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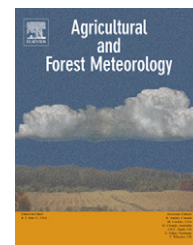
Historical and projected climate data for natural resource management in western Canada

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ABSTRACT

In this paper we present a comprehensive set of interpolated climate data for western Canada, including monthly data for the last century (1901–2006), future projections from general circulation models (68 scenario implementations from 5 GCMs), as well as decadal averages and multiple climate normals for the last century. For each of these time periods, we provide a large set of basic and derived biologically relevant climate variables, such as growing and chilling degree days, growing season length descriptors, frost free days, extreme minimum temperatures, etc. To balance file size versus accuracy for these approximately 15,000 climate surfaces, we provide a stand-alone software solution that adds or subtracts historical data and future projections as medium resolution anomalies (deviations) from the high resolution 1961–1990 baseline normal dataset. For a relative quality comparison between the original normal data generated with the Parameter Regression of Independent Slopes Model (PRISM) and derived historical data, we calculated the amount of variance explained (R^2) in original weather station data for each year and month from 1901 to 2006. R^2 values remained very high for most of the time period covered for most variables. Reduction in data quality was found for individual months (as opposed to annual, decadal or 30-year climate averages) and for the early decades of the last century. We discuss the limitations of the database and provide an overview of recent climate trends for western Canada.

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1. Introduction

With growing concern over climate change, interpolated climate data have become increasingly important for biological research and applications in forest management, conservation policy development, and infrastructure planning. Virtually every study in the field of climate change impact and adaptation research requires a variety of data that may include climate normal data, projections from general circulation models (GCMs), long-term historical climate records, or information about recent climate trends. Such data are usually not easily accessible at the appropriate resolution, in a consistent format, and for a comprehensive set of relevant climate variables. In two previous papers we have developed models of climate normal data for British Columbia and the Yukon Territories and a software solution to estimate many biologically relevant variables (Hamann and Wang, 2005; Wang et al., 2006). In this paper, we compile and test a comprehensive set of historical and projected climate data for an extended area that now covers British Columbia, Alberta, Saskatchewan, Manitoba, and the Yukon Territory.

Climate grids for Canada are available from various regional, continental and global-scale climate interpolation efforts. A global scale dataset for the 1950–2000 period ''WorldClim'' has been developed by Hijmans et al. (2005) using the smoothing spline software ANUSPLIN (Hutchinson, 1995; Hutchinson and Gessler, 1994). Mitchell and Jones (2005) developed coarse resolution global monthly historical data for the 1901–2002. The ANUSPLIN software package has also been used to develop monthly historical data at approximately 10 km resolution for minimum and maximum temperature and monthly precipitation for Canada and the United States for the 1901–2000 period (McKenney et al., 2006). Another modeling group at Oregon State University uses the Para-meter-elevation Regression on Independent Slopes Model (PRISM) to develop monthly climate grids for North America at resolutions ranging from 30 arcsecond ($\sim$800 m) to 2.5 arcmi-nutes ($\sim$4 km) (Daly et al., 2000, 2002; Daly, 2006). More regionally, daily temperature and precipitation grids have been developed for Alberta for the 1961–1997 period (Shen et al., 2001). Comparisons of interpolated data have found ANUSPLIN and PRISM data to produce comparable results and to be superior to several other modeling methods (Daly, 2006; Milewska et al., 2005; Price et al., 2000; Simpson et al., 2005).

We find that all of the above cited climate databases have their strengths and limitations and that the authors have addressed various trade-offs in different ways: First, resolution of spatial coverages have to be balanced against the size of the climate database. A useful resolution for climate normal data that seems to emerge as a standard is 30 arcseconds (approxi-mately 800 m), corresponding to widely used digital elevation models (USGS, 1996). At this resolution, climate gradients due to topography are usually quite well represented and the resulting coverages for a single climate variable are still reasonably small even at continental scales (Hijmans et al., 2005). However, monthly historical data for multiple variables quickly amounts to thousands of spatial coverages and in order to limit the total size of the database, a resolution of 10 km or more is usually chosen (McKenney et al., 2006; Mitchell and Jones, 2005).

A second important decision for producing gridded climate data is the method of interpolation. Many papers have discussed the merits and limitations of various interpolation techniques (e.g. Attorre et al., 2007; Daly, 2006; Hamann and Wang, 2005; Price et al., 2000; Simpson et al., 2005). We want to emphasize the importance of another technical aspect. Usually, interpolations are based on absolute climate values observed at weather stations. However, for series of inter-polated historical data this method is vulnerable to missing values in weather station coverage (Mitchell and Jones, 2005). Missing values for station data in certain years may lead to temporary changes in interpolated surfaces that are highly undesirable when analyzing biological response to historical climate data. An alternative approach used by us and Mitchell and Jones (2005) is to interpolate anomalies from climate normals. Lack of station data still leads to interpolated values that do not reflect the true climate anomalies, but these values can be forced to approach a zero anomaly (or the climate normal), which can be better handled in biological analysis. The trade-off here is that new weather stations that lack records to calculate the climate normal reference cannot be used for interpolation.

The central objective of this paper is to make climate databases from a variety of sources useful and accessible for biologists and natural resource managers. We have therefore chosen data and methods that we think are best for biological applications, particularly the climatic characterization of sample locations (e.g. survey plots, collection sites) and the study of historical biological response to climate (e.g. in growth or phenology). The database we present covers monthly, seasonal, and annual climate variables as well as 20 derived, biologically relevant climate variables, such as various growing and chilling degree days, growing season length descriptors, frost free days, extreme minimum tem-peratures, etc. For each variable we also provide historical data for the last century (1901–2006) and projections from 5 GCMs (CGCM2, CISRO2, ECHAM4, HADCM3, PCM) $\times$ 4 SRES Emission Scenarios (A1FI, A2, B1, B2) $\times$ 3 standard time-slices (2020s, 2050s, 2080s), plus projections for the next 10 decades for selected GCMs, for a total of 68 future scenarios. This database includes approximately 15,000 climate surfaces. To balance file size versus accuracy, we provide a stand-alone software solution that downscales medium resolution historical and projected anomaly surfaces, and then overlays these devia-tions onto a high resolution 1961–1990 baseline normal dataset. We thoroughly test the approach of using medium resolution anomalies instead of high resolution surfaces against original weather station data, discuss limitations of the database (particularly the loss of spatial heterogeneity in anomaly data due to the preferred interpolation approach), and discuss how the data may be used for climate change impact and adaptation research.

2. Methods

2.1. Climate normal data

This study builds on 2.5 arcminute (approximately 4 km) resolution interpolated climate data of average monthly minimum temperature, maximum temperature, and precipita-tion for the 1961–1990 normal period. These climate grids have been developed by Daly et al. (2002) using PRISM. We have previously shown that this method is particularly well suited for modeling precipitation in mountainous regions on British Columbia and the Yukon Territories (Hamann and Wang, 2005), and that a combination of bi-linear interpolation and elevation adjustment can be used for ''intelligent'' downscaling of temperature data to higher resolution in mountainous regions, thereby improving the statistical precision and accuracy of temperature estimates and derived climate vari-ables (Hamann and Wang, 2005; Wang et al., 2006). In this study we apply the same methodology to an extended study area, now covering the Yukon Territory, British Columbia, Alberta, Saskatchewan, Manitoba and parts of the United States (Fig. 1). Because of insufficient weather station coverage, the Northwest Territories were not covered in this study.

2.2. Historical and projected climate data

We use interpolated climate data developed by Mitchell and Jones (2005) for the 1901–2002 period at 30 arcminute resolu-
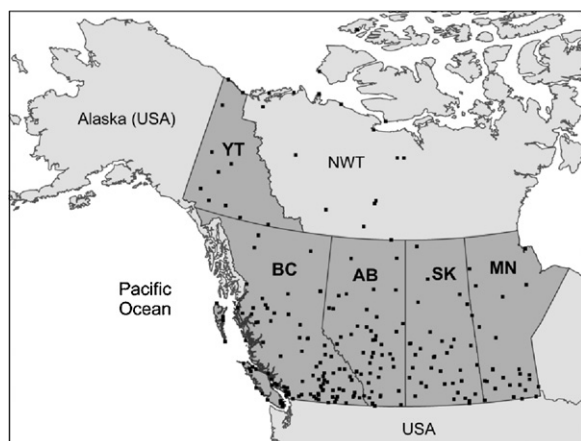
Fig. 1 – Map of the study area in western Canada (dark grey), showing locations of weather stations with data for the 1901–2006 period. Yukon Territory (YT), British Columbia (BC), Alberta (AB), Saskatchewan (SK) and Manitoba (MN).

tion with worldwide coverage (CRU TS 2.1). By subtracting the 1961–1990 average from their gridded surfaces of individual years and months, we recovered their original anomaly surfaces (deviations from the 1961–1990 normal). These anomalies were then downscaled with bi-linear interpolation and overlaid on high resolution PRISM generated climate normal data, described above, which provides much better estimates of absolute climate values than Mitchell and Jones' (2005) low resolution climate normals. The same procedure is used to generate climate surfaces from GCM projections for the 2020s, 2050s, and 2080s from five general circulation models. This includes the second generation Canadian model CGCM2 (Flato et al., 2000), the Australian model CSIRO2 (Watterson et al., 1995), ECHAM4 from the Max-Planck Institute of Meteorology and the Meteorology Institute of Hamburg University (Roeckner, 1996), the third generation model HADCM3 of the Hadley Climate Center, United Kingdom (Johns et al., 2003), and the Parallel Climate Model, PCM (Washington et al., 2000). For each GCM, we included four SRES emission scenario implementations (A1FI, A2, B1, B2), provided through the TYN SC 2.0 dataset by Mitchell et al. (2004). The A1 scenario family represents rapid economic and population growth that peaks in mid-century and declines thereafter. The A2 scenario assumes a continuously increasing global population and regionally fragmented, slower economic growth. The B1 scenario assumes the same global population growth as A1, but rapid changes toward a resource-efficient service and information economy. The B2 scenario represents continuous population growth (lower than A2) and local, environmentally sustainable economies that have less emphasis on growth and globalization (Nakicenovic et al., 2000).

To update the historical anomalies by Mitchell and Jones (2005) with more recent climate grids, we obtained weather station data from the Adjusted Historical Canadian Climate Database (Mekis and Hogg, 1999; Vincent, 1998; Vincent and Gullett, 1999; Vincent et al., 2002). The number of stations with complete monthly data ranged from 90 to 120 for temperature and 120–210 for precipitation with the best coverage in the 1980s and 1990s. Monthly anomalies for the 2000–2006 weather station data were calculated as the difference of the observed temperature data from the 1961–1990 normal for each station. Precipitation anomalies were expressed as percentage of the 1961–1990 normals. Interpolation of anomalies calculated for weather stations was then carried out using thin plate spline method implemented by PROC G3GRID (SAS Institute Inc., 2005). For consistency with Mitchell and Jones (2005) grids we conducted visual comparisons of climate surfaces for three overlapping years (2000 through 2002). We chose a spline smoothing factor of 0.01 (PROC G3GRID, option SMOOTH), which resulted in visually similar results to Mitchell and Jones' (2005) surfaces, which are based on different interpolation methods.

2.3. Relative quality comparison of historical data

Because PRISM climate normals as well as anomalies for the 1901–2002 period were calculated from all available station locations in the study area, we can only carry out relative quality comparisons of interpolated data as there is no independent test dataset available. This is not a problem for this study because our objective is not to evaluate the interpolation techniques themselves, but to verify that the quality of historical climate data is not degraded by the procedure of overlaying medium resolution anomaly surfaces on high resolution baseline data. For this comparison, we evaluate how well historical gridded data, overlaid on the high resolution normal, accounts for variance explained (R^2) in original weather station data. R^2 is a useful measure for this comparison because it quantifies the statistical precision of the estimate. We are less concerned with statistical accuracy for this test, because we evaluate historical anomalies from the climate normal model, which we have previously shown to have reasonably good statistical accuracy (Hamann and Wang, 2005). To provide a sense of the magnitude of errors in units of degree Celsius and millimeters precipitation, we also calculated the average deviation (absolute values) of interpolation estimates from observed station data.

To keep the quality check for historical data for 106 years manageable, we evaluated only five variables, representing two annual climate summaries: mean annual temperature (MAT) and mean annual precipitation (MAP); two monthly variables: mean warmest month temperature (MWMT) – July, mean coldest month temperature (MCMT) – January; and one seasonal variable: mean summer precipitation (MSP) – May to September. Estimates for each year and each variable were extracted from interpolated grids for all station locations to calculate R^2 values between estimated and observed data for each year. This evaluation was also carried out separately for the western Cordillera mountain ranges and the Canadian Prairies to detect potential data issues in regions with mountainous topography. To have a direct comparison of original and derived 30-year normal periods, we also evaluated the precision of the five variables for the anomaly derived 1931–1960 climate normal versus the original 1961–1990 normal data.

Table 1 – R^2 values and the average deviation in absolute values (in parentheses) to compare the quality of original interpolated climate data (1961–1990) and a derived surface (1931–1960). The dataset was subdivided into a primarily mountainous area (BC and YT), and an area consisting primarily of plains (AB, SK, MB).				
Variable	Mountains		Plains	
	1961–1990	1931–1960	1961–1990	1931–1960
Mean annual temperature	0.98 (0.6 °C)	0.97 (0.8 °C)	0.98 (0.3 °C)	0.97 (0.4 °C)
Mean warmest month temperature	0.94 (0.7 °C)	0.93 (0.9 °C)	0.95 (0.3 °C)	0.93 (0.5 °C)
Mean coldest month temperature	0.97 (1.3 °C)	0.97 (1.5 °C)	0.96 (0.9 °C)	0.94 (1.3 °C)
Mean annual precipitation	0.97 (93 mm)	0.96 (99 mm)	0.98 (45 mm)	0.80 (55 mm)
Mean summer precipitation	0.94 (27 mm)	0.92 (28 mm)	0.90 (18 mm)	0.70 (24 mm)

2.4. Software integration of climate data

All grid manipulations, data extraction from grids, interpolation steps, lapse-rate elevation adjustments, and calculations of summary variables described above were carried out with a custom software application that we make freely available.[1] The algorithms used in the ClimateBC v1 and v2 software package were previously described in detail (Hamann and Wang, 2005; Wang et al., 2006). The software package ClimateBC v3 corresponding to this paper remains largely unchanged except for faster downscaling algorithms and the integration of 4000 monthly climate surfaces for historical data, and 2500 monthly climate surfaces for GCM projections. Another 8500 surfaces of derived variables and seasonal or annual summary variables are generated by the software package on demand. We also added a second equivalent software package ClimatePP v3 that covers the Canadian Prairie provinces Alberta, Saskatchewan and Manitoba.

3. Results and discussion

3.1. Quality of historical climate normals

For the first comparison between original PRISM climate normal data and historical data, we overlay a low resolution (30 arcminutes) 1931–1960 anomaly surface onto the 1961–1990 baseline data to obtain a different climate normal period. This comparison has been carried out separately for the Mountain Cordilleras and the Canadian plains (Table 1). The R^2 values as well as the average error of climate estimates indicate that the derived 1931–1960 normal period maintains good statistical precision. This first comparison demonstrates how well the method of using low resolution anomaly surfaces to obtain historical climate estimates works. For accessibility and usage of the climate databases that we provide, it is essential that we only need a single high resolution surface and all other time periods can be derived from low-resolution anomalies. Further, there appears to be no major quality differences between mountainous areas and plains (Table 1), and this is due to a previously described lapse-rate based elevation adjustments for mountainous areas (Hamann and Wang, 2005; Wang et al., 2006).

For completeness we briefly describe the elevation-adjustment step in principle: when the PRISM climate normal surface is queried through the ClimateBC/PP software packages, the program first finds the four 2.5 arcminute resolution cells that surround the location of interest (e.g. a sample point) and reads the original PRISM based climate estimates and the elevation values on which the climate estimates are based. The program then generates a first estimate of climate values and elevation for the location of interest through simple bi-linear interpolation. If this elevation estimate is different than the location of interest, say, the interpolated elevation value is 650 m, but the location of interest is located in a valley and actually has an elevation of only 500 m, temperature values will be adjusted upwards using a set of formulas for individual climate variables that vary with geographic location (Wang et al., 2006). This step is carried out by the ClimateBC/PP software whenever an elevation value for the location of interest is provided.

3.2. Quality of monthly, seasonal, annual historical data

In the second comparison we look at historical climate estimates for shorter periods than 30-year normals, i.e. individual years, seasons, and months of the last century. Naturally, we expect the quality of these estimates to be degraded. Because of stochasticity in weather patterns, it will always be more difficult to estimate a climatic variable for shorter periods such as individual years, seasons, months, or days (Shen et al., 2001). Testing of the anomaly derived climate surfaces of annual variables for individual years shows that statistical precision remains very high, except for the first third of the century (Fig. 2, MAT and MAP). Also, our own interpolations that update Mitchell and Jones (2005) dataset for the most recent years are of similar quality and the surfaces for the overlapping years 2000, 2001, and 2002 visually conform when displayed as maps (data not shown). The seasonal variable MSP shows considerably more variation in statistical precision among individual years. Monthly temperature variables have quite high R^2 values compared to their corresponding 30-year normal (Fig. 2, MWMT, MCMT). However, they show sharp declines in precision for approximately one out of 10 years.

These results show clearly that particular weather patterns that are unique to an individual month or season cannot always be accounted for by the climate grids that we evaluated. Any local stochastic variation in weather patterns that does not conform to rules that can be incorporated into interpolation models could cause the observed loss of precision. To give an example, the ''rule'' incorporated in

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[1] Available for download at http://www.ualberta.ca/~ahamann/climate.html or from the mirror site at http://www.genetics.forestry.ubc.ca/cfcg/climate-models.html.
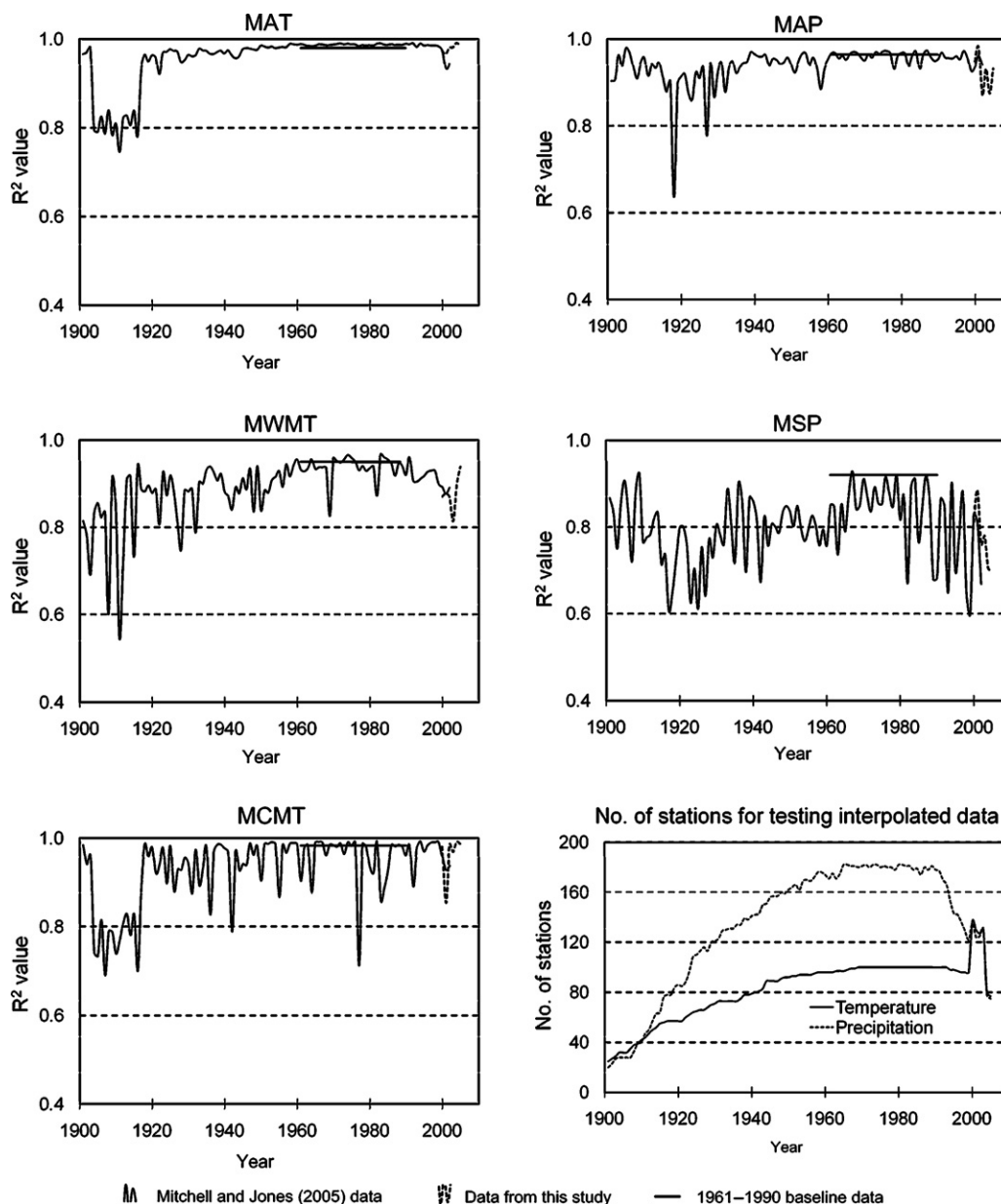
Fig. 2 – R^2 between observed and interpolated mean annual temperature (MAT), mean warmest month temperature (MWMT), mean coldest month temperature (MCMT) data, mean annual precipitation (MAP) and mean summer precipitation (MSP) for the 1901–2002 period and corresponding values for the 1961–1990 normals comparison with observed data. Number of stations for data comparison for each year is also shown.

virtually all interpolation models that temperature decreases as elevation increases does not apply under inversion weather patterns in winter, a regular occurrence in mountain valleys. The PRISM 30-year climate normal model, in fact, models these temperature inversions. But these inversions do not occur everywhere in every winter with the same frequency, so modeling temperature for an individual winter month is much more difficult than for a 30-year climate average. High R^2 values for the mean coldest month temperature (Fig. 2, MCMT) indicate that a particular winter does not have pronounced local stochasticity, and the coarse resolution anomaly surfaces almost perfectly capture the deviation of an individual month from long-term climate normals. The spikes

of low R^2 values point toward winter months with unique weather patterns that could not completely accounted for. Since precipitation variables show stochastic behavior to a much higher degree than temperature (Bonsal et al., 2003), it is not surprising that the precision of historical precipitation estimates for individual months are more variable and generally lower than for temperature.

3.3. Advantages and disadvantages of the anomaly approach

From an end-user perspective, the question arises whether these climate surfaces are suitable (or at least the best
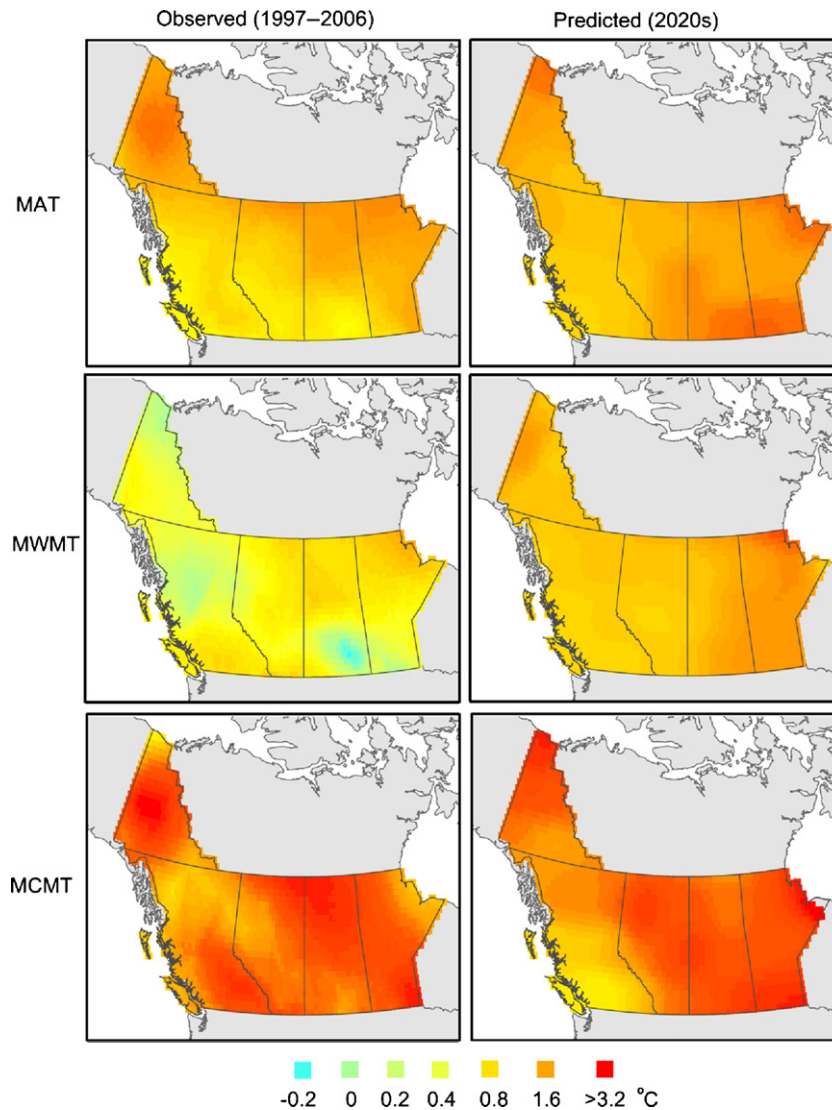
Fig. 3 – Maps of anomalies (deviations from the 1961–1990 normal) of a recent 10-year average (1997–2006) and predicted by CGCM2-B2 for the 2020s for mean annual temperature (MAT), mean warmest month temperature (MWMT) and mean coldest month temperature (MCMT).

available) to analyze biological response to past climate variation. Unlike many others, Mitchell and Jones (2005) interpolate anomalies (deviations from the 1961–1990 normal) and not the absolute station values. Thus, they sacrifice data from new or temporary weather stations that have no or poor coverage for the required 1961–1990 reference period. This substantially reduces the potential to account for local stochastic weather patterns that are prevalent over shorter time intervals. Visual inspection of anomaly surfaces provides a good sense for the lack of fine-scale spatial variation in interpolated anomalies, both due to the low resolution and the choice of smoothing parameters (e.g. Fig. 3). Therefore, users of this database should be aware that historical time series obtained for nearby sample points are very similar, although we will argue later that this does not matter for most practical applications.

An alternative to the "anomaly approach" is to interpolate all available station data for the historical time interval of interest. While there are less than 200 stations for western Canada that meet the standards of completeness by the World Meteorological Organization for the 1961–1990 normal period, there are approximately 3000 stations with useful data for short time periods. These additional stations can be used to generate interpolated coverages for shorter historical time intervals that better capture climate patterns that are unique for a particular time interval (McKenney et al., 2006). Also, sophisticated methods exist that utilize the space–time covariability observed during short intervals with dense station networks to even better account for spatial variability due to particular weather patterns, e.g. empirical orthogonal function decomposition (Richman, 1986). However, the "direct interpolation approach" leads to variations among grids for different time intervals that are driven by the temporal presence of short-term weather stations (or missing values in long-term stations). Secondly, the approach becomes inferior to the anomaly method when station coverage is very sparse
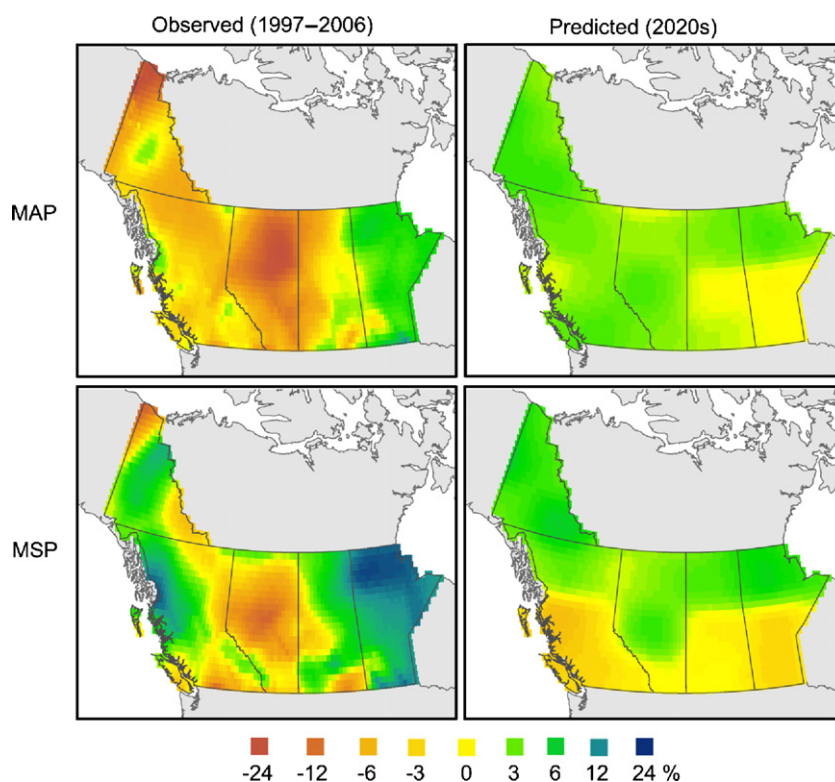
Fig. 4 – Maps of anomalies (deviations from the 1961–1990 normal expressed as percentage) of a recent 10-year average (1997–2006) and predicted by CGCM2-B2 for the 2020s for mean annual precipitation (MAP) and mean summer precipitation (MSP).

(e.g. for the early century or for northern latitudes), because the interpolation model has to be built exclusively from stations available for the period of interest. This again leads to variation among grids for different time intervals that are not driven by differences in climate but by the quality of the interpolation models for different time periods.

In contrast, under the ''anomaly approach'' surfaces can be forced towards zero if there is little or no station data, i.e. the climate estimates approach the 1961–1990 normal period. This is very graceful behavior for the study of biological response to historical climate: envision a regression of a biological response variable over an independent climate variable. Erroneous values due to lack of data in the independent variable approach the center of the distribution (zero anomaly) and minimally influence the relationship. Although the database we provide never leads to anomaly surfaces to completely default to zero, anomalies show less amplitude in some northern regions for the early century, i.e. starting to approach zero. We consider this behavior a convincing argument for using the ''anomaly method'' for our study area, whereas "direct interpolation approach" may be applied with more confidence in Europe or the United States, where the historical network of weather stations is much better.

3.4. Recent climate trends for western Canada

Environment Canada provides graphs of climate trends, expressed as a regression of climate over time, for various geographic regions of Canada (MSC, 2006). Here we make use

of our gridded historical database to show recent climate trends in a different and spatially more explicit way. It is widely acknowledged that global temperatures have started to increase more rapidly due to the effect of greenhouse gases since the 1980s, preceded by a cooling trend for several decades (IPCC, 2007, Chapter 3). To visualize these recent changes starting in the 1980s, we display anomalies of the latest decade for which we have data (1997–2006) as a difference from the 1961–1990 reference period. Obviously, the shorter the time period for which an anomaly is calculated (a decade in this case), the less indicative the result is of a trend because of cyclical or stochastic climate variability, especially for precipitation. We also plot 2020s projections from a median general circulation model (CGCM2-B2) as a reference.

Recent temperature trends in western Canada roughly follow the direction and magnitude of the CGCM2-B2 projections (Fig. 3). While most GCMs predicted more warming in winter temperatures than in summer temperatures, the differences appear to be more pronounced in the observed trends. Average winter temperature changes over the last quarter century already exceed projections for the 2020s for most regions in western Canada. Observed trends in precipitation (Fig. 4) are different from CGCM2-B2 projections and, in fact, projections from any GCM. This is not surprising as the confidence in GCM projections of precipitation changes are generally low (IPCC, 2007, Chapter 8). Observed data shows up to 20% less annual precipitation for Alberta and up to 10% less precipitation for British Columbia with the exception of the Rocky Mountains along the southern BC/AB border and a

section of coastal British Columbia around 55° latitude, where we observe a strong increase in summer precipitation by approximately 20%. Similar patterns of change have also been found in long-term statistical trend analysis for the study area (Rodenhuis et al., 2007).

An explanation for these changes may lie in historical trends in the northern jet stream. In a recent paper, Archer and Caldera (2008) show that since 1979 the northern jet stream has significantly moved northward (approximately half a degree latitude over the last 25 years), risen in altitude, and weakened in strength. Jet streams are meandering, high-altitude, westerly air streams that are responsible for the formation and evolution of storm tracks. When they move away from a region, high pressure and clear skies tend to predominate. Over the Pacific and the Pacific Northwest, Archer and Caldera (2008) find a significant north-shift of the jet stream and more complex seasonal and spatial patterns of change over continental North America. Such shifts could potentially account for regional precipitation changes that we observe in our study area, e.g. drier southern climate conditions displacing the main storm tracks over central Alberta at around 56° latitude.

3.5.   Example applications

We have previously identified an area of increased summer precipitation in Coastal British Columbia and recognized it as a cause for an unprecedented Dothistroma needle blight epidemic of lodgepole pine in western BC (Woods et al., 2005). Interestingly, virtually all GCMs predict drier climate for this area, which would imply that a shift in forestry practices towards increased use of lodgepole pine would be a sensible adaptation strategy. This serves as a good illustration that adaptation strategies for local, on-the ground management should not solely be based on GCM projections, which are meant to indicate the future directions of climate change at large, continental scales. While observed trends may or may not continue into the future at the same rate, we believe that they are the most realistic basis for developing adaptation strategies, and should be used in combination with GCM projection. Managers should prepare for making changes to management based on models, but only implement those adaptation strategies when observed trends on the ground confirm the predictions. This database, which will be regularly updated, can be used for decision support.

Secondly, we suggest that the spatial coverages of observed anomalies that we present in this paper may be used for modeling applications in a similar way as GCM projections. For illustration, we use a simple ecosystem climate envelope model, equivalent to Hamann and Wang (2006) to model Canadian ecozones for the 1997–2006 average and compare them with results from CGCM2-B2 projections (Fig. 5). Both predict similar expansion of the Prairie grassland ecosystems into current boreal forest ecosystems. The area of predicted
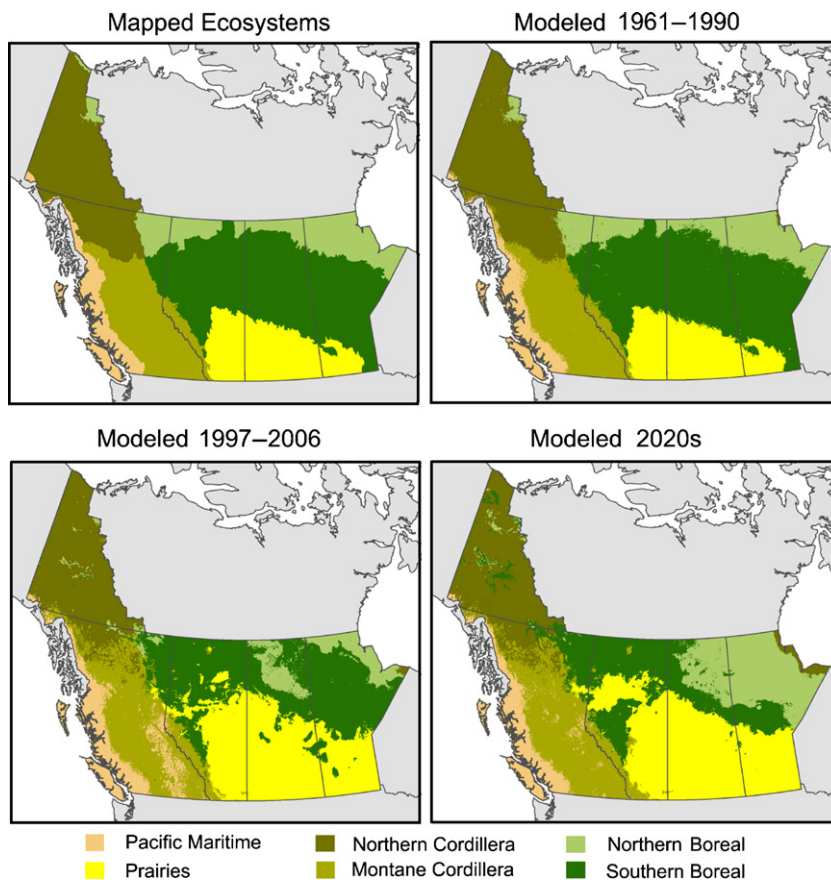

Fig. 5 – Mapped ecosystems and modeled ecosystem climate envelope based on baseline climate normals (1961–1990), a recent 10-year average (1997–2006) and projected climate for the 2020s based on the Canadian Global Circulation Model (CGCM2-B2).

transitions has, in fact, seen large dieback and productivity loss of aspen and spruce (Hogg et al., 2008). The combined information from GCM projections, climate trends that have already materialized, and observed biological response make a strong case for implementing adaptation strategies in this area, e.g. reforestation programs should rely on more drought tolerant species or genotypes in the future.

3.6. Limitations

The ClimateBC and ClimatePP software packages provide easy access to historical and future climate data at any resolution. It should be kept in mind, however, that there are important limitations that we want to recap at the end of this paper. As previously discussed, the shorter the historical time interval of interest, the less reliable the climate surfaces are due to the inability to represent unique local weather patterns over short time intervals. The databases are best suited to analyze biological response to inter-annual variability where the climate variables of interest cover several months (e.g. growing season length, mean annual precipitation, spring temperature). Regarding spatial accuracy, climatic features such as rain shadows, temperature inversions, slope and aspect effects are modeled at a scale of several kilometers, suitable to represent mountain ranges. Lapse-rate driven temperature differences as a function of elevation are accurately represented at a much finer scale, informative at a resolution of hundreds of meters. Small-scale climate features such as frost pockets or local slope and aspect effects are not represented.

Acknowledgements

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