A Modeling Framework for Assessing the Potential Impacts of Climate Change in Northeastern Alberta

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Introduction

This paper provides a framework for modeling the effects of climate change on key indicators of interest to regional land-use planning teams. The framework is based on input from a technical workshop held on October 16, 2008, as well as follow-up with technical experts and a review of the scientific literature. Our intent is to provide planning teams with a workable modeling approach and guidance with respect to the selection of parameter values. Our approach places a priority on assumptions and parameters grounded in the scientific literature. Specific recommendations are highlighted in bold text.

The following assumptions served to bound the scope of the modeling framework:

- ALCES will be used as the modeling platform;
- The temporal scope of ALCES model runs will be approximately 50 years;
- Hydrological impacts will be explored through a separate modeling initiative;
- The model will be used, at least initially, in northeastern Alberta;
- We are limited to the existing base of scientific knowledge because planning is about to get underway; and
- Forestry companies will continue to regenerate sites to their original composition after harvest or fire.

Climate Inputs

Climate projections are readily available, but a choice has to be made as to which climate model and which climate scenario to use. Differences among climate projections increase with time, but are not substantial until after 2050 (Barrow and Yu 2005). **We propose that the CGCM2-B2 projection be used for the regional planning initiative, as a representative non-extreme example of potential climate change.** CGCM2-B2 is one of the five projections that was identified as being representative of the range of future conditions by Barrow and Yu (2005). **If time and resources permit, additional climate projections should be included to better bound the range of potential change.** Andreas Hamann at the University of Alberta has been exploring the range of variance among climate projections and his research could help identify the projections that would provide the greatest learning in a planning context (e.g., extreme cold/wet and extreme warm/dry).

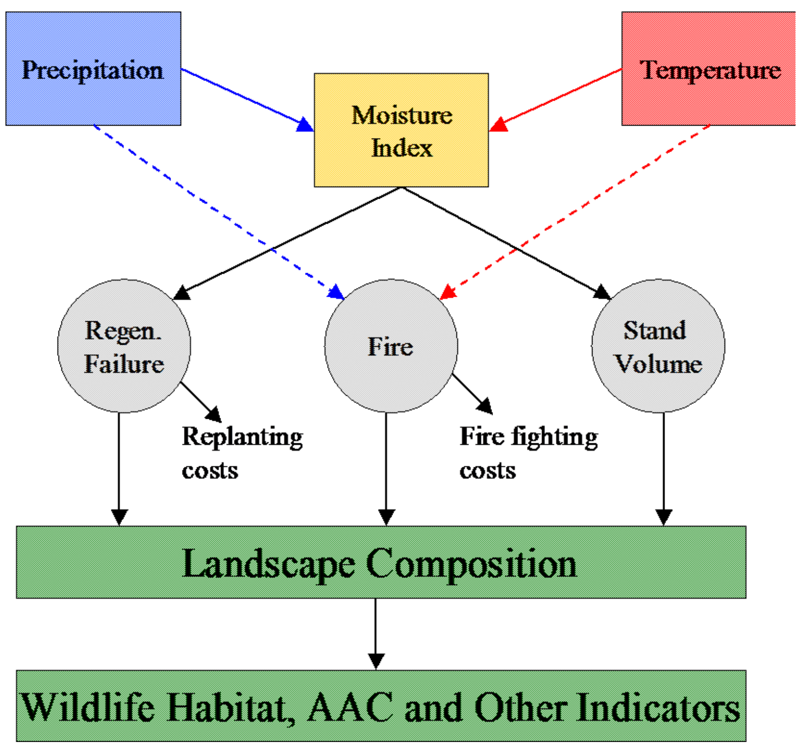
The CGCM2 model provides the projected change in mean temperature and precipitation in time steps of ten years at a very coarse resolution (approximately 6 tiles for the entire province). These coarse-scale projections can be combined with fine-scale historical weather pattern data using the Alberta Climate Model to generate climate projections at a resolution of 1 km^2. Provincial maps of mean decadal temperature and precipitation through to 2050 have been produced using this approach and are available for use in the regional planning process. These maps can easily be summarized into the regional annual mean values for temperature and precipitation that ALCES requires as input.

An important driver of many ecological processes such as fire and plant growth is available moisture. Available moisture is directly related to precipitation but it is also related to temperature and elevation through their effects on evaporation (Hogg 1997). An indicator of available moisture can be determined by summing monthly values for precipitation minus potential evapotranspiration over the course of one year (Hogg 1997). This indictor, termed climate moisture index (CMI), can be calculated directly from climate projection data, which are available on a monthly basis, and provided to ALCES as an input.

For some ecological processes, climate variability will have a greater influence on outcomes than changes in the mean climate, at least in the near term (Weber and Flannigan 1997; Sauchyn 2008). Therefore, climate variability should be included in the modeling process. The variance in annual temperature and precipitation can be derived from historical weather station data, which is available for the past 100 years. In addition, a 200-year dataset of reconstructed annual stream flow data for northern Alberta, providing a proxy of CMI, has been provided by Dave Sauchyn for use in ALCES.

Modeling Upland Landscapes

We recommend that uplands and wetlands be modeled separately because of important differences in ecological processes and because they are managed differently. The following diagram summarizes our conceptual climate model for uplands:



Fire

The potential for wildfire is strongly influenced by temperature and precipitation (Flannigan et al. 2008). However, many other factors also play an important role in determining the overall rate of burn. Some of these factors, such as the length of the fire season and the potential for lightening storms, will be affected by global warming (Flannigan et al. 2008). Given the complexity of these processes and interrelationships, estimates of the future rate of burning are quite variable, reflecting different fire modeling assumptions and choices of parameter values (Flannigan and Van Wagner 1991; Flannigan et al. 2005; Tymstra et al. 2007; Balshi et al. 2008).

Rather than try to predict the future rate of fire within ALCES on the basis of just annual temperature and precipitation values, the direction from the climate workshop was to provide the future rate of fire to ALCES as an input (derived from fire modeling studies). The upper bound of recent modeling estimates is that **the average area burned in western Canada may double by 2050 (Balshi et al. 2008). We suggest this value be used as the upper bound of annual area burned in ALCES and that a 50% increase be used to represent an intermediate value.** Note that the model would begin with the current rate of fire and increase to the target value by end of the simulation (Fig. 1). Estimates of the annual variance in the rate of fire are unavailable for future periods; therefore, when simulating fire stochastically the range of variability will have to be derived from historical fire records.

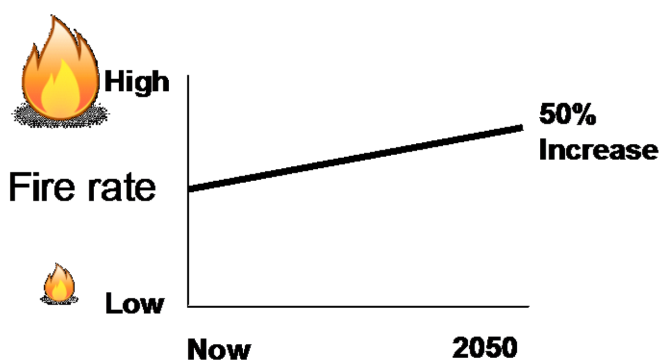


Fig. 1. Example of how an increase in the rate of fire would be applied in ALCES.

Stand volume

In ALCES, total stand volume is derived using yield curves that define volume as a function of stand age (Fig. 2). These curves can be thought of as trajectories of tree growth and mortality at the stand level in which temporal and spatial variability have been averaged out. Each forest type has its own yield curve. Total volume for the study area is calculated by summing (volume * hectares) for each forest type/age class combination.

Fig. 2. Total volume yield curve for softwood stands in the Central Mixedwood Natural Subregion, developed by Karl Peck for use in ALCES.

Studies in northern Alberta and Saskatchewan by Ted Hogg and colleagues indicate that, in aspen stands, tree growth and loss of biomass are strongly linked to long-term climate (Hogg 1994; Hogg et al. 2005; Hogg et al. 2008). More specifically,

Total Biomass per ha = 147.4 + 3.44(CMI)

where CMI is calculated as annual precipitation minus potential evapotranspiration averaged over 40 years (Hogg et al. 2008). **Using this equation and CMI values derived from climate projections one can determine how stand biomass may change under scenarios of global warming.** This information can be supplied to ALCES as a yield adjustment factor to modify (negatively bias) the default yield curves for aspen. The methodology for calculating the adjustment factor as well as other technical details is provided in Appendix 1.

Researchers have also studied the relationship between available moisture and the growth of conifer species, though not in northeastern Alberta (Barber et al. 2000; Watson and Luckman 2002; Chhin et al. 2008). As in aspen, the growth rate of conifers is highly correlated with available moisture (Fig. 3). A study by Hogg and Wein (2005) in Yukon showed that the growth rates of aspen and spruce are highly correlated, with annual precipitation being the strongest predictor of growth in both cases (Fig. 4). Based on these findings **it should be reasonable to apply the yield adjustment factor derived for aspen (as above) to conifer stands in northeastern Alberta.** Alternative approaches do exist, but on balance the aspen biomass approach appears best suited to our application.

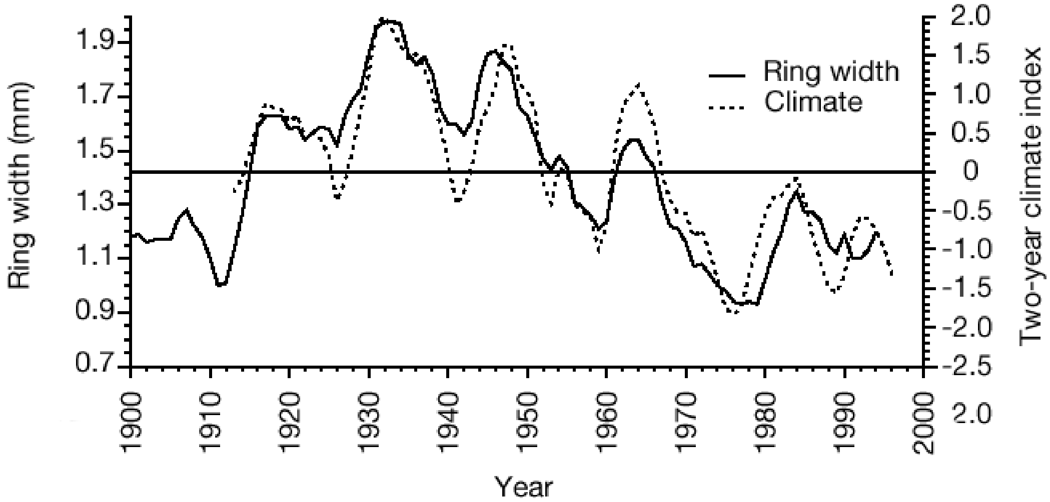


Fig. 3. Tree-ring properties for white spruce in relation to Fairbanks climate during the twentieth century. Climate values are normalized with zero mean and scaled as standard deviation units. Data from Barber et al. 2000: Fig. 5b.

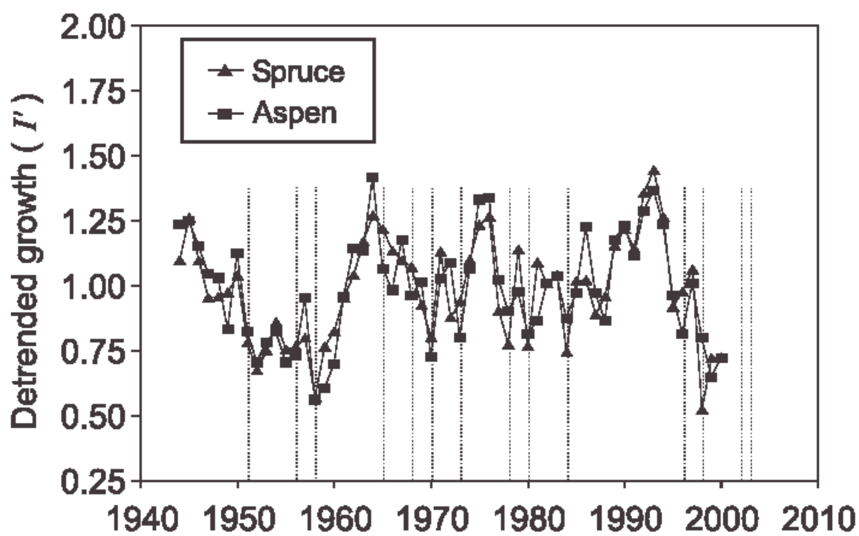


Fig. 4. Detrended mean growth of aspen and white spruce in 12 mature mixedwood stands near Whitehorse. Major drought years are shown by vertical dotted lines. Data from Hogg and Wein 2005: Fig. 5.

Regeneration

As the climate warms in coming decades an increasing number of forest stands in what is currently the Boreal Natural Region will be exposed to a climate resembling that of the Parkland Natural Region (Fig. 5). According to bioclimatic envelope theory, this should, in time, lead to a change in forest composition in the affected areas (Hamann and Wang 2006). Specifically, if left unmanaged, the conifer and deciduous mixedwoods typical of Alberta’s boreal will be replaced by open stands of aspen in combination with shrubs and

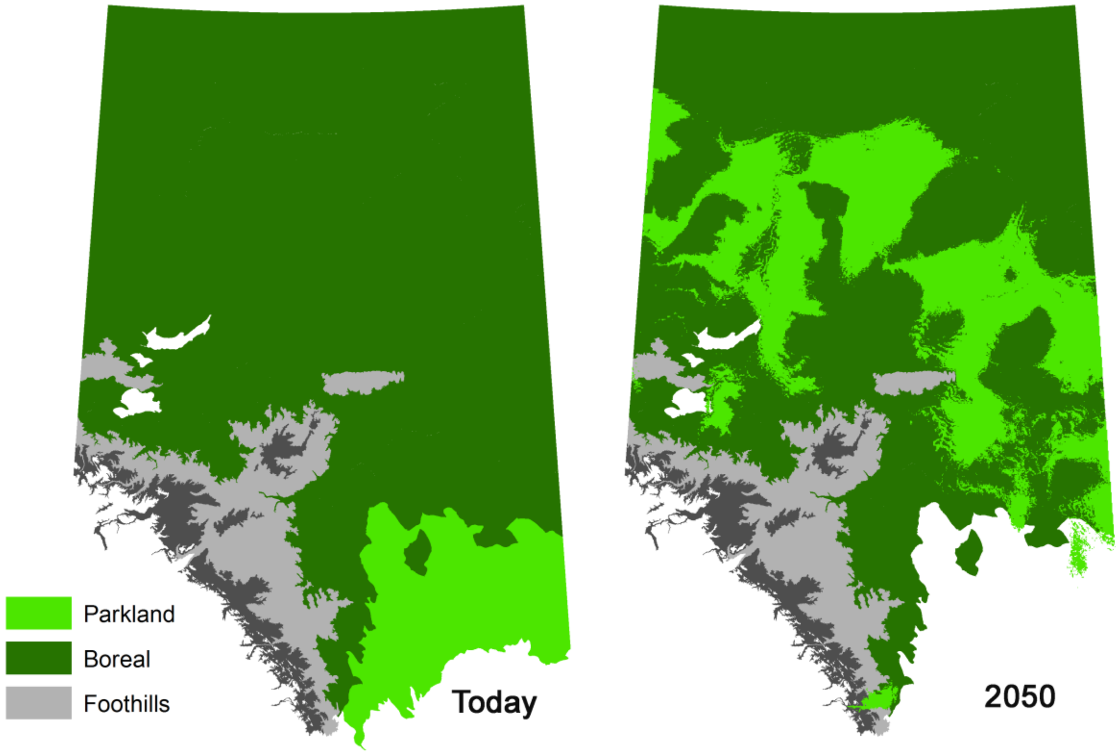


Fig. 5. Distribution of Boreal and Parkland Natural Regions today and in 2050 based on CGCM2-B2 climate projections.

grasses, characteristic of the parkland. In effect, conifer species largely drop out of the system and the remaining aspen stands become more open and scattered. Although this is only a modeling prediction, pollen records indicate that these are exactly the changes that occurred during a previous warming episode, 6,000 years ago (Strong and Hills 2003).

It is unlikely that such a transition would occur quickly. This is because mature individuals of most conifer species have substantial tolerance to climatic fluctuations and can persist for extended periods outside of their usual climatic envelope (Hogg 1994). For example, white spruce trees can be found in farm shelter belts and island populations in many parts of western Canada's grassland ecoregion (Hogg and Schwarz 1997; Chhin and Wang 2002). But while mature spruce trees can persist under these low moisture conditions, their ability to regenerate here is low (Hogg 1994; Hogg and Schwarz 1997; Chhin and Wang 2002). Therefore, a transition to a new vegetation type is likely to be slow as long as mature trees are present, but may proceed quickly if the mature trees are killed by a disturbance, leaving a site that is struggling to regenerate (Schindler 1998; Hogg and Wein 2005).

In managed forests, conifer stands are replanted after major disturbances such as harvesting and fire. So it is not vegetation transition per se that is of interest, but the potential for regeneration failure and the costs associated with replanting. Research by

Hogg and Schwarz (1997) shows that the rate of white spruce regeneration approaches zero in grassland ecosystems, is intermediate in parkland ecosystems, and reaches a plateau in boreal systems (Fig. 6). On the basis of these findings **we suggest that an appropriate starting point for modeling regeneration failure in northeastern Alberta is to assume a 50% reduction in regeneration success for conifer stands exposed to a parkland climate.** The methodology for determining changes in climatic envelope are provided in Appendix 2.

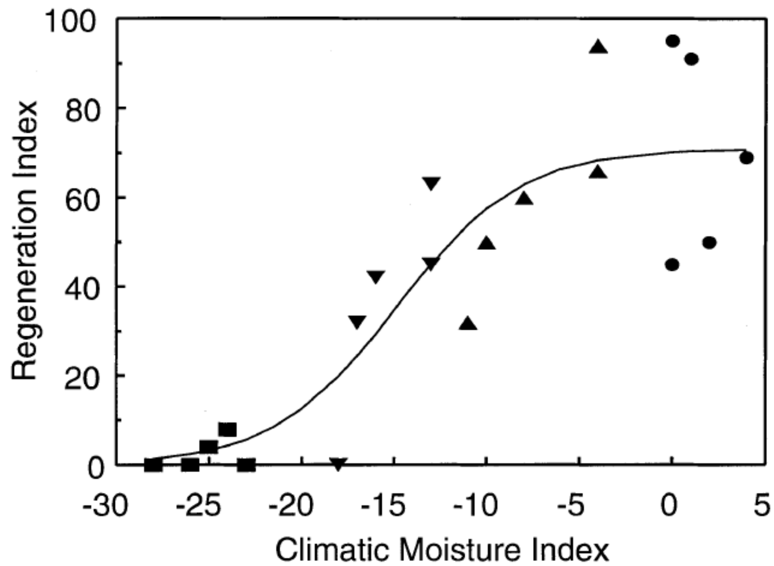


Fig. 6. Mean Regeneration Index (N = five sites at each of twenty nodes) for white spruce in relation to CMI. Symbols indicate nodes located in the grassland (■), the southern aspen parkland (▼), the northern aspen parkland (▲), and boreal forest (●). Also plotted is the best-fitting logistic equation. Data from Hogg and Schwarz 1997: Fig. 4.

Insect damage

Insects cause significant volume losses and tree mortality and researchers believe that the rate of damage is likely to increase under climate change (Fleming and Candau 1997). However, the complexity of insect population dynamics is such that researchers have difficulty predicting outbreaks, even under current conditions (Fleming and Volney 1995). Because of this, reliable projections of the rate of insect damage under global warming are not available. Therefore, **the rate of insect damage in ALCES simulations may have to be derived from historical records. The planning team may wish to increase this base rate by 50% when running climate scenarios to explore the impact such an increase would have on the rest of the system.** If the model is found to be sensitive to this change, additional research should be undertaken to quantify, or at least bound, the potential impact of insects in the future.

Modeling Wetlands

Transition dynamics

Research from Alaska, where a drying trend has been underway since the 1950's, provides some insight into how lowland systems respond to reduced moisture. Klein et al. (2005) provide a transition model, applicable to lowland systems, and quantify the changes observed between 1950 and 1996 when the annual water balance (comparable to CMI) declined from 13.7 cm to 8.3 cm (Fig. 7). In addition, transects were used to describe the woody vegetation in water bodies described as "closed basin" on 1950 maps, but partially dried in 1996. These transects indicated an overall shift from a wetland to facultative woody plants. In another study, Riordan et al. (2006) used remotely sensed imagery from the 1950s to 2002 to inventory over 10,000 closed-basin ponds in eight regions across Alaska. They found an average decline of 11.6% in the area of ponds, with three regions showing a decline of over 25%.

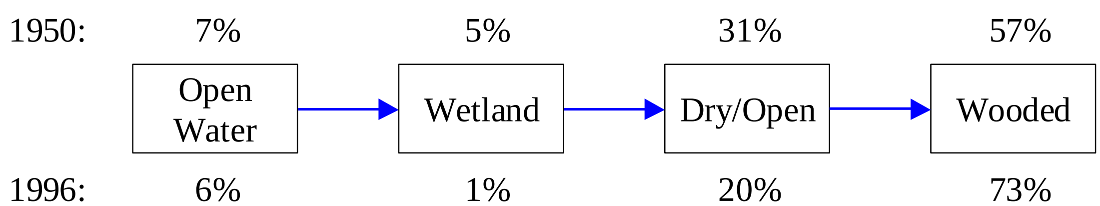


Fig. 7. Transitions between wetland classes based on random point classification of aerial photos from 1950 and 1996. The percentage of the study area in each class is shown for 1950 and 1996. Data from Klein et al. 2005: Fig. 3.

The **Alaska research could be applied to northeastern Alberta as a first approximation**. But the wetland categories used in Alaska are not well defined and they differ from those generally used in ALCES, so a translation step is required. Adjustments must also be made to account for differences between Alaska and Alberta in the degree of change in moisture index and the methodology used to calculate the moisture index. The Klein et al. projected change for open water appears robust because it is very similar to the value obtained by Riordan et al. (2006). But the other transitions need to be treated with caution when applied to Alberta because of the various uncertainties.

In our opinion, the practical utility for regional planners of coarse-scale modeling of wetland transitions remains an open question. One issue that may be of interest is whether the drying of lowland systems will result in an increase in the distribution of white spruce. But the "wooded" category in the Klein et al. model refers to black spruce and shrub species, not white spruce. We found no studies in the literature that quantify the potential rate of transition from black spruce to white spruce. Wirth et al. (2008) suggest that this transition is likely to be mediated by fire, but they provide no guidance as to potential rates of change. It must also be considered that there will be a considerable lag before newly established white spruce stands on black spruce sites are allocated to the managed forest land base. So the practical importance of the black spruce to white spruce transition over the next 50 years may be quite limited.

Another issue of potential interest is the effect of wetland transitions on caribou habitat. In northeastern Alberta, caribou range is centered on large peatland complexes (Schneider et al. 2000). Increases in the amount of upland vegetation in these areas as a result of climate change will likely attract other ungulate species that had previously avoided them (James et al. 2004). This in turn will increase the local predator population, increasing the rate of mortality for caribou (James et al. 2004).

Carbon dynamics

Peatlands contain approximately 56% of the organic carbon stored in all Canadian soils (Tarnocai 2006). Understanding the dynamics of peatland carbon is therefore a topic of intense research. There is a general consensus that, as a consequence of climate change, peatlands will transition from a net sink of global carbon to a net source (Tarnocai 2006; Wieder et al. in press). Declining water tables and increasing rate of fire are believed to be the primary factors that will drive this transition (Trettin et al. 2006; Wieder et al. in press).

Wieder et al. (in press) provide a model for predicting changes in carbon as a function of temperature and the rate of fire for peat systems in the Wabasca region. This model could form the basis for modeling carbon dynamics in ALCES. But the model does not take hydrology into account and, therefore, does not provide a complete accounting of future changes in peatland carbon.

In our opinion, the modeling of peatland carbon is an issue of high importance that requires additional attention. Relevant expertise exists in the research community but was not represented at the climate workshop. Additional efforts should be made to access this expertise with the aim of developing a more comprehensive approach to modeling peatland carbon dynamic in ALCES.

Hydrology

The hydrological module of ALCES links the inputs and exchanges of water among each of the following hydrological compartments: atmosphere, land cover, surface water, and subsurface aquifers. Water in the model enters a study area via three processes: 1) precipitation; 2) surface flow (i.e., rivers), and 3) subsurface flow (i.e., groundwater). The impacts of climate change on the hydrological regime of a study area are mediated by the major processes that determine the fate of precipitation: runoff, evaporation, and aquifer recharge. Because the **modeling of hydrology is being advanced through a separate initiative by Alberta Environment**, it will not be discussed in detail here.

Modeling Climate Variability

The land-use modeling initiative is intended to support the planning process by allowing planners to compare alternative management scenarios on the basis of their effects on indicators of interest. For practical reasons, comparisons will generally be made on the basis of the average outcome. But in some cases it will be useful to add climate variability to the modeled system in order to explore the range and distribution of potential outcomes. For example, it may be more important to know that a given water system has a 30% probability of going dry over the next 50 years than it is to know the mean flow rate over the same time period.

David Sauchyn and colleagues at the Prairie Adaptation Research Collaborative at the University of Regina have studied historical patterns of climate variability in western Canada. A summary of their findings and recommendations, with reference to northeastern Alberta, is provided in Appendix 3. A key point is that year-to-year variability in precipitation has both a random element, reflecting short-term climatic stochasticity, and a non-random element, reflecting multiple cycles with different periodicities.

As currently structured, ALCES simulates variability in annual climate as a random process (e.g. random draw from a normal distribution). It does not have the ability to simulate long-term cyclical behaviour in variability, but this could be accomplished with additional coding. For example, instead of generating variability within the model, ALCES could be directed to read the Sauchyn tree ring dataset as an input. Monte Carlo simulations could be conducted by selecting a random starting point along the dataset for each run.

It is important to note that the incorporation of climate variability complicates the modeling process in terms of parameterization, running the simulations, and interpreting the results. When the model is to be used to support a non-technical land-use planning team working on a tight time schedule, complication is a real cost that should not be discounted. Therefore, before activating the variability "lever" in ALCES, careful consideration needs to be given to what will be gained. Specifically, is there a reasonable expectation that the additional insights will be forthcoming that will help the planning team? In our view, the answer to this question depends on the indicator of interest.

The nub of the issue is how the indicator responds to variability in precipitation. If the response is significantly non-linear, then the inclusion of cyclical precipitation patterns should be considered. For example, if farmers can withstand one or two years of drought, but go bankrupt if drought extends beyond four years, this indicates a non-linear system with a breakpoint. A watercourse that goes dry after three or more years of consecutive drought is another example.

An additional consideration is whether enough is known about the indicator to quantify its response to multiple years of consecutive drought. This is likely to be a limiting factor in predominately natural systems, such as northeastern Alberta. For example, we simply do not know what a boreal forest will do in response to a severe five-year drought because it has never been studied. In this case, complex modeling of climatic cycles will not provide any additional insights because the model is unable to meaningfully use the additional information.

For the ecological processes included in this modeling framework, for application to NE Alberta, our specific recommendations are:

- **Fire:** If there is an interest in tracking the variability in annual area burned we recommend that variability estimates be derived from provincial fire records. It would not be appropriate to use tree-ring variance data because the rate of fire is not linked to precipitation in the model.
- **Insect damage:** We recommend the same approach to modeling variability as used for fire (but substituting historical insect damage records).
- **Stand volume:** In the model, the effects of annual fluctuations in climate on stand biomass are averaged over the lifespan of trees. Therefore, including climate variability in the simulation will have no effect on the outcome.
- **Regeneration failure and landscape transitions:** These processes are likely to be highly sensitive to climatic variability. But we have only a rudimentary understanding of the processes involved, so detailed modeling is not appropriate at this time. The emphasis should be on sensitivity testing the mean outcomes.
- **Hydrology:** Climatic variability should be included in the modeling of hydrological processes and long-term cyclical patterns should be captured through the use tree-ring variance data.

Acknowledgements

We thank all of the workshop participants for their contributions, which formed the foundation of this report. We also thank Stan Boutin, Andreas Hamann, Ted Hogg, Werner Kurz, Karl Peck, Dave Sauchyn, Brad Stelfox, Dale Vitt, and Xianli Wang for supplying data, research papers, and additional insights after the workshop.

References

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. 2008. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Glob. Change Biol. **14**: 1-23.

Barber, V., Juday, G.P. and Finney, B. 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature **405:** 668-673.

Barrow, E. and Yu, G. 2005. Climate scenarios for Alberta . Prairie Adaptation Research Collaborative, Regina, SK.

Chhin, S. and Wang, G.G. 2002. Spatial and temporal pattern of white spruce regeneration within mixed-grass prairie in the Spruce Woods Provincial Park of Manitoba. J. Biog. **29**: 903-912.

Chhin, S., Hogg, E.H., Lieffers, V., and Huang, S. 2008. Influences of climate on the radial growth of lodgepole pine in Alberta. Botony **86**: 167-178.

Flannigan, M. and Van Wagner, C. 1991 Climate change and wild-fire in Canada. Can. J. For. Res. **21**: 66–72.

Flannigan, M., Logan, K., Amiro, B., Skinner, W. and Stocks, B. 2005. Future Area Burned in Canada . Climatic Change **72**: 1-16.

Flannigan, M., Stocks, B., Turetsky, M. and Wotton, M. 2008. Impacts of climate change on fire activity and fire management in the circumboreal forest. Glob. Change Biol. **14**: 1-12.

Fleming, R. and Volney, J. 1995. Effects of climate change on insect defoliator population processes in Canada's boreal forest: some plausible scenarios. Water, Air, Soil Poll. **82**: 445-454.

Fleming, R. and Candau, J. 1999. Influences of climatic change on some ecological processes of an insect outbreak system in Canada's boreal forests and the implications for biodiversity. Env. Mon. Asses. **49**: 235-249.

Hamann, A. and Wang, T. 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecol. **87**: 2773–2786.

Hogg, E. 1994. Climate and the southern limit of the western Canadian boreal forest. Can. J. For. Res. **24**: 1835-1845.

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

Hogg, E. and Schwarz, A. 1997. Regeneration of planted conifers across climatic moisture gradients on the Canadian prairies: implications for distribution and climate change. J. Biogeog. **24**: 527-534.

Hogg, E.H. and Wein, R.W. 2005. Impacts of drought on forest growth and regeneration following fire in southwestern Yukon, Canada. Can. J. For. Res. **35**: 2141-2150.

Hogg, E., Brandt, J., and Kochtubajada, B. 2005. Factors affecting interannual variation in growth of western Canadian aspen forests during 1951-2000. Can. J. For. Res. **35**: 610-622.

Hogg, E., Brandt, J. and Michaelian, M. 2008. Impacts of a regional drought on the productivity, dieback, and biomass of western Canadian aspen forests. Can. J. For. Res. **38**: 1373-1384.

James, A.R., Boutin S., Hebert D., and Rippin A. 2004. Spatial separation of caribou from moose and its relation to predation by wolves. J Wildl. Manag. **68**: 799-809

Klein, E., Berg, E., and Dial, R. 2005. Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. Can. J. For. Res. **35**: 1931-1941.

Riordan, B., Verbyla, D., and McGuire, A.D. 1996. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. J. Geo. Res. **111**: 1-11.

Sauchyn, D., Barrow, E., and Lapp, S. 2008. Explorations of climate variability in Alberta: past, present and future. Prairie Adaptation Research Collaborative, Regina, SK.

Schneider, R.R., Wynes, B., Wasel, S., Dzus E., and Hiltz M. 2000. Habitat use by caribou in northern Alberta. Rangifer **20**: 43-50.

Schindler, D.W. 1998. A dim future for boreal waters and landscapes. BioSci. **48**: 157-164.
Strong, W. and Hills, L. 2003. Post-Hypsithermal plant disjunctions in western Alberta, Canada . J. Biogeog. **30**: 419-430.
Tarnocai, C. 2006. The effect of climate change on carbon in Canadian peatlands. Glob. Plan. Change **53**:222-232.
Trettin, C., Laiho, R., Minkkinen, K., and Laine, J. 2006. Influence of climate change factors on carbon dynamics in northern forested peatlands. Can. J. Soil Sci. **86**: 269-280.
Tymstra, C., Flannigan, M.D., Armitage, O., and Logan, K. 2007. Impact of climate change on area burned in Alberta's boreal forest. Int. J. Wildl. Fire **16**: 153-160.
Watson, E., and Luckman, B. 2002. The dendroclimatic signal in Douglas-fir and ponderosa pine tree-ring chronologies from the southern Canadian Cordillera. Can. J. For. Res. **32**: 1858-1874.
Weber, M.G. and Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: Impacts on fire regimes. Environ. Rev. **5**:145-166.
Wieder, R., Scott, K., Kamminga, K., Vile, M., and Vitt, D. In press. Postfire carbon balance in boreal bogs of Alberta, Canada. Glob. Change Biol.
Wirth, C., Lichstein, J., Dushoff, J., Chen, A., and Chapin, F. 2008. White spruce meets black spruce: dispersal, postfire establishment, and growth in a warming climate. Ecol. Monog. **78**: 489-505.

Appendix 1: Calculating a Yield Adjustment Factor for Aspen

1. Select a central location in the NE Alberta planning region and calculate the annual CMI for 1960-2000 using historical climate data for that location.
2. For the same location, calculate the annual CMI from 2001-2050 using output from the CGCM-B2 climate model.
3. Assemble all CMI values into a linear sequence (1960-2050).
4. Calculate the estimated aspen biomass/ha for the year 2000 using CMI values from (1) and the Hogg et al. (2008) biomass equation. This is the baseline biomass.
5. Estimate the annual aspen biomass for future years up to 2050 using CMI values from (3) and the Hogg et al. (2008) biomass equation. Each year the 40-year sample of CMI values used in the biomass equation moves ahead one year.
6. For each year until 2050, determine the percentage change in biomass between the current estimate and the baseline estimate.
7. Apply the percentage change from (6) to the baseline aspen yield curve, under the assumption that the baseline yield curve corresponds to the baseline biomass estimate calculated in (4).

Notes:

- The spatial resolution of global climate models is very coarse, so the projected changes in climate are uniform across most of the NE Alberta planning region. Furthermore, the biomass equation is linear which means that all stands will experience the same percentage decline in the rate of growth if subjected to the same decrease in CMI. For these reasons there is no benefit in doing the biomass calculations in a spatially explicit manner.
- A caveat to the previous note is that the biomass equation is only applicable to sites that are moisture limited. Hogg et al. (2008) indicate that the equation should not be used where CMI values exceed those in their study (i.e., 14 cm positive water balance per year). Some high elevation sites in the NE Alberta planning region, such as the top of the Birch Mountains, do have CMI values above 14 cm. But by in large, these sites do not appear to contain significant amounts of merchantable forest. Nevertheless, it would be best to check the inventory data and adjust for merchantable timber in wet regions if necessary.
- Individual stands experience substantial year-to-year variability in climate and this is reflected as variance in year-to-year growth rates (see Figs. 2 and 3). But fluctuations in growth rate are not the same as fluctuations in total stand biomass. Total *stand* biomass reflects the growth of trees over their entire lifespan, and as such, is responsive to long-term climate, not year-to-year fluctuations. Total *forest* biomass is even less responsive to annual climate variability because any variance in growth rate among stands is averaged over a large area. For these reasons adjustments to long-term yield curves should be based on long-term regional climate trends (e.g., 40-year CMI), not year-to-year fluctuations in climate or growth rate.

Appendix 2: Modeling Regeneration Failure in ALCES

1. Conduct a spatial analysis of the northward shift in the parkland climate envelope in 2050 using the bioclimatic envelope projections developed by Andreas Hamann for the CGCM2-B2 climate projections (see Fig. 5).
2. Determine the composition of merchantable forest in the affected boreal forest (i.e., the part of the boreal that is now under a parkland climate).
3. Using (2) calculate the proportion of the total area of each forest type that is exposed to a parkland climate in 2050. This is the "potential transitional".
4. Provide ALCES with the area of "potential transitional" by year for each forest type, assuming a linear increase between 2000-2050.
5. In ALCES, apply the user-supplied regeneration failure rate to the current area of "potential transitional" after fire or harvest.

Notes:

- Modeling regeneration failure is important for capturing the effects of a drying climate on coniferous species (see main text). In aspen stands it may be better to capture the effects of drying through changes in biomass. This is because mature aspen is more likely to respond to drought through declines in biomass (due to stem die-back) but less likely to experience serious regeneration failure (because of its ability to regenerate from deep root systems).

Appendix 3: Measuring and Modeling Climate Variability in Northeastern Alberta

Dave Sauchyn, PARC, University of Regina

Introduction

The report "A Modeling Framework for Assessing the Potential Impacts of Climate Change in Northeastern Alberta" dated December 01, 2008, makes a case for including scenarios of climate variability in the modeling of land use change in northeastern Alberta:

> "For some ecological processes, climate variability will have a greater influence on outcomes than changes in the mean climate, at least in the near term. Therefore, climate variability should be included in the modeling process." (p. 3)
>
> "for a manager it may be more important to know that a given water system has a 30% probability of going dry over the next 50 years than it is to know the mean flow rate over the same time period." (p. 11)

The proposed approach to incorporating climate variability is presented under the heading "Modeling Stochasticity":

> "ALCES is typically run multiple times and the average outcome is provided as output. In practice stochastic runs that are averaged in this way provide the same results as running the simulation using just the mean rate of fire in the absence of stochasticity."

Characterizing the climate system as stochastic implies that it is random or non-deterministic such that multiple model outcomes cancel out in the absence of systematic variability. This treatment of the climate system as stochastic is contrary to a large body of research that has identified quasi-periodic cycles in regional climates and linked this systematic variability to teleconnections, or internal forcing mechanisms, such as oscillations in sea surface temperature (ENSO, PDO, etc.).

A Record of Climate Variability for Northern Alberta

Cycles of predominantly wet and dry weather are evident in instrumental records, but the short length of most records enables the detection of only relatively short cycles. Various natural archives also record a measureable response to variations in temperature and moisture, and over decades to millennia. Tree rings are among the proxies of highest resolution. A tree-ring record is both a climate proxy and chronology of annual resolution. Tree growth at dry sites records the local water balance because the main growth limiting factor is available soil moisture. Therefore there tends to be a statistically significant correlation between ring-width indices and hydroclimate variables; especially water levels since they represent, like soil moisture, the balance between inputs of precipitation and outputs by evaporation.

At the University of Regina Tree-Ring Lab, we have collected old wood from more than 120 dry sites in Alberta, Saskatchewan, the Northwest Territories and Montana. The focus of this research is an improved understanding of the nature and causes of hydroclimatic variability in this region as a context for detecting changes in the hydrosphere imposed by global warming. Our tree-ring index chronologies are calibrated using instrumental data that correlate with standardized ring-width. Annual and seasonal stream gauge records are among the most readily available hydroclimate data and tend to correlate with tree-ring indices because net or effective precipitation is the water available for tree growth and runoff. This correlation is evident in Figure A1, a plot of the gauge record of the Hay River and the annual stream flow from 1790 to 2000 as reconstructed from a set tree-ring chronologies collected in northern Alberta and the southern NWT. There is a very similar pattern of decadal variability in both the tree rings and stream flow. From year to year, the response of stream level and tree growth to climate can be offset by one year, but this lag is modeled in the reconstruction of flow. The tree rings are an especially good proxy of drought; low flows correspond to narrow tree rings. The tree rings underestimate high flows, on the other hand, since there is a limit to amount of water uses by trees and in wet years other factors become growth limiting. The proxy flow record for the Hay River also is shown in Figure A2 as a bar code; annual flows are coded by percentile from the lowest (< 10%) to the highest (> 80%) river levels. This plot captures visually the long-term variability in the hydrologic regime and illustrates how the period of stream gauging is not necessarily representative in terms of the timing and frequency of wet and dry spells.

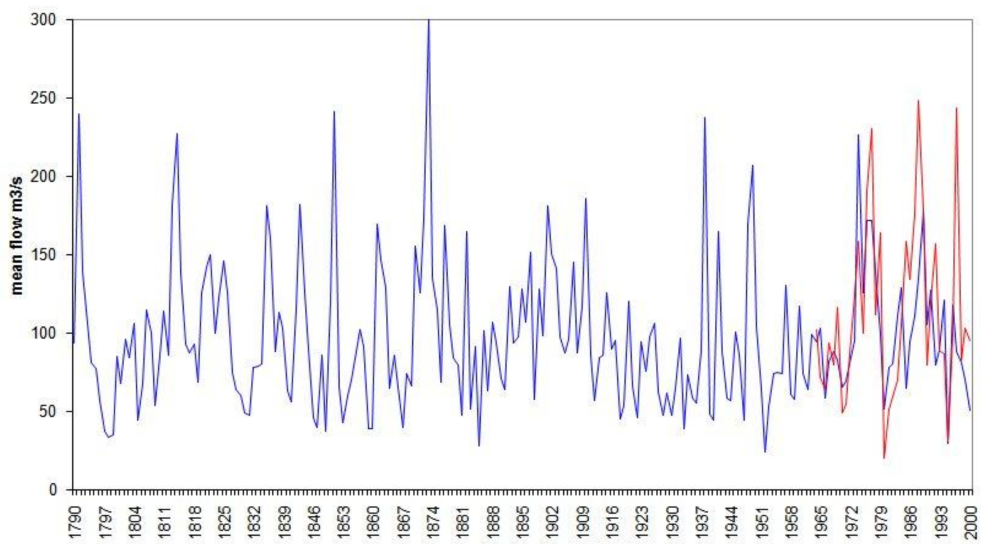


Figure A1. Observed (red) and reconstructed (blue) flow of the Hay River, northern Alberta.

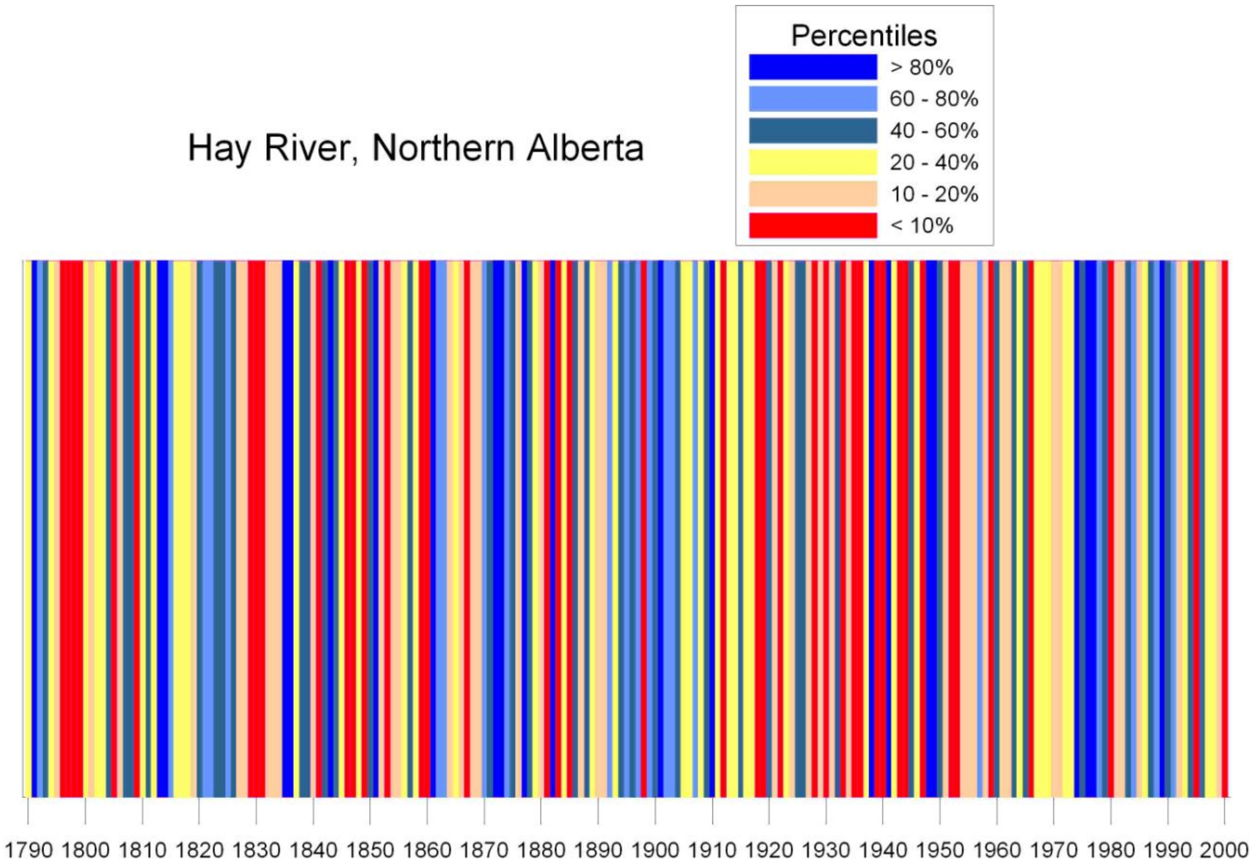
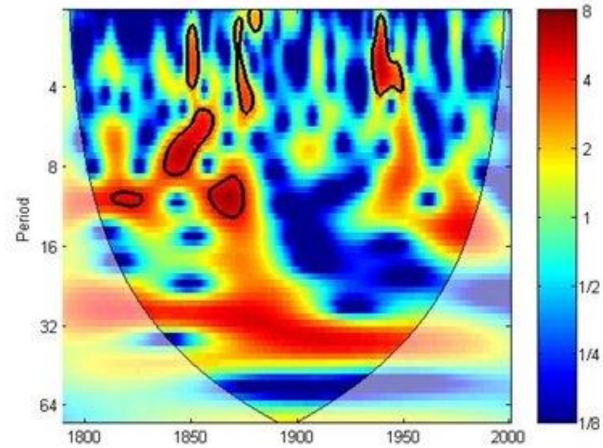


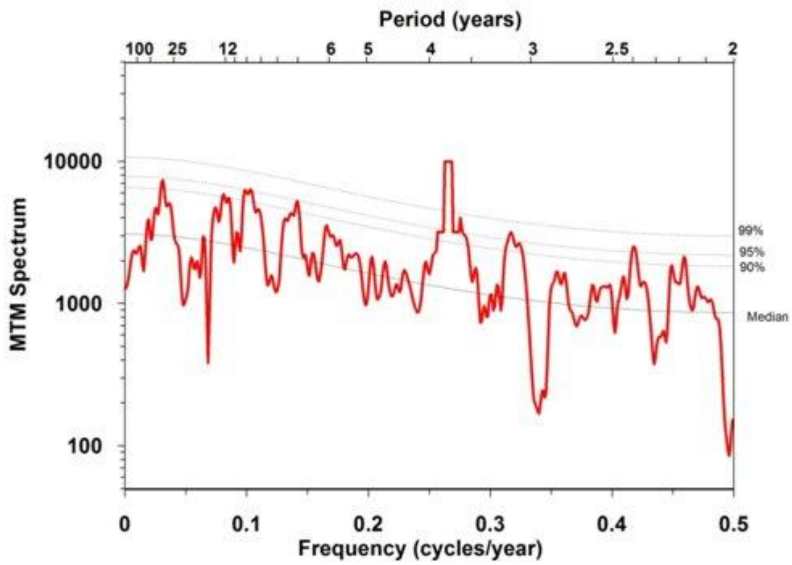
Figure A2. A bar code of the reconstructed flow of the Hay River; annual flows are coded by percentile from the lowest (< 10%) to the highest (> 80%) river levels.

A scan of the bar code in Figure A2 suggests some systematic variability in hydroclimate at varying frequencies. These frequencies can be extracted using spectral analysis. A wavelet analysis (Figure A3; top) displays the main modes of variability in both frequency and time domains. It reveals the inconsistency of the spectra over the length of the record. A multi-taper method (MTM) of spectral analysis (Figure A3; bottom) gives the exact frequency/period of the spectral peaks and their statistical significance.

This 211-year proxy record for the Hay River demonstrates some systematic variation in the hydroclimate of northern Alberta; it is not the function of random processes. The "bar code" and spectral analyses illustrate, visually and quantitatively (respectively), this systematic variation. The significant (> 95%) interannual (2.4-3.7 years) variability almost certainly reflects the strong influence of El Nino South Oscillation (ENSO) on the climate of the western Americas. Periodicity at inter-decadal (10-13 years) to multi-decadal (~ 32 years) time scales is not as strong but still evident. The Wavelet plot indicates that the power of these spectra vary over time as the teleconnections, sea surface temperature anomalies of differing periodicity, vary in strength over time and interact to amplify or suppress their relative influence on the hydroclimate of western Canada.

Wavelet Analysis





Sig.	Years
90%	32.0
95%	9.7
90%	7.1
99%	3.7
95%	3.2
95%	2.4
90%	2.2

Figure A3. The results of spectral analysis of the Hay River reconstructed flow record. The wavelet analysis (top) plots main modes of variability in both frequency and time domains to illustrate the inconsistency of the spectra over the length of the record. The MTM spectral analysis (bottom) gives the exact frequency/period of the spectral peaks and their statistical significance.

PARC Recommendation

The climate system is exceedingly complex, such that it seems stochastic or at least can be modeled as such. There are however systematic variations in climate as shown here. These cycles can have profound effects on natural and human systems as the intensity and duration of wet and dry episodes vary over time. These hydroclimate cycles underlie the trends imposed on the hydrosphere by global warming. Therefore **a modeling framework for assessing the potential impacts of climate change in northeastern Alberta should include simulations of both the trends associated with global warming and the cycles identified here**.

We [PARC] recommend that the impacts of climate change be modeled using

1. Shifts in precipitation and temperature derived from GCM experiments that represent median, and extreme (cold.wet, warm.dry) scenarios for northeastern Alberta.
2. Departures from mean conditions (climate variability) derived from several simulations of annual or seasonal gross or net (P-E) precipitation that we generate using statistic methods. These simulation will be constrained by historical means and extremes values, and the spectral properties (cycles) of the instrumental and tree-ring records. Thus while we cannot know future climate, we can produce a set of probable climates that have the known natural variability of the regional climate system.
3. Eventually, scenarios of climate variability derived from global and regional climate models that simulate the periodic behavior of the instrumental and proxy hydroclimate records. Several months of research will be required to identify and process the model runs.

Trends in the mean versus short-term departures from average conditions represent variation in the climate systems at different scales; however, the mean is sensitive to the extremes and conversely the degree variability changes with the mean state. Whereas global warming and other climate trends correlate with external radiative controls on the climate systems, the short-term variability occurs in response to internal mechanisms, feedbacks and teleconnections. Global climate models (GCMs), the only reliable source of scenarios of future climate, explicitly model the external controls and therefore the most robust outputs from GCMs are trends in temperature over several decades and large (continental) regions.

Further research is required to develop modeled projections of future climate variability from the global climate models that best simulate the quasi-periodic climate cycles described above. Climate models of higher resolution provide data for smaller regions and time spans and thus more reliable simulations of interannual to interdecadal variability. The spatial domain of the Canadian Regional Climate Model (CRCM) has been recently expanded to provide much more model output for western Canada. The combined analysis of CRCM outputs and long proxy reconstructions of the regional hydroclimate should enable us to provide projections and probabilities of departures (e.g. drought) from mean conditions with increasing reliability.

Appendix 4: Workshop Participants and Contributors

Name	Affiliation	Area of Expertise
Bob Anderson	ASRD	Regional planning
Harry Archibald	AENV	Climate adaptation
Craig Aumann	ARC	Land-use modeling
Caroline Bampflyde	AENV	Water
John Begg	ASRD	Regional planning
Dan Farr	University of Alberta	ALCES
Lee Foote	University of Alberta	Wetland dynamics
Andreas Hamann	University of Alberta	Vegetation modeling
Ted Hogg	CFS	Vegetation modeling
Terry Kosinski	ASRD	Wildlife/biodiversity
Julie Lefebvre	ASRD	Facilitator
Ted Nason	ASRD	Biodiversity
David Price	Can. For. Service	Vegetation modeling
David Sauchyn	Prairie Adapt. Res. Coll.	Climate change
Rick Schneider	University of Alberta	Vegetation modeling
John Stadt	ASRD	Forests/biodiversity
Cordy Tymstra	ASRD	Fire
Dale Vitt	S. Illinois University	Peatland dynamics
Barry Wilson	Silvatech	Land-use modeling