a Douglas-fir forest. Boundary-Layer Meteorol. 10:475-488.

Taylor, K.E., R.J. Stouffer and G.A. Meehl. 2012. An overview of CMIP5 and the experiment design. Bull. Am. Met. Soc. 93:485-498.

van der Kamp, D., G. Bürger, T.Q. Murdock. 2011. Future Projections of Drought and Fire Weather Severity in Southeast British Columbia Using Statistical Downscaling. Pacific Climate Impacts Consortium, University of Victoria, 35 pp

Wang, T., A. Hamann, D.L. Spittlehouse, S.N. Aitken. 2006. Development of scale-free climate data for Western Canada for use in resource management. Int. J. Climatol. 26: 383-397.

Wang, T., A. Hamann, D.L. Spittlehouse, and T.Q. Murdock. 2012. ClimateWNA -- High-Resolution Spatial Climate Data for Western North America. J. Appl. Meteorol. Climatol. 51: 16-29.

Appendix I: Global Climate Models

Table I.1: The Intergovernmental Panel on Climate Change (IPCC) identifiers (ID) of the global climate models, modelling centre name and location (adapted from Murdock and Spittlehouse (2011).

IPCC ID	Center and Location
BCCR-BCM2.0	Bjerknes Centre for Climate Research (Norway)
CCCMA-CGCM3.1 (T47 or T63)	Canadian Centre for Climate Modelling and Analysis (Canada)
CSIRO-Mk3.0	CSIRO Atmospheric Research (Australia)
CNRM-CM3	Meteo-France, Centre National de Recherches Meteorologiques (France)
MIUB-ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group (Germany and Korea)
GFDL-CM2.0	US Dept. of Commerce, NOAA Geophysical Fluid Dynamics Laboratory (USA)
GISS-AOM	NASA/Goddard Institute for Space Studies (USA)
FGOALS-g1.0	LASG/Institute of Atmospheric Physics (China)
INM-CM3.0	Institute for Numerical Mathematics (Russia)
IPSL-CM4	Institut Pierre Simon Laplace (France)
MIROC3.2 (medres or hires resolution)	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC) (Japan)
MRI-CGCM2.3.2	Meteorological Research Institute (Japan)
MPI-ECHAM5	Max Planck Institute for Meteorology (Germany)
NCAR-CCSM3	National Center for Atmospheric Research (USA)
NCAR-PCM	
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research, Met Office (UK)
UKMO-HadGEM1	

Appendix II: Emission Scenarios

Emissions scenarios or pathways are a representation of possible future emissions trajectories of greenhouse gases such as CO_2, CH_4, N_2O and CFCs and particulates like soot. They are based on assumptions about future population growth, technological development, sources of energy, global cooperation, e.g., A1F, A2, A1B, B1, B2, (IPCC 2007). Figure A1 shows the CO_2 trajectory for the most commonly used emissions scenarios.

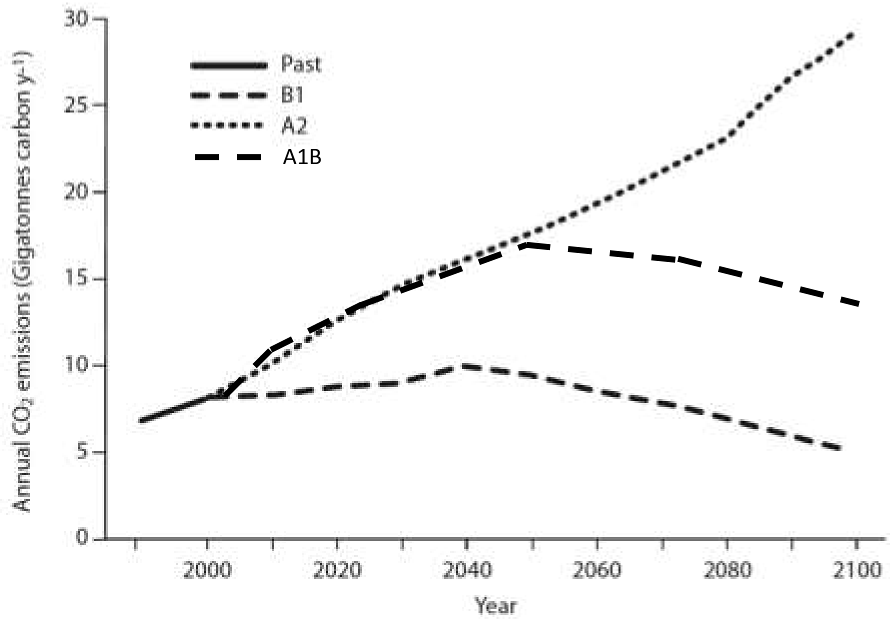

Figure II.1. Carbon dioxide (CO_2) emission trajectories for the B1, A2 and A1B scenarios. Other gases follow a similar path. (Adapted from IPCC 2007).

IPCC 's 5th Assessment Report will be based on a new set of emissions scenarios called representative concentration pathways (RCP) (Taylor et al. 2012). They are somewhat similar in trajectory to those used in the 4th Assessment. There are two pathways that bound the range shown in Figure II.1 and two intermediate pathways.

Appendix III: Extension Article in BCAgrologist Newsletter

BCIA Newsletter Winter 2011/12

Climate Change Information for British Columbia

Climate information is necessary to aid resource management activities such as allocation of water resources, selection of agricultural crops or tree species for reforestation, and road design. Usually, planning is based on the past climate. However, future climate change resulting from the increasing atmospheric concentration of greenhouse gases means that we must revise how we use climate data. Global climate models (GCMs) project a 1 to 3 degree Celsius increase in annual temperature and a 2 to 10 percent increase in annual precipitation for British Columbia by the 2050's. A recent report from the International Panel on Climate Change (IPCC) indicated that what is currently a 20-year return period warm extreme event could become a 5 year event; while a 20-year return period extreme precipitation event could have a 10-year return interval.

Until recently, detailed projections of climate change were not readily available to policy advisors and planners in government, industry and the consulting community, or to the general public. Information was contained in large data bases that required extensive technical expertise to access and use.

Recent developments in communication tools are improving access to such information for users with a wide range of technical capabilities. For example, web sites such as that of the Pacific Climate Impacts Consortium (PCIC) at the University of Victoria, or HectaresBC maintained by the BC government, and stand alone software packages, such as ClimateBC and ClimateWNA, are making climate change information readily available. Documents outlining the recent historic changes in climate as well as projected future changes in BC and guidelines for using climate change information are available through the PCIC website. More information will become available in 2012 with the release of the latest global climate model analyses. Also in 2012, projects funded through the Future Forest Ecosystems Scientific Council and the Regional Adaptation Collaborative will present results of comprehensive analyses on adaptation to climate change in BC.

The following is a list of some of the resources that are currently available to aid agrologists in considering potential future changes in climate in BC and in developing adapting options.

Web sites:

Plan2 adapt: Climate change projections for BC regional districts: illustrative maps, range of uncertainty plots and summary tables, with guidance for interpretation. http://pacificclimate.org/tools-and-data/plan2adapt

PCIC Regional Analysis Tool: visualize all GCM projections prepared for the IPCC 2nd, 3rd, and 4th assessments: define a custom region and get maps, plots, download data, and metadata pertaining to it. http://pacificclimate.org/tools-and-data/regional-analysis-tool

Future Forest Ecosystem Scientific Council (FFESC): http://www.for.gov.bc.ca/hfp/future_forests/council/index.htm

Software:

ClimateWNA - provides selected climate variables for any point in western North America. Can be used to create gridded historic data and future GCM projections elevation-correct to any point. An earlier, extensively used version is ClimateBC. Available for free at: www.genetics.forestry.ubc.ca/cfcg/ClimateWNA/ClimateWNA.html

A web-based version of ClimateWNA with a reduced set of applications can be accessed at: www.genetics.forestry.ubc.ca/cfcg/ClimateWNA_web

HectaresBC: Overlay high-resolution historical climate and selected climate projections with other geographical layers. http://www.hectaresbc.org/app/habc/HaBC.html

Climate Wizard: A web-based tool that provides simple analyses and graphical depictions of how climate has and is projected to change within specific geographic areas throughout the world. http://ClimateWizard.org

Publications:

IPCC, 2011: Summary for Policymakers. Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, C.B. Field, et.al. (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/

Murdock, T.Q and D.L. Spittlehouse, 2011. Selecting and using climate change scenarios for British Columbia. Pacific Climate Impacts Consortium, Univ. Victoria. http://pacificclimate.org/resources/publications

Pike et al. 2010. Climate Change Effects on Watershed Processes in British Columbia, Chapter 19. In: Pike, R.G., et al. (Eds.), Compendium of forest hydrology and geomorphology in British Columbia. Land Management Handbook 66, B.C. Min. Forests and Range, For. Sci. Prog., Victoria, B.C. and FORREX Forest Research Extension in Natural Resources, Kamloops, BC, pp 699-747. http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm

Rodenhuis et al., 2009. Hydroclimatology and future climate impacts in British Columbia. Pacific Climate Impacts Consortium, Univ. Victoria, BC. http://pacificclimate.org/resources/publications

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Appendix IV: Calculating Monthly Degree Days Above 5°C

Data used in this analysis are the 1951-80 normals of monthly mean temperature and monthly degree days >5°C ($DD5_m$) for 416 Environment Canada stations in BC, YK, and AB (Figure IV.1). This figure only shows data between -4 and 8°C for clarity. Equations used in ClimateWNA are based on all data.

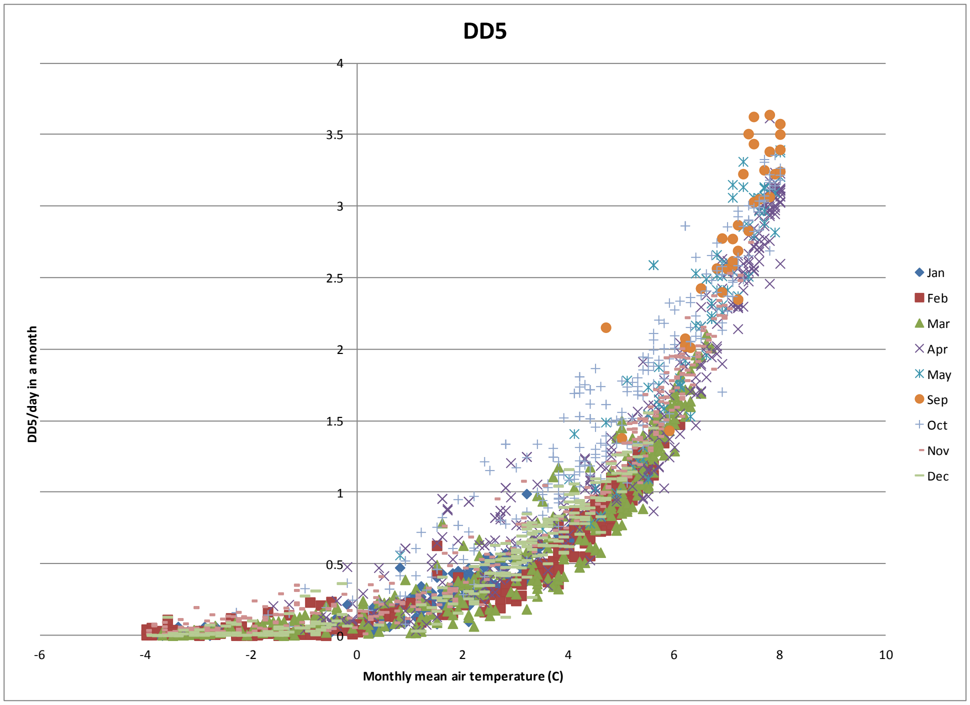

Figure IV.1: Number of degree days >5°C (DD5) per day in a month and monthly mean temperature (°C) for September through May. Data above 8°C and below -4°C are not included for clarity. The few points below 8°C for June through August are not included. Data are the 1951-80 normals of monthly mean temperature and DD5 for 416 Environment Canada stations in BC, YK, and AB.

Table IV.1: Statistics on the equation DD5/day = a*exp((b* T_m). The standard error of the estimate (s.e.) was multiplied by days in the month to get the monthly error. T_m is the monthly mean air temperature. Analysis was done using SigmaPlot 11.

	Nov, Dec and Jan	Feb and Mar	April and May	Sept and Oct
a	0.1731	0.1131	0.2556	0.4188
b	0.382	0.4366	0.3164	0.2612
Adjusted R^2	0.965	0.947	0.941	0.928
s.e. (DD/day)	0.11	0.12	0.24	0.24
s.e. (DD/month)	3	4	7	7

The following algorithm was used to calculate monthly degree days >5°C ($DD5_m$) in the time series analysis in the main body of the report.

IF $T_m \leq -4C°$, $DD5_m = 0$ [1]

IF $T_m \geq 8\ C°$, $DD5_m = (T_m - 5) * N_m$ [2]

Else $DD5_m = a_m * \exp(b_m * T_m) * N_m$ [3]

where a_m and b_m are the monthly coefficients listed in Table IV.1 (April and May values were used for June through August), T_m is the monthly mean air temperature and N_m is the number of days in the month (m).

Summing $DD5_m$ from equations [1-3] produced an excellent estimate of the measured annual totals. The relationship is Measured =0.997*Calculated +13.3, R^2=0.996, (forcing the equation through zero gives a slope of 1.005), MAE=22.5 degree days. This is a small improvement over the previous method (Wang et al. 2006) which had an offset of 75 with a slope of 1.0.

Appendix V: Presentations Based on Work Done Under Project 014

“Selecting and using climate change projections” - Regional Adaptation Collaborative and FFESC researchers, conference call, April 2010. T.Q. Murdock and D.L. Spittlehouse

“Beyond average – variability and extremes in climate change” - Southern Interior Silviculture Committee annual meeting, Naramata, April 2010. D.L. Spittlehouse

“Spatial climate data for climate change studies” - MoFR, Research Branch seminar, Victoria, May 2010.

“Downscaling extremes with EDS, TreeGen and BSCD” - Poster - American Geophysical Union annual meeting, San Francisco, Dec. 2010, G. Bürger, T.Q. Murdock, A.T. Werner, S. Sobie.

"ClimateBC and its use in predicting responses of forest ecosystems, tree species and populations to climate change in British Columbia" at "Climate Change Adaptation - Sustainable Forest Management Workshop", Vancouver, Feb., 2011.

“Challenges in providing data for climate change studies” - Climate Change Adaptation - Sustainable Forest Management Workshop, Vancouver, Feb. 2011. D.L. Spittlehouse

“Historical climate and future projections for BC” - Meeting of the British Columbia Biodiversity Adaptation and Carbon Conservation Priorities Mapping Project, Vancouver, BC, Feb 2011, T.Q. Murdock.

“Historical climate and future projections for BC” - Agriculture and Agri-Food Canada & Environment Canada: Weather, Climate, and Risk Prediction Workshop, Kelowna, BC, Feb 2011, T.Q. Murdock.

“Climate Change Overview” - ICLEI Adaptation Initiative BC Climate Science Workshop Vancouver, BC, May 2011, T.Q. Murdock.

“ClimateWNA_ Access to high spatial resolution climate data for western North America” – Canadian Geophysical Union Conference, Banff, May 2011. D.L. Spittlehouse

“BCSD Downscaled Transient Climate Projections for Eight Select GCMs over British Columbia, Canada. Validation of empirical-statistical downscaling methods in a varying climate system” - Canadian Meteorological Oceanographic Society Conference, Victoria, BC, Canada. June 2011, A.T. Werner.

“Validating the downscaling of Climdex extremes for multiple methods” - Canadian Meteorological Oceanographic Society Conference, Victoria, BC, Canada, June 2011, G. Bürger.

“Regional climate model projections for adaptation in the Canadian Columbia Basin: Application of Climate Model Results to Regional Adaptation” - Canadian Meteorological Oceanographic Society Conference, Victoria, BC, Canada, June 2011, T.Q. Murdock.

“Projections of climate change extremes in British Columbia” - Canadian Meteorological Oceanographic Society Conference, Victoria, BC, Canada, June 2011, T.Q. Murdock.

“ClimateWNA- Access to high spatial resolution climate data for western North America” – Canadian Meteorological and Oceanographic Soc. Conference, Victoria, June 2011. D.L. Spittlehouse

“Past and future climate: Southern Vancouver Island” - ICLEI Adaptation Initiative, City of Victoria Climate Change Adaptation Team, Victoria, BC, July 2011, T.Q. Murdock.

“Past and future climate in BC” - BC Ministry of Transportation and Infrastructure, Climate Adaptation - Engineering Design Standards Meeting, Victoria, BC, T.Q. Murdock.

"Downscaling and translating climate scenarios into ecological and forest scenarios" - International conference on Response of Forests and Adaptation Management to Climate Change, Yichun, Heilongjiang, China, August, 2011, T. Wang.

“Climate change and forest management” - International conference on Response of Forests and Adaptation Management to Climate Change, Yichun, Heilongjiang, China, August, 2011, D.L. Spittlehouse

“Validating the downscaling of Climdex extremes for multiple methods” - Poster - Pacific Northwest Climate Science Conference, Seattle, WA, Sept 2011, S. Sobie, G. Bürger, T.Q. Murdock, A.T. Werner.

“Climate modeling and silviculture decision-making” - FORREX Webinar Series, Silviculture Practices Dialogue Series 2: Forest Dynamics and Climate Change, Jan 2012, T.Q. Murdock.

4 guest lectures in Dept. Geography and Dept. Psychology, Univ. Victoria, and Forestry, UBC, Vancouver - T.Q. Murdock

Participate in workshop to development of climate change impacts pages for resource management to be added to the Pacific Climate Impacts Consortium’ s plan2 adapt web site. T.Q. Murdock, D.L. Spittlehouse, A.Werner.

Development of Module 2 of the "Climate Insights" course, Pacific Institute for Climate Solutions, Univ. Victoria, Victoria. Jan. 2012,T.Q. Murdock.

“Climate change: what are the observed and predicted changes” - Western Forest Insect Work Conference, Penticton, BC, Mar 2012, D.L. Spittlehouse.

"Downscaling and translating climate scenarios into ecological and forest scenarios" - Western Forest Insect Work Conference, Penticton, BC, Mar 2012, T. Wang.