CONSTRUCTING SCENARIOS OF FUTURE CLIMATE AND WATER SUPPLY FOR THE SSRB: USE AND LIMITATIONS FOR VULNERABILITY ASSESSMENT

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Abstract:

This paper describes scenarios of climate change and water supply constructed to assess vulnerability of communities to future conditions in the South Saskatchewan River Basin (SSRB). Output from five Global Climate Models (GCMs) forced with various future emission scenarios were used to construct a range of future scenarios of temperature and precipitation (i.e., median, warmest-wettest, warmest-driest, coolest-wettest, and coolest-driest) over the SSRB. Downscaling using the stochastic weather generator, LARS-WG, was also carried out at Lethbridge, Alberta, and Swift Current, Saskatchewan, and results were compared to future scenarios derived using the coarse resolution GCMs solely. The results between the GCM and LARS-WG scenarios were comparable; both showing increases in monthly temperatures, increases in winter precipitation, and typically decreasing summer precipitation, but with amplified variability. Scenarios of future flows of the South Saskatchewan River and its tributaries were derived by coupling the HadCM3 TAR model scenarios with the hydrological model WATFLOOD. Flow decreased and the dominant flow season shifted from summer to spring for some rivers.

Sommaire

Cet article établi des scénarios de changements climatiques et d'approvisionnement en eau afin d'évaluer la vulnérabilité des collectivités aux conditions futures dans le bassin de la rivière Sakatchewan-Sud (BRSS). Les résultats obtenus de cinq modèles du climat du globe (MCG) et de cinq différents scénarios concernant les futures émissions furent combinés pour établir une gamme de scénarios de températures et de précipitations (c.-à-d. médiane, plus chaud-plus humide, plus chaud-plus sec, plus froid-plus humide, plus froid-plus sec) pour le BRSS. Une réduction à l'échelle à l'aide d'un générateur stochastique de conditions météorologiques, le LARS-WG, a été effectuée à Lethbridge, en Alberta, et à Swift Current, en Saskatchewan, et les résultats furent comparés seulement à des scénarios futurs issus des MCG à résolutions grossières. Les résultats des scénarios des MCG et du LARS-WG étaient similaires. Les deux scénarios indiquaient une augmentation des températures mensuelles, une augmentation des précipitations l'hiver, et généralement une diminution des précipitations en été, mais avec une plus grande variabilité. Des scénarios projetant les futurs débits d'eau de la rivière Saskatchewan-Sud et de ses tributaires furent établis en couplant des scénarios issus des modèles HadCM3 TAR avec le modèle hydrologique WATFLOOD. Les scénarios prévoient une baisse du débit et que la saison principale d'écoulement passerait de l'été au printemps pour certaines rivières.

1. Introduction

A key component of the conceptual framework, and associated research methodology, of the IACC project is the assessment of future vulnerability to climate change. Achieving one of the project objectives "To examine the effects of climate change risks on the identified vulnerabilities"[1] requires that we develop future scenarios for climate risks identified by the studied communities. Those risks or current vulnerabilities, discussed in other articles in this volume, are mostly related to water. The river basins, the Elqui in Chile and South Saskatchewan in Canada, are arid and semi-arid, respectively, and dry environments have the most variable hydroclimate. In the southern part of Canada, the highest year-to-year variation in precipitation is in the prairies. The only region with a coefficient of variation (standard deviation/mean) above 25% nearly coincides with the South Saskatchewan River Basin (SSRB).

In the SSRB, the climate risks most often identified in the studied communities of Hanna, Taber, Outlook, Cabri, Stewart Valley and Blood Indian Reserve were drought, extreme weather events, such as intense thunderstorms and associated hail and flash floods, and low river flows affecting potable water. The vulnerability of these rural communities to climate change will depend on the extent to which these regional climate risks are affected by global warming. This paper presents scenarios of the future climate and hydrology of the SSRB using outputs from runs of Global Climate Models (GCMs) forced with anthropogenic greenhouse gases to simulate global warming.

A climate change scenario is a plausible representation of a future climate that is constructed from consistent assumptions about future emission of greenhouse gases (GHGs) and other pollutants, for explicit use in investigating the potential impacts of anthropogenic climate change.[2] Scenarios are not forecasts of future climate, but rather are intended to provide adequate quantitative measures of uncertainty represented with a range of plausible future paths.[3] Future greenhouse gas concentrations are an unknown because we cannot predict the kinds and extent of activities humans will engage in that will reduce or increase them.

Three types of climate scenarios provide input to hydrological, agricultural, socio-economic, and biophysical models for impact and sensitivity studies: (1) synthetic; (2) analogue (temporal and spatial); and, (3) derived from GCMs. Synthetic and analogue scenarios capture a wide range of possible future climates, and are useful for identifying thresholds or discontinuities of response beyond which effects are no longer beneficial or are detrimental.[4 5] Synthetic scenarios apply an arbitrary change to a particular variable of an observed time series; for example, adding 20C to the monthly average temperature. This new time series, however, maintains the variability of the original time series. Analogue scenarios represent potential future climate by using the observed climate regime from a typically warmer previous period or other location as an anticipated future climate. Temporal analogues are derived from either instrumental or paleoclimatic records. As these scenarios represent real historical climate states, they are physically possible and can be constructed for various climate variables. With spatial analogues one weakness is the lack of correspondence between climatic and non-climatic features between regions; therefore, these scenarios may not represent physically plausible scenarios for conditions in the study region. Also, most drivers of the analogue climates are likely natural variations, rather than a response to GHG-induced warming.

Global climate models "are the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations"[6]; therefore, they were used in this study for the construction of future climate scenarios. GCMs are fully coupled mathematical representations of the complex physical laws and interactions between ocean/atmosphere/sea-ice/land-surface.[7] They simulate the behaviour of the climate system on a variety of temporal and spatial scales using a three-dimensional grid over the globe. A high level of confidence can be placed in climate models based on the fact they are[8]: (1) fundamentally based on established physical laws, such as conservation of mass, energy and momentum, along with numerous observations; (2) able to simulate important aspects of the current climate; and, (3) able to reproduce features of past climates and climate changes. Climate models have accurately simulated ancient climates, such as the warm mid-Holocene of 6000 years ago and trends over the past century, combining both human and natural factors that influence climate.

GCM experiments simulate future climate conditions based on estimated warming effects of carbon dioxide (CO_2), other GHGs, and the regional cooling effects of increasing sulphate aerosols beginning in the late 19th century or early 20th century using scenarios of future radiative forcing. The Intergovernmental Panel on Climate Change Third Assessment Report (IPCC-TAR)[9] published 40 different emission scenarios providing a range of future possible GHG emissions and atmospheric concentrations from socio-economic scenarios labelled SRES (Special Report on Emission Scenarios).[10] The recent IPCC Fourth Assessment Report (AR4)[11] describes the latest vintage of GCMs and experiments currently available. Most GCM experiments also consist of multiple (or ensemble) simulations for each of these experiments representing different initial boundary conditions of the GCM at the beginning of the experiment. Impact studies are adopting the combination of scenarios derived from ensemble simulations and scenarios reproducing multi-decadal natural climate variability from long GCM control simulations.[12]

2. Scenarios of the Future Climate of the SSRB Derived from GCMS

2.1. Constructing Climate Change Scenarios

Developing a climate scenario for an impact study requires that data for the relevant climate variable(s) be available from both the GCMs and the 'climatological' record, for two time periods typically each of 30 years: some future time period such as the 2020s, 2050s or the 2080s (i.e., 2010–2039, 2040–2069, and 2070–2099) and the baseline climate (1961–1990)*(see description below). A climate change scenario constructed using GCM output is typically expressed as a percentage change in precipitation or temperature change in degrees from a mean baseline of 1961–90 to a future 30-year period. These differences or ratios are then used to adjust the observed climatological baseline dataset to develop a future climate scenario. A 30-year time period is used to differentiate between the climate change signal and the inter-annual and inter-decal variability within the time series.

One of the limitations of GCMs for constructing climate change scenarios is the difference in climate sensitivity between models. Due to parameteriza-

* The baseline dataset or 'normal' period is representative of the observed, present-day meteorological conditions and describes the average conditions, spatial and temporal variability and anomalous events. The current 30-year normal period as identified by the WMO (World Meteorological Organization) is 1961–1990.[14]

tion and simplification of modeling processes and feedbacks, GCM simulations may respond quite differently to the same forcing.[13] While GCMs probably capture a large part of the uncertainty in modeling responses, they do not encapsulate the range of uncertainties in future emission scenarios. By choosing an array of GCMs and several future emission scenarios (SRES), a broad range of future climate scenarios (e.g., warmest-wettest, warmest-driest, coolest-wettest, and coolest-driest) can be generated to capture much of the uncertainty.

2.2. Data

The Fourth Assessment Report (AR4) of the IPCC[15] lists 24 climate models; only seven had the required variables of daily maximum/minimum temperature and precipitation for both the 1961–90 historical and future 2040–69 period (Table 1). The SRES[16] experiments A1B, A2 and B1 were available for the AR4 models. Output from the HadCM3 TAR (Third Assessment Report) also were used because the AR4 did not provide the required variables for this model; the A2 and B2 experiments were available for various runs of the HadCM3 TAR model, and this GCM has been used for previous climate change research in western Canada.[17] [18] [19] GCM output for the AR4 models (daily and monthly) was obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset.[20] Monthly and daily HadCM3 TAR output was available, respectively, from the IPCC Data Distribution Center[21] (IPCC-DDC) and the Climate Impacts LINK Project.[22] The 20th Century experiment (20CM) from each GCM provided the baseline period (1961–1990) output from the AR4 models and the SRES scenario experiments for the HadCM3 model.

Baseline observed historical gridded (0.50) climate data (monthly precipitation, maximum and minimum temperature), covering North America from 1901–2000, were recently generated by the Canadian Forest Service.[23] The GCM output was interpolated to the historical data 0.5 degree grid, using the linear interpolation routine in Matlab 7.1, and mapped to illustrate future climate scenarios for the basin.

2.3. Future Climate Change Scenarios: SSRB

Figure 1 is scatter plot of climate change scenarios, the change in summer season average temperature (degrees C) and precipitation (%), for the 2050's (2040–69) relative to the 1961–1990 period for the seven GCMs and experiments. Five model experiments were chosen to represent the range of possible climates: MIROC3.2 MEDRES A2(1) (warm/dry: +3.30C/-17.3%), HadCM3 TAR a2(1) (warm/wet: +2.90C/+4%), CGCM3.1/T47 B1(1) (cool/dry: +2.10C/-6.5%), CSIRO MK3.0 A1B(1) (cool/wet: +1.30C/+10.3%), and CGCM3.1/T47 B1(2) (median: +2.20C/+2.2%).

Figure 2 presents maps of the SSRB showing the annual average temperature (°C) change scenarios for the 2050s for the five climate models relative to the 1961–90 baseline period. Temperature increases range from +1 to +3.5oC, with the greatest increase projected in the eastern part of the basin. Figure 3 maps the annual precipitation change scenario (%) throughout the basin for the 2050s period relative to the baseline. MIROC3.2 MEDRES A2(1) is the only GCM projecting a decrease (in the central area of the basin); all others show an increase in annual precipitation over the entire basin. These projections of increased annual temperatures, amplified during winter, and decreased summer and increased winter/spring precipitation, also extend over most of southwestern Canada.[24]

Spring/summer soil moisture is essential in the SSRB particularly for dryland farming. The Climate Moisture Index (CMI), the difference between annual precipitation (P) and annual potential evapotranspiration (PET), is a fairly simple indicator of soil moisture.[25] [26] PET values were calculated using the Thornthwaite equation because of its relatively simple routine; only mean monthly temperature and day length are required, and data for limited variables are available from the GCMs. Figure 4 maps the May-June-July P-PET (mm) for the 1961–90 period, 2020s, 2050s, and the 2080s for the median CGCM 3.1/T(47) B1(2) scenario. Overall, with decreased precipitation and increased temperatures in summer, the climate moisture index is decreasing (increasing soil moisture deficit) throughout the basin, particularly in the central and eastern portions which rely heavier on rainfall for soil moisture compared to irrigated areas. Areas that have access to irrigation or supplementary water may actually benefit from increases in summer temperatures; different crop type choices may be available with a longer growing season and more heat units.[27]

2.4. Future Climate Scenarios: Specific Sites

The GCM grid cells centred on Lethbridge, Alberta, and Swift Current, Saskatchewan, were selected for a more detailed analysis of future monthly minimum/maximum temperature and precipitation scenarios (Figure 5). Swift Current has a slightly cooler climate, particularly during the winter months, compared to Lethbridge; however, the two stations have similar seasonal precipitation distribution and annual amounts. GCMs project greater increases in minimum temperature (5oC at Swift Current and 4oC at Lethbridge) than maximum temperature during winter and spring. Increases in maximum monthly temperature of 1–4oC are more consistent among months.

Monthly scenarios of future precipitation (Figure 5) show that most models project changes in seasonal variability at both sites with higher winter and lower summer precipitation; annual total precipitation increases. Future monthly variability is highest during the late spring through summer, and into early fall, which is when most of the annual precipitation falls. This summer/fall variability relative to winter likely reflects the weaker ability of the models to simulate convective precipitation than frontal. Lethbridge tends to have an overall increase in all seasons except summer, with June precipitation decreased by nearly 10 mm. Most models also show decreases during July through September, leaving this season in a moisture deficit. Similarly, at Swift Current the majority of models show a drier summer and more variability with otherwise more precipitation particularly in winter and spring.

3. Scenarios of Future Flows of the SSRB Derived by Coupling GCM Scenarios and Hydrological Models

To assess the future trends in streamflow for the SSRB, GCM estimates of future temperature and precipitation were used in a simple hydrological model, WATFLOOD. This modeling exercise serves as an example of the applicability of GCM scenarios in future planning of water resources. WATFLOOD is a physically-based hydrologic model[28] representing the dominant vertical fluxes, precipitation, interception, infiltration. This model provides a horizontal utility that allows for overland, inter- and base flows to route water to the channel; the routing aspect demands that the model is fully distributed in space. The only distributed forcing time series data necessary for WATFLOOD are temperature and precipitation, making it suitable for coupling with GCM indicators of future climate. Other pieces of information used within WATFLOOD are elevations, the extent of the watershed, and other topographic features such as land cover characteristics, reservoir and channel properties.

Initially, the hydrologic model was run for the current climate; WATFLOOD was driven using current climatology in the form of station-observed temperature and precipitation data. The flows generated were compared to naturalized streamflow to ensure that the hydrologic model could replicate streamflow. In order to assess the influence of climate change within the South Saskatchewan River Basin, selected IPCC TAR temperature and precipitation change scenarios were used as input, and future scenario modeled flows were compared to the modeled current flows.

There are 21 stations with complete 1961–90 temperature and precipitation records. As high resolution spatial precipitation gauging enhances accuracy when modeling channel output, additional precipitation records were extracted to force WATFLOOD for the 1961–90 period.[29] There are 775 climate stations that have daily precipitation records for more than five years during the 30-year period.

The choice of climate scenarios was based on an analysis[30] of all publicly available GCM scenario outputs. The potential change in temperature was applied as offsets and precipitation was normalized and these values were applied during a data gridding process, resulting in anticipated distribution of future temperature and precipitation across the basin. Due to the coarse temporal and spatial scale of the available GCM data, a spatially weighted average change in temperature and precipitation was applied over the entire basin at a monthly time step. The significance is that the temperature and precipitation patterns of the current climate were simply replicated with a step change to provide the estimate of future climate temperature and precipitation patterns.

The example presented in this paper is the streamflow estimate yielded from the suggested climate change as represented by the A2(1) scenario of the Hadley HadCM3 TAR GCM. The projected HadCM3 changes to 1961–90 temperature and precipitation are presented in Figure 6, and are essentially a moderate view of future climate with a mean increase in temperature of less than 2.5ºC and a slight increase in precipitation of about 6.4%. The GCM projects that all seasons will be warmer, and that fall (Sept-Nov), winter (Dec-Feb), and spring (Mar-May), will be wetter, while the summer months (Jun-Aug) will be drier.

The 29 years of simulated flows (October 1, 1961 to September 30, 1990) for each of the six scenarios were averaged for each month, and the A21 scenario results are shown in Figure 7. While the perturbations are applied uniformly across the basin, the response in annual future flows differs between the sub-basins (see Figure 7). The Oldman basin shows flows the least affected by the future change in climate with an average annual reduction in flow of 0.01%, with the Bow River showing changes of -7.6%, the Red Deer -12.6%, and the average decrease in flows of the South Saskatchewan into Lake Diefenbaker was 8.5%.

There are differences in the seasonality of current modeled flows across the basin (Figure 8). With current climatology, the flows in the Oldman basin are spring dominated, while the Bow River at Calgary exhibits summer dominated flows. Further downstream the current flows for the Bow River at the mouth are approximately equal in the spring and summer; similarly, current summer and spring flows are equally weighted for the South Saskatchewan at Lake Diefenbaker, although there is slightly more summer than spring flow to the reservoir.

Future flows for the Bow River at Calgary are also summer dominated, although the spring to summer flow ratio increases slightly, and future downstream flows at the mouth shift to a spring dominated flow system. The Oldman system essentially retains its spring flow dominated system. The integration of flows in the South Saskatchewan River shifts from a slightly summer dominated system in current flows, to a future flow regime that is slightly dominated by spring flows.

4. Limitations of GCMs as the Source of Climate Change Scenarios

While climate models are "the only credible tools"[31] currently available for simulating future climate scenarios, they have limitations that apply in general to climate impact studies and, specifically, to our attempt to link future climate to current climate risks in the SSRB. The coarse spatial resolution (100s km) is a commonly cited drawback of GCM derived climate scenarios. This problem is particularly acute for a study like ours where the aim is to evaluate the vulnerability of individual rural communities by providing future climate and water scenarios. Fortunately much of the SSRB, beyond the eastern slopes of the Rocky Mountains, has relatively low relief and homogenous land cover. Even so, we are applying single values of climate variables for GCM grid boxes (thousands of km^2) to small rural communities. Various methods of downscaling have been developed to overcome this spatial resolution limitation downscaling using relationships between observed large-scale atmospheric processes and station-scale data. Downscaling provides information required for water resources management at scales much finer than the current resolution of any GCM for the interpretation of impacts related to climate change or climate variability.[32]

4.1. Downscaling: Two Approaches

The two common approaches to the downscaling of climate scenarios are dynamical and statistical. The confidence that may be placed in downscaled climate change information is foremost dependent on the validity of the large-scale fields from the GCM. Dynamical downscaling involves the use of high-resolution (regional) climate models (RCMs) to obtain finer resolution climate information from coarse-scale GCMs.[33] RCMs are nested within a GCM that provides the initial and lateral boundary driving conditions. The RCM incorporates better parameterization and more direct representation of some small, fine-scale processes and features such as topography and land cover inhomogeneity.[34] RCMs are more computationally demanding than global-scale models[35]; therefore, RCM data are typically available for only one run of a single model for limited time spans. The latest version of the CRCM.4.2.0 (Canadian Regional Climate Model) has output available for the CGCM3 SRES A2 and the time period of 2041–2070 with a 45-km horizontal grid-size[36]; previous versions of CRCMs provided data for a 20-year window (2046–2065). As illustrated in Figure 1, on the other hand, there are numerous runs of various GCMs providing a range of future climates or scenarios.

Statistical downscaling methods are much more popular than dynamical downscaling techniques for deriving future climate scenarios; they are a cheap way of obtaining climate change data at higher temporal or spatial resolution than can be provided by the GCM. The statistical downscaling of GCM data is based on a statistical model linking the climate simulated by the GCM and the current climate characterized by instrumental data. This technique has been widely applied to derive daily and monthly precipitation at higher spatial resolution for impact assessments.[37] [38] SDSM (Statistical Downscaling Model)[39] and LARS-WG (Weather Generator)[40] are two popular methods of statistical downscaling.

Here we provide downscaled future scenarios for Lethbridge and Swift Current using the LARS-Weather Generator and ask "Does downscaling provide better results than the climate scenarios derived from GCMs and presented in section 2.4?"

Future climate change scenarios were derived for the 2050s at Lethbridge and Swift Current using the five GCMs described in 2.3 above to adjust the LARS-WG parameters. Monthly-observed homogenized precipitation and minimum/maximum temperature datasets, used to calibrate the model, were obtained for the entire study area for 1961–90 from Environment Canada.[41] [42] Figure 5 compares the future monthly minimum/maximum and precipitation climate scenarios at the two stations between those derived using GCMs (section 2.4) and downscaled with LARS-WG. Overall, the results of the downscaled monthly station data are very similar to those derived from the GCMs. The principal difference between the two scales of climate scenarios is the monthly precipitation variability. At Lethbridge, the LARS-WG results show greater variability for the months of February, June, August, November and December. At Swift Current, March, April and August have greater precipitation variability than derived using GCMs. The scenarios from the coarse resolution GCMs are not substantially different from those derived using downscaling. Downscaling is more labour intensive, suggesting, in this case, that downscaling does not necessarily provide better results.

LARS-WG also generates a series of wet and dry days, and the agriculturally important extreme events of frost and high temperature. At both stations there is a decreased number of days below freezing (<0° C) and an increased number of hot days (>30° C) in the summer months (late spring into early fall; Figure 9). In July and August the models project that the number of days >30° C could double. Changes to the length of wet and dry spells are variable and fluctuate around the 1961–90 average monthly number of days; therefore, it is difficult to draw any conclusions. On average, the majority of the models favour increasing wet spell length for the winter months and increasing dry spell length for the late summer months. We are less concerned about changes in the winter months as compared to spring and summer when the impacts of drought are more severe.

4.2. Climate Variability

Because GCMs simulate atmospheric and oceanic states and processes at a global scale, the most robust projections are for the largest areas and for multi-decadal mean values; thus, the IPCC-TGICA[43] places highest confidence in the projections of global temperature trends expressed as the difference between a baseline of 30 years and a future 30-year time-slice. The GCM projections have decreasing reliability for progressively smaller areas and time periods, and for water-related variables versus temperature. Here we are interested in a single watershed and water-related events; thus, the coarse resolution is a constraint, although the SSRB spans 5–11 GCM cells (depending upon the grid cell size of the GCM). More problematic, however, is the greater sensitivity of the rural communities to climate variability, departures from mean conditions, than climate change, to shifts in the mean. Most of the climate risks identified by the communities are departures from mean conditions (e.g., droughts, floods, frost) and not a shift in mean conditions as projected by GCMs. Data on future extremes and variability have been extracted from GCMs for large regions; but, once again, the reliability declines as the region of interest decreases in size.

Despite these constraints, we derived, with caution, some scenarios on the degree of variability that might be expected under the climate change scenarios presented above. This analysis is a preliminary step to investigating long-term trends and variability of future climate scenarios using the Climate Moisture Index of P-PET, as modeled by the CGCM3.1/T67 covering the total Prairie Provinces area. An eight-year low pass digital filter[44] was used to smooth the annual P-PET for each grid cell to retain information that was coarser than the frequency of eight years. Principle Component (PC) analysis was used to analyze and compare trends between the 1961–90 observed P-PET and the 20th century modeled P-PET and the future SRES (A1B, A2, and B1) P-PET experiments. The B1 scenario is close to the median, and the A2/A1B scenarios tend to be warmer/drier scenarios (Figure 1) relative to all the models tested. Figure 10a shows the standardized PC1 for the change in P-PET over the Prairie Provinces; negative/positive values represent drier/wetter conditions. There is a strong Pacific Decadal Oscillation (PDO) pattern evident, switching from a positive phase in 1947, to negative and again positive in 1977. During negative PDO phases the sea surface temperature is warmer in the North Pacific and cooler along the west coast of North America, bringing generally cooler wet conditions to the Prairies[45]. The opposite pattern exists for positive PDO phases, and we expect drier conditions. The negative PDO pattern dominates during 1947–1976, but positive PDO indices occur in 1957–58 and 1969–1970, and are observed in the P-PET PC1 as negative values during these periods. During the 1977–78 "regime shift,"[46] when the

PDO shifted from a negative to positive phase (Figure 11), the P-PET for the PC1 values become negative (Figure 10a). This teleconnection between positive PDO phases and dry periods on the prairies has been well documented.[47 48 49] Our preliminarily results indicate that, at timescales great than eight years, the 20th century model reproduces a similar pattern to the observed data (see Figure 10a), placing increased confidence in the GCMs ability to produce future climate scenarios.

Future P-PET scenarios based on the standardized PC1 and SRES experiments also maintains similar natural variability as the observed and modeled P-PET (Figure 10b), but an increased moisture deficit (more negative P-PET) is projected by the three experiments extending to the end of this century. This decline in moisture is associated with decreasing precipitation and increased temperatures during the spring/summer period.

The variability of future climate will be a function of the natural climate cycles modulated by greenhouse gas warming. Research on the nature and degree of this modulation is in early stages, but one approach involves the analysis of natural climate variability that will underlay the variation in future climate. Historical weather data contain detailed information on the variability of climate at daily to decadal scales; however, these records are relatively short in western Canada, at most 120 years, and mostly considerably shorter. Longer records that pre-date the instrumental period are available from climatically sensitive geological and biological archives. Figure 12 is a plot of the annual flow of the South Saskatchewan River for the period 1402–2002. Axelson[50] developed a statistical relationship between streamflow and tree growth in the basin; both respond to the effective precipitation (P-PET) that recharges the soil moisture balance, and is discharged from the basin in the stream channel. This plot of departures from the mean flow illustrates that negative departures or drought occurs periodically and with greater duration and severity before the 20th century; thus, communities in the basin can expect severe and prolonged drought, simply because it is characteristic of the long-term hydroclimatic variability, with or without human-induced global warming.

5. Conclusions

Output is available from various GCMs to develop scenarios of the future climate of the SSRB, and model stream flows, and thereby assess future vulnerabilities and climate risks. Application of these scenarios to vulnerability assessment, however, requires an understanding the source, derivation and limitations of the scenarios because model projections are only simulations of possibilities. Some climate risks cannot be properly evaluated because current models and methods do not provide reliable information at the relevant spatial and temporal scale for the variables identified by stakeholders. For example, one important variable not examined is the change in wind frequency and speed, which can have dramatic effects on snow sublimation and evaporation of water from soil and storage ponds.

GCM scenarios suggest the SSRB will experience an increase in both temperature and precipitation by 2050. Less precipitation is expected in summer, and more in winter, increasingly in the form of rain with rising temperatures. Warmer temperatures will result in a longer growing season, but there also will tend to be less available soil moisture in mid to late summer. The projected changes in temperature will influence snow accumulation in the mountains which feed the rivers that communities depend on for their water supply. Decreased runoff, and a shift in the dominant flow season from summer to spring, will cause river flows to decrease throughout the summer and fall months. Increased temperatures will result in an increased number of days with net positive evaporation from soil, storage dugouts, rivers, lakes, and reservoirs. When a median GCM scenario is coupled with a hydrological model, mean flows for the 2050s are reduced for all the major streams in the SSRB. The flows of the South Saskatchewan River into Lake Diefenbaker are reduced by 8.5%. Also with earlier peak flow, there is an increase in the ratio of spring to summer flow.

These new scenarios of the future climate and surface water supplies of the SSRB represent the shift in average conditions that communities and institutions can expect. This is critical information in anticipation of the impacts of climate change, but not necessarily the most relevant information for the rural communities, or at least those studied by IACC project researchers.[51] [52] [53] The major climate risks (drought, flooding, storms) and vulnerabilities identified through the community assessments are departures from mean conditions and sensitivities to this climate variability and extreme events; therefore, this paper supplemented the conventional GCM scenarios of climate change with sources of hydroclimatic data at finer scales: downscaled GCM output, annual Climate Moisture Index (CMI) data from a GCM, and proxy climate (tree-ring) records that capture the natural hydroclimatic variability that underlies the trends imposed by global warming. These approaches and information are necessitated by the nature of vulnerability to climate change on the Canadian plains as revealed through the "bottom up" approach to vulnerability assessment undertaken in the IACC project. The "top down" approach of providing conventional GCM-based scenarios of shifts in mean conditions also is useful in terms of informing stakeholders about the directions of climate change, whether or not they perceive these trends as immediate climate risks.

Our scenarios of the mean conditions and variability of future climate and water resources have considerable implications for economic, environmental and social processes within the SSRB. The forces driving the Prairies' climate, its variability and its water resources, need to be understood in greater depth for society to be better prepared for the future. Planning and implementing adaptation to climate change requires communities and institutions to develop practices and policies that can be implemented when there is uncertainty about future conditions.

Tables and Figures

CLIMATE MODELING CENTRE	MODEL	SRES SIMULATION	GRID CELL SIZE (DEGREES)	DIMENSIONS
Canadian Centre for Climate Modelling and Analysis Canada	CGCM3 (T47)	A1B*, A2*, B1*	3.75° × 3.75°	238.125–256.875W 44.52–55.77N
	CGCM3 (T63)	A1B, A2, B1	2.81° × 2.810	241.8725–258.7475W 46.04–57.29N
Met Office Hadley Centre UK	HadCM3	A2*, B2 (TAR)	3.75° × 2.55°	241.885–260.625W 46.25–56.25N
National Institute for Environmental Studies Japan	MIROC3.2-MEDRES	A1B*, A2*, B1*	2.8125° × 2.8°	240.468–257.343 W 44.64–55.84N
Geophysical Fluid Dynamics Laboratory USA	GFDL 2.0	A1B, B1	2.5° × 2.00	241.875–259.375W 46–56N
Max-Planck-Institut for Meteorology Germany	ECHAM5-OM	A1B, A2, B1	1.875° × 1.87°	240.9375–257.8125W 46.629–55.979N
Australia's Commonwealth Scientific and Industrial Research Organization Australia	CSIRO-MK3.0	A1B, A2, B1	1.875° × 1.87°	240.9375–257.8125W 46.6312–55.637N

*More than one experiment was carried out for these emission scenarios.

Table 1. Information about the climate models chosen for this study: the country of origin, SRES simulations available, grid cell size and dimensions of the area for each model. The output is available from the IPCC Fourth Assessment Report (2007) for all models except the HadCM3 from the Third Assessment Report (2001) at the IPCC Data Distribution Centre (http://www.ipcc-data.org/) and Program for Climate Model Diagnosis and Intercomparison (http://www-pcmdi.llnl.gov).

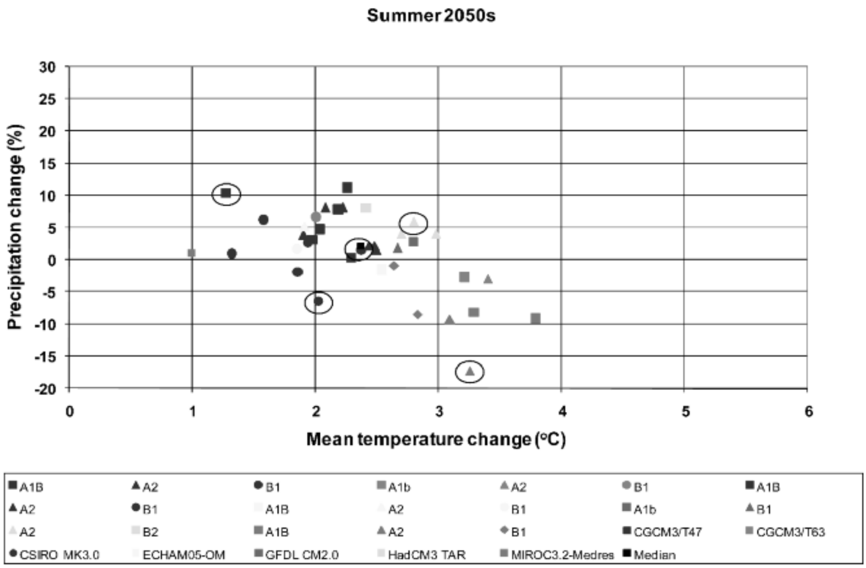

Figure 1. Scatter plot indicating mean temperature (°C) and precipitation (%) change for the SSRB for the 2050s summer. The models were chosen based on the availability of the required climate variables: daily minimum and maximum temperature and daily precipitation. The colours correspond to the GCM and the symbols identify the scenario. MIROC Medres A2(1) (warm/dry), HadCM3 TAR A2(a) (warm/wet), CGCM3.1/T47 B1(1) (cool/dry), CSIRO MK3.0 A1B(1) (cool/wet), CGCM3/T47 B1(2) (median) are all circled. (Value in brackets identifies the run number).

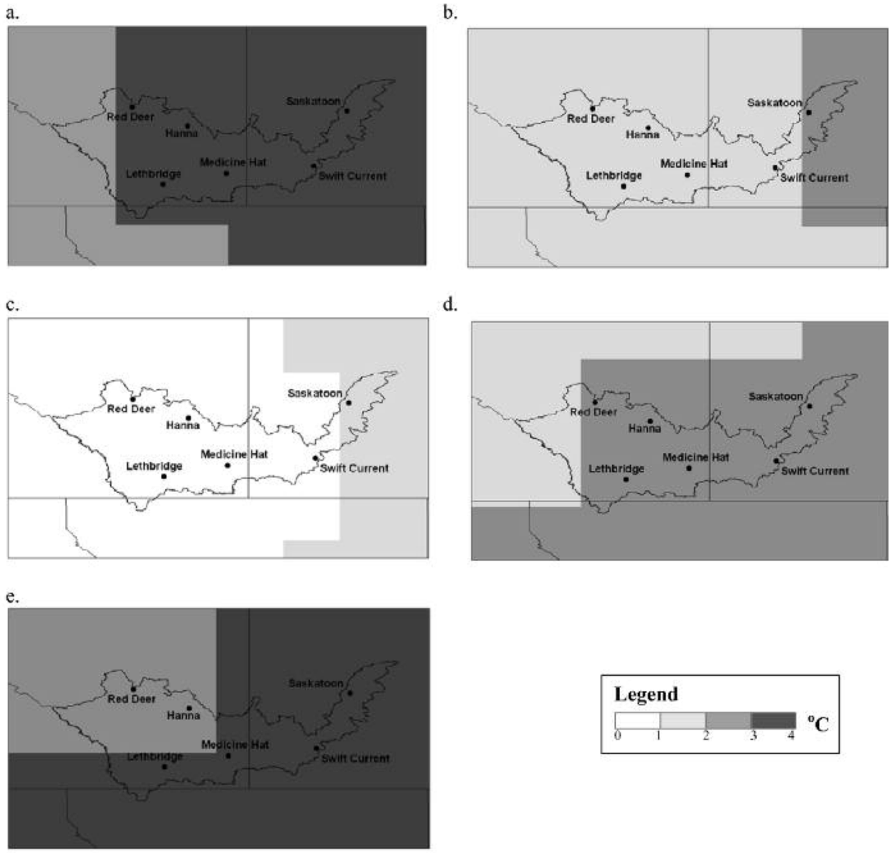

Figure 2. Maps of annual temperature change scenarios (°C) for the 2050s relative to 1961–90. a. CGCM3.1 T47 B1(1) (cool/dry) b. CGCM3.1 T47 B1(2) (median) c. CSIRO MK3.0 A1B(1) (cool/wet) d. HadCM3 TAR a2(1) (warm/wet) e. Miroc Medres a2(1) (warm/dry).

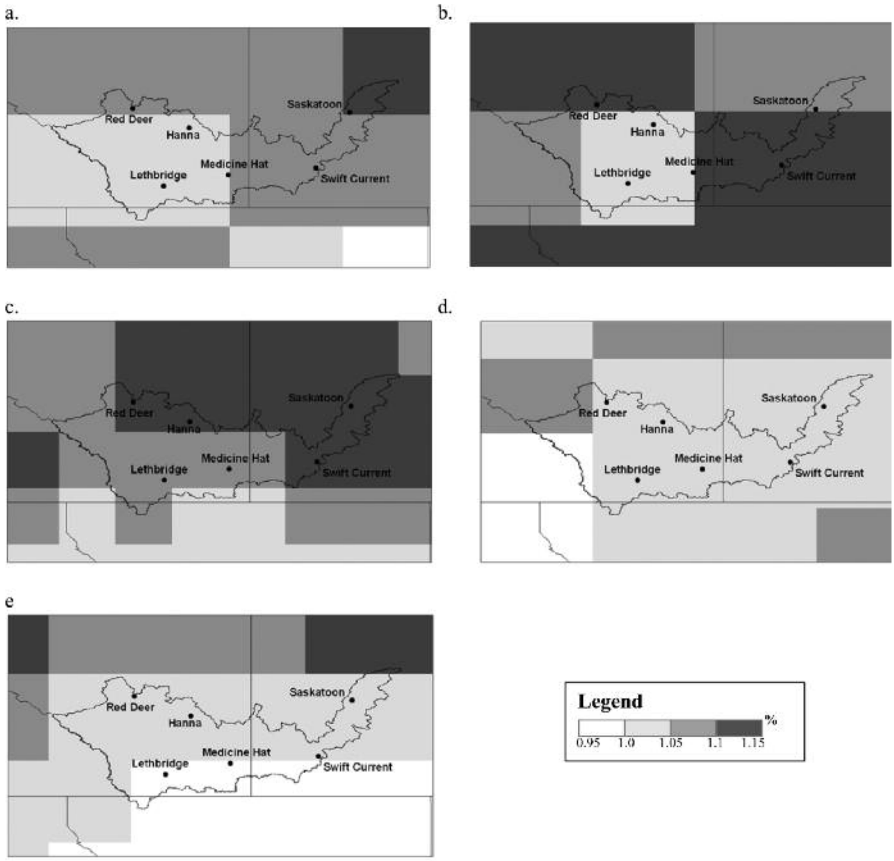

Figure 3. Maps of annual precipitation change scenarios (%) for the 2050s relative to 1961–90. a. CGCM3.1 T47 B1(1) (cool/dry) b. CGCM3.1 T47 B1(2) (median) c. CSIRO MK3.0 A1B(1) (cool/wet) d. HadCM3 TAR a2(1) (warm/wet) e. Miroc Medres a2(1) (warm/dry).

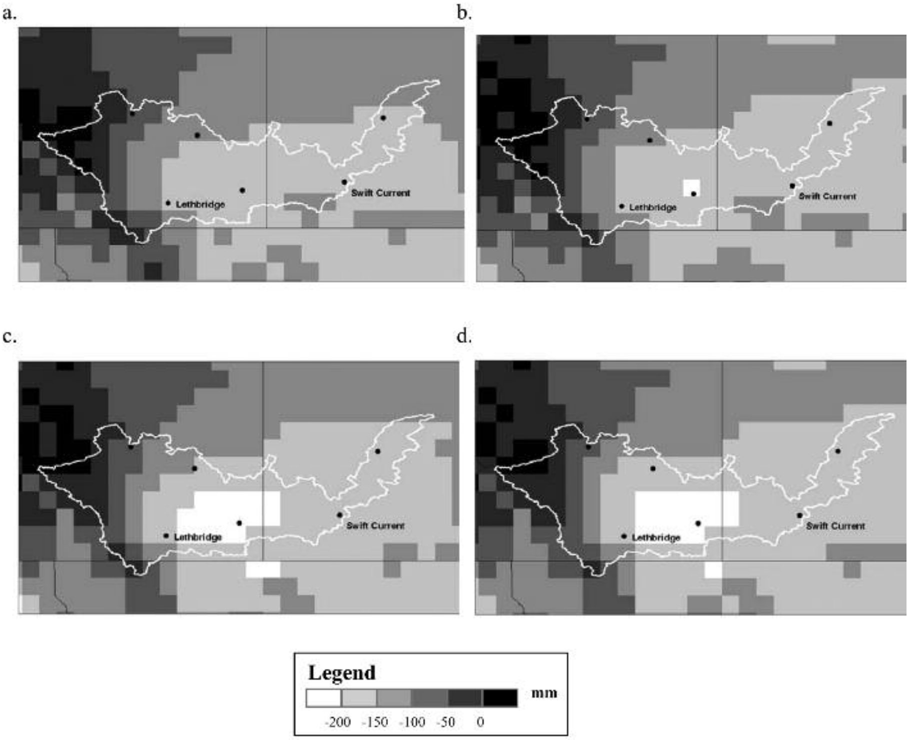

Figure 4. Future Climate Moisture Index (P-PET (mm)) maps for May-July using CGCM3.1/T47 B1(2) (Median) Scenario (a) 1961–90 (b) 2020s (c) 2050s (d) 2080s.

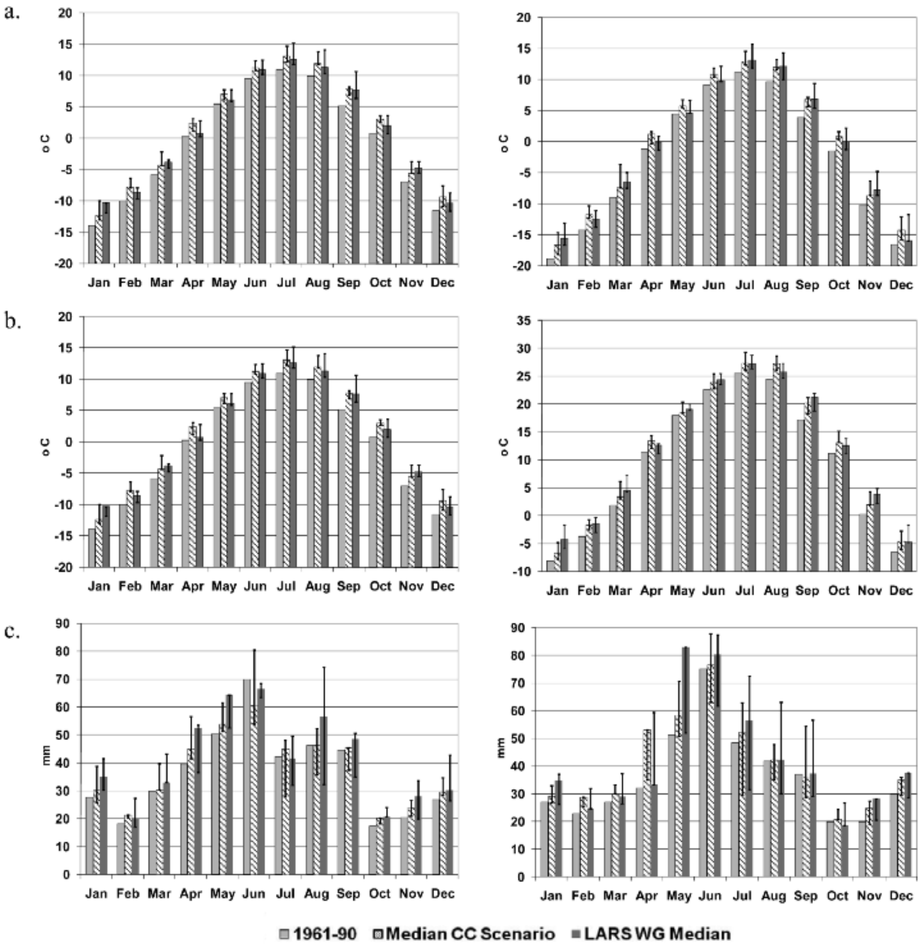

Figure 5. Lethbridge, AB (left side) and Swift Current, SK (right side) future climate scenarios: Solid grey bars represent the monthly averages for the baseline 1961–90 period and the hatched bars represent the median (CGCM3 B1(2)) scenario for the 2040–2069 period, derived directly from the GCM and downscaled using the LARS-WG. The error bars represent the full range of values from five GCMs. (a) minimum temperature (b) maximum temperature (c) precipitation.

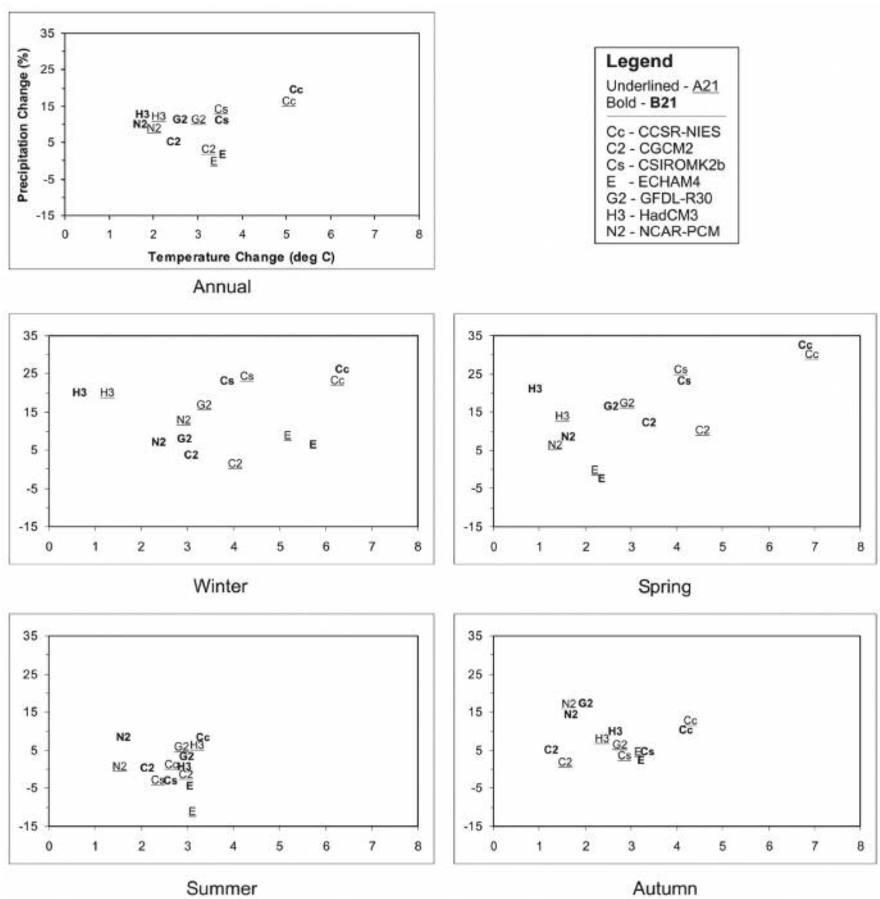

Figure 6. Plots showing the regional averages of projected annual and seasonal change in mean temperature and precipitation based on SRES A2 and B2 scenarios for the 2050 (2040–69) climate.

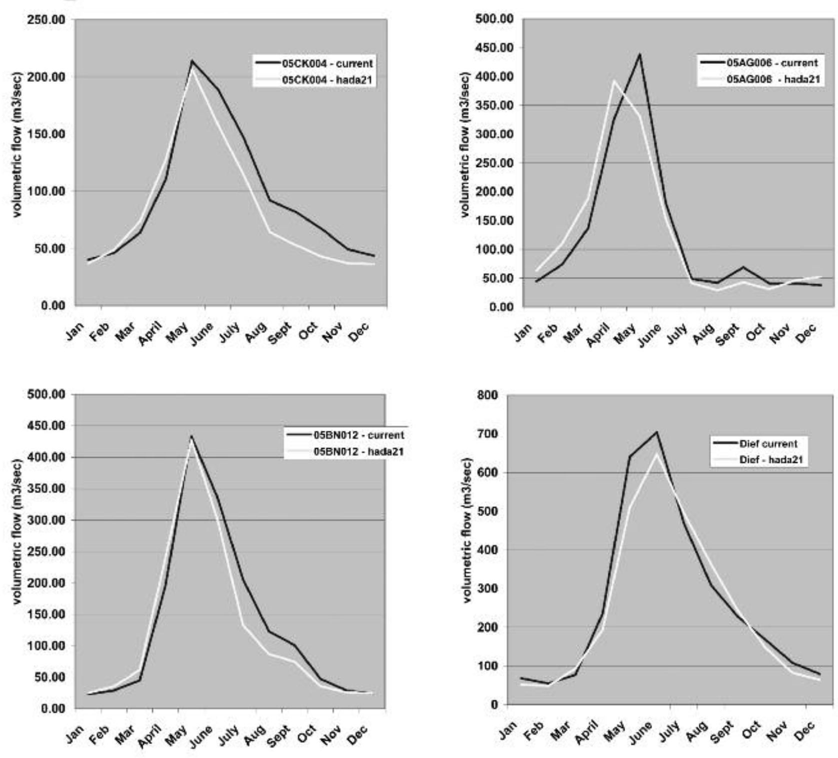

Figure 7. Response in annual future flows for the sub-basins.

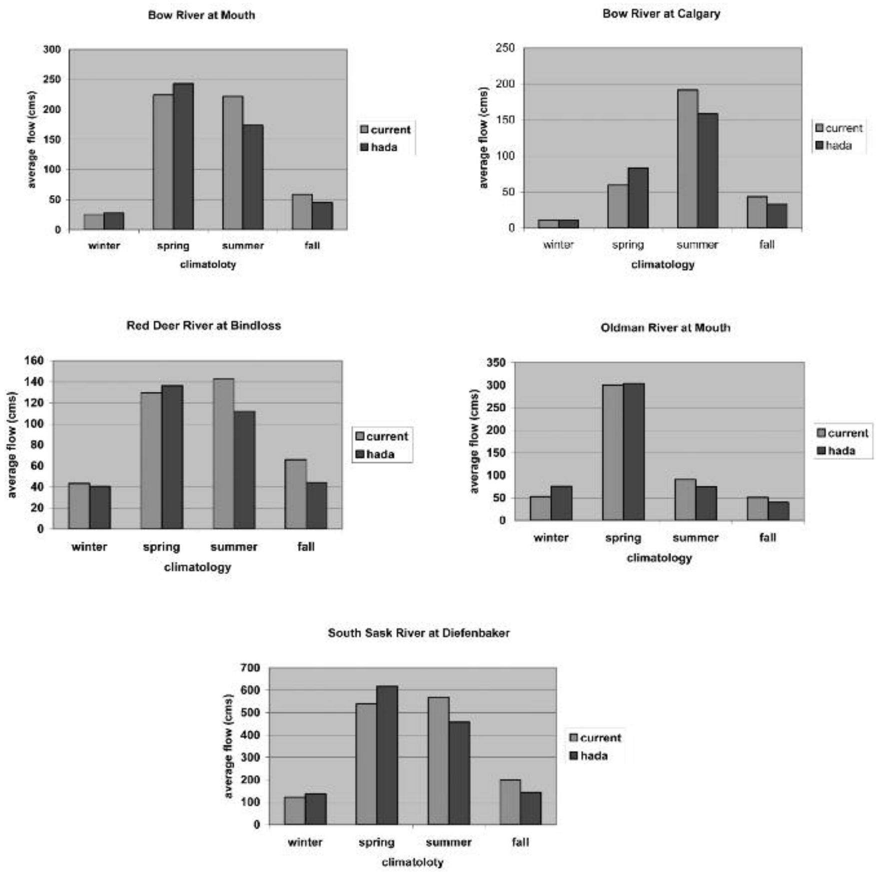

Figure 8. Seasonal response of modeled 1961- 90 stream flows compared to the modeled flows from 2040–2069.

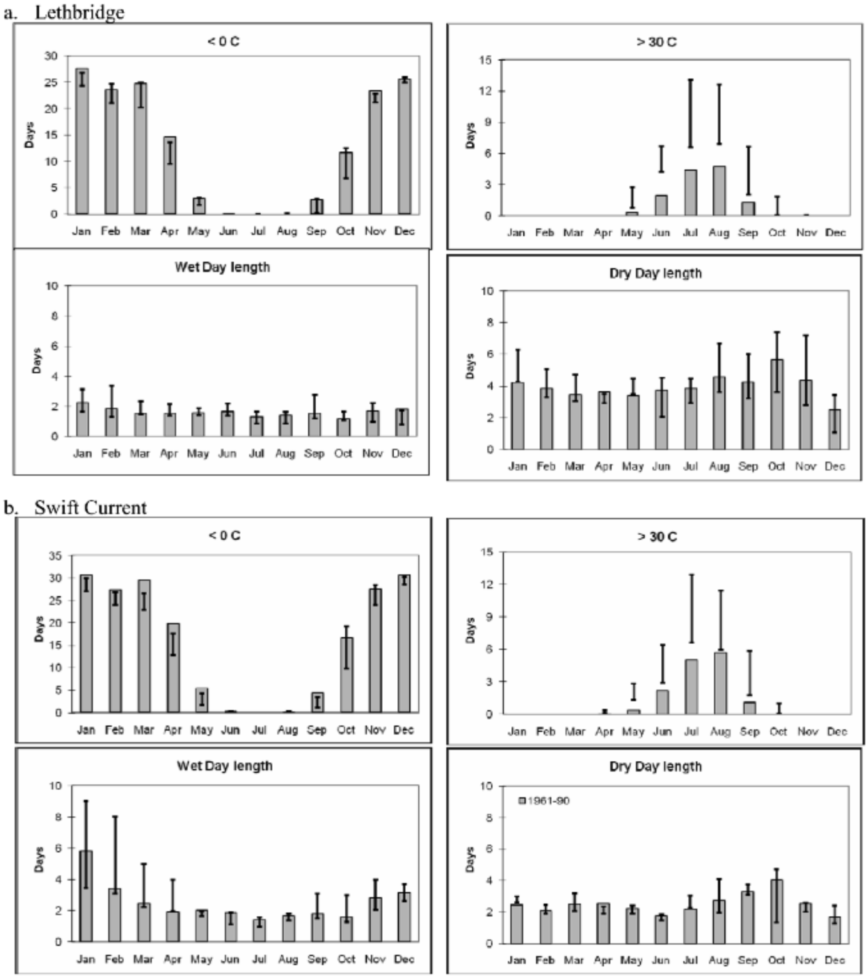

Figure 9. Results from LARS-WG at (a) Lethbridge and (b) Swift Current; grey bars represent the monthly values for the 1961–90 baseline period and the heavy vertical lines represent the range in 2050s projected climate for the five GCMs. Variables compared are the length of temperature spells below 0° C and above 30° C, and monthly dry-day and wet-day lengths.

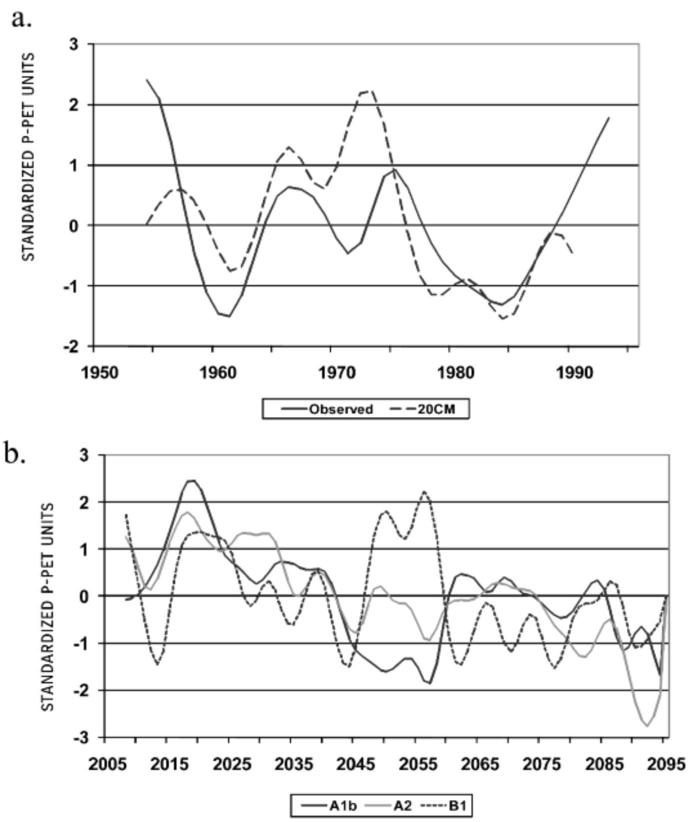

Figure 10. The first principal component of annual P-PET values for timescales greater than eight years. a. Compares the observed and 20CM modeled trends. b. Compares the future scenarios. The first eigenvalue explains 86% of observed and over 95% of the GCM annual P-PET variance for the 1961–90 period.

Monthly values for the PDO index: 1900—February 2007

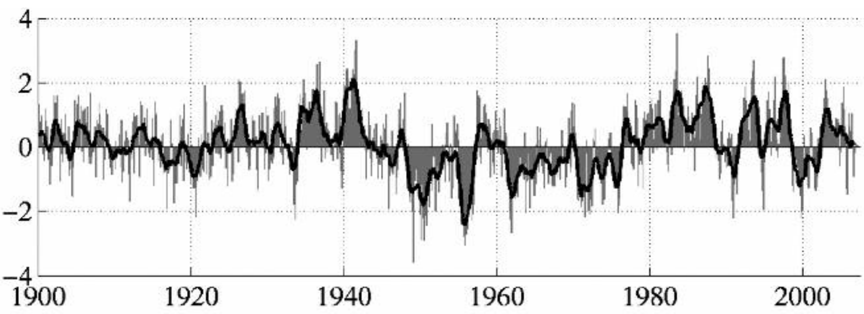

Figure 11. Monthly PDO index values: 1900–February 2007.[54]

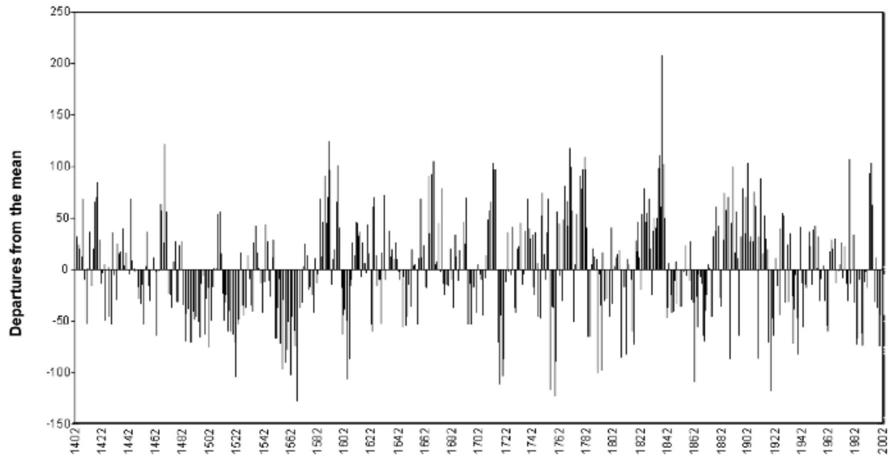

Figure 12. Reconstructed annual flow of the South Saskatchewan River for the period 1402–2002.[55] The vertical bars represent departures from the mean flow. Prolonged periods of low flows are evident prior to the instrumental period starting in the early 20th century.

Endnotes:

1. Hurlbert et al., this volume.
2. Intergovernmental Panel on Climate Change (IPCC), “Contribution of Working Group I to the Third Assessment Report of Intergovernmental Panel on Climate Change,” in J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linde, X. Dai, K. Maskell, and C.A. Johnson (eds.), *Climate Change 2001: The Scientific Basis* (Cambridge, U.K. and New York, N.Y., U.S.A.: Cambridge University Press, 2001.): 881.
3. IPCC, *Climate Change 2001: The Scientific Basis,* 881.
4. M.L. Parry and T.R. Carter, *Climate Impact and Adaptation Assessment: A Guide to the IPCC Approach* (London: Earthscan, 1998).
5. E.M. Barrow, B. Maxwell and P. Gachon, “Climate Variability and Change in Canada: Past, Present and Future,” Climate Change Impacts Scenarios Project, National Report, Environment Canada, Meteorological Service of Canada, Adaptation Impacts Research Group, Atmospheric and Climate Sciences Directorate Publication (Canada: 2004): 114.
6. Intergovernmental Panel on Climate Change-Task Group on Scenarios for Climate and Impact Assessment (IPCC-TGCIA), “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” (2007): 66.

7. J.B. Smith and M. Hulme, “Climate Change Scenarios,” in *Handbook on Methods of Climate Change Impacts Assessment and Adaptation Strategies. Version 2.0,* by J. Feenstra, I. Burton, J.B. Smith, and R.S.J. Tol (eds.), 3–1 to 3–40 (Vrije Universiteit, Amsterdam: United Nations Environment Programme and Institute for Environmental Studies, 1998).
8. D.A. Randall, R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, and K.E. Taylor, “Climate Models and Their Evaluation,” in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), *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, UK and New York, NY, USA: Cambridge University Press, 2007).
9. IPCC, “Technical Summary,” in J.T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.), *Climate Change 2001: The Scientific Basis—Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge and New York: Cambridge University Press, 2001): 62.
10. N. Nakicenovic, J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K.Riahi, A. Roehrl, H.H. Rogner, A. Sankovski, M. Schlesinger, P.Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi, *IPCC Special Report on Emissions Scenarios* (Cambridge, United Kingdom and New York, NY, USA Cambridge University Press, 2000): 599.
11. IPCC, “Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,” in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, *Climate Change 2007: The Physical Science Basis* (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007): 996.
12. M. Hulme, E.M. Barrow, N. Arnell, P.A. Harrison, T.E. Downing, and T.C. Johns, “Relative Impacts of Human-Induced Climate Change and Natural Climate Variability,” *Nature* 397 (1999): 688–91.
13. Barrow et al., 114.
14. IPCC-TGCIA, “General Guidelines.”
15. IPCC, *Climate Change 2007,* 996.
16. Nakicenovic et al., *IPCC Special Report on Emissions Scenarios,* 599.
17. B. Bonsal and T.D. Prowse, “Regional Assessment of GCM-Simulated Current Climate over Northern Canada,” *Arctic* 59, no. 2 (2006): 115–28.
18. B. Bonsal, T.D. Prowse and A. Pietroniro, “An Assessment of GCM-Simulated Climate for the Western Cordillera of Canada (1961–90),” *Hydrological Processes* 18 (2003): 3703–16.
19. J. Toyra, A. Pietroniro, and B. Bonsal, “Evaluation of GCM Simulated Climate over

the Canadian Prairie Provinces," *Canadian Water Resources Journal* 30, no. 3 (2005): 245–62.

20. Program for Climate Model Diagnosis and Intercomparison (2007). Available at: http://www-pcmdi.llnl.gov. (cited February 14, 2008).
21. IPCC–Data Distribution Centre (DDC). Available at: http://www.ipcc-data.org (cited December 12, 2007).
22. UK Meteorological Office, Hadley Centre. Climate Impacts LINK Project, British Atmospheric Data Centre, 2003. Available at: http://badc.nerc.ac.uk/data/link/. (cited November 9, 2008).
23. D.W. McKenney, J.H. Pedlar, P. Papadopol, and M.F. Hutchinson, "The Development of 1901–2000 Historical Monthly Climate Models for Canada and the United States," *Agricultural and Forest Meteorology* 138 (2006): 69–81.
24. J.H. Christensen, B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton, "Regional Climate Projections," in *Climate Change 2007.*
25. C.J. Willmott and J.J. Feddema, "A More Rational Climatic Moisture Index," *Professional Geographer* 44 (1992): 84–87.
26. E.H. Hogg, "Temporal Scaling of Moisture and the Forest-Grassland Boundary in Western Canada," *Agricultural and Forest Meteorology* 84 (1997): 115–22.
27. E.M. Barrow and G. Yu, "Climate Scenarios for Alberta: a Report Prepared for the Prairie Adaptation Research Collaborative (Parc) in Co-operation with Alberta Environment" (University of Regina, Saskatchewan, 2005): 73.
28. N. Kouwen, E.D. Soulis, A. Pietroniro, J.R. Donald, and R.A. Harrington, "Grouped Response Units for Distributed Hydrologic Modelling," *Journal of Water Resources Planning and Management* 119, no.3 (1993): 289–305.
29. Kouwen, personal communication.
30. J. Toyra, A. Pietroniro, and B. Bonsal, "Evaluation of GCM Simulated Climate over the Canadian Prairie Provinces," *Canadian Water Resources Journal* 30, no. 3 (2005): 245–62.
31. IPCC-TGCIA, "General Guidelines," 66.
32. V. Venugopal, G.E. Foufoula, and V. Sapozhinikov, "A Space-Time Downscaling Model for Rainfall," *Journal of Geophysical Research: Atmospheres* 104, no. 16 (1999): 19–705.
33. IPCC, "Technical Summary," 62.
34. IPCC, *Climate Change 2001,* 881.
35. L. E. Hay, and M. P. Clark, "Use of Statistically and Dynamically Downscaled Atmospheric Model Output for Hydrologic Simulations in Three Mountainous Basins in the Western United States," *Journal of Hydrology* 282, no. 1–4 (2003): 56–75.
36. Canadian Centre for Climate Modelling and Analysis (2007). Available at: http://www.cccma.ec.gc.ca. (cited February 12, 2008).

37. M.A. Semenov and E.M. Barrow, "Use of a Stochastic Weather Generator in the Development of Climate Change Scenarios," *Climatic Change* 35 (1997): 397–414.
38. R.L. Wilby, C.W. Dawson, and E.M. Barrow, "SDSM—a Decision Support Tool for the Assessment of Regional Climate Change Impacts," *Environmental Modelling and Software* 17 (2002): 147–59.
39. Wilby, "SDSM," 147.
40. M.A. Semenov and E.M. Barrow, "Lars-WG a Stochastic Weather Generator for Use in Climate Impact Studies, Version 3.0., User Manual," 2002.
41. É. Mekis and W.D. Hogg, "Rehabilitation and Analysis of Canadian Daily Precipitation Time Series," *Atmosphere-Ocean* 37, no. 1 (1999): 53–85.
42. L.A. Vincent, X. Zhang, B.R. Bonsal, and W.D. Hogg, "Homogenization of Daily Temperatures over Canada," *Journal of Climate* 15 (2002): 1322–34.
43. IPCC-TGCIA, "General Guidelines," 2007.
44. IPCC-TGCIA, "General Guidelines," 2007.
45. B. Bonsal and R. Lawford, "Teleconnections between El-Nino and La-Nina Events and Summer Extended Dry Spells on the Canadian Prairies," *International Journal of Climatology* 19 (1999): 1445–58.
46. Nathan J. Mantua and Steven R. Hare, "The Pacific Decadal Oscillation," *Journal of Oceanography* 58, no. 1 (2002): 35–44.
47. Bonsal and Lawford, "Teleconnections between El-Nino and La-Nina," 1445.
48. B. Bonsal and E. Wheaton, "Atmospheric Circulation Comparisons between the 2001 and 2002 and the 1961 and 1988 Canadian Prairie Droughts," *Atmosphere-Ocean* 43, no. 2 (2005): 163–72.
49. Mantua and Hare, "The Pacific Decadal Oscillation," 35.
50. Jodi Axeslon, "Historical Streamflow Variability in the South Saskatchewan River Basin Inferred from a Network of Tree-Ring Chronologies" (University of Regina: M.Sc. thesis, 2007).
51. Hurlbert et al., this volume.
52. Magzul et al., this volume.
53. Wandel et al., this volume.
54. N.J. Mantua, S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, "A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production," *Bulletin of the American Meteorological Society* 78 (1997): 1069–1079. Available from http://jisao.washington.edu/pdo/ (cited December 12, 2007).
55. Axeslon, "Historical Streamflow Variability."