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Differences and sensitivities in potential hydrologic impact of climate change to regional-scale Athabasca and Fraser River basins of the leeward and windward sides of the Canadian Rocky Mountains respectively

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Abstract Sensitivities to the potential impact of Climate Change on the water resources of the Athabasca River Basin (ARB) and Fraser River Basin (FRB) were investigated. The Special Report on Emissions Scenarios (SRES) of IPCC projected by seven general circulation models (GCM), namely, Japan's CCSRNIES, Canada's CGCM2, Australia's CSIROMk2b, Germany's ECHAM4, the USA's GFDLR30, the UK's HadCM3, and the USA's NCARPCM, driven under four SRES climate scenarios (A1FI, A2, B1, and B2) over three 30-year time periods (2010–2039, 2040–2069, 2070–2100) were used in these studies. The change fields over these three 30-year time periods are assessed with respect to the 1961–1990, 30-year climate normal and based on the 1961–1990 European Community Mid-Weather Forecast (ECMWF) re-analysis data (ERA-40), which were adjusted with respect to the higher resolution GEM forecast archive of Environment Canada, and used to drive the Modified ISBA (MISBA) of Kerkhoven and Gan (Adv Water Resour 29(6):808–826, 2006). In the ARB, the shortened snowfall season and increased sublimation together lead to a decline in the spring snowpack, and mean annual flows are expected to decline with the runoff coefficient dropping by about 8% per °C rise in temperature. Although the wettest scenarios predict mild increases in annual runoff in the first half of the century, all GCM and emission combinations predict large declines by the end of the twenty-first century with an average change in the annual runoff, mean maximum annual flow and mean minimum annual flow of −21%, −4.4%, and −41%, respectively. The climate scenarios in the FRB present a less clear picture of streamflows in the twenty-first century. All 18 GCM projections suggest mean annual flows in the FRB should change by ±10% with eight projections suggesting increases and 10 projecting decreases in the mean annual flow. This stark

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contrast with the ARB results is due to the FRB's much milder climate. Therefore under SRES scenarios, much of the FRB is projected to become warmer than 0°C for most of the calendar year, resulting in a decline in FRB's characteristic snow fed annual hydrograph response, which also results in a large decline in the average maximum flow rate. Generalized equations relating mean annual runoff, mean annual minimum flows, and mean annual maximum flows to changes in rainfall, snowfall, winter temperature, and summer temperature show that flow rates in both basins are more sensitive to changes in winter than summer temperature.

1 Introduction

Water managers regularly use historical streamflows to facilitate watershed planning. Strictly speaking, such approaches are only valid when the historical and future climates are stationary. However, anthropogenic climate change due to ever increasing greenhouse gas emissions (from about 315 ppmv in 1959 to 390 ppmv in 2007, IPCC (2007)) has the potential to drastically alter climates at all spatial scales and thereby invalidate hydrological analysis methods that depend on the assumption of a stationary climate (e.g., Dettinger et al. 2004; Stewart et al. 2004).

In the First Assessment Report of the IPCC (Intergovernmental Panel on Climate Change), atmospheric General Circulation Models (GCMs) were run to equilibrium under current ($1{\times}CO_2$) and doubled ($2{\times}CO_2$) emission forcings (Cubasch and Cess 1990) to estimate the potential effect of these emissions on global climate. These models were then coupled with Oceanic Circulation Models in the Second Assessment Report (Gates et al. 1996) and forced with transient greenhouse emissions to allow for the estimation of the rate at which climate changes might occur. In the Third Assessment Report (TAR), a series of emission scenarios from the Special Report on Emission Scenarios (SRES) (IPCC 2000) were used to evaluate the effects of a range of government policy options through their effects on population growth, technological, and economic development (IPCC 2001). The results of each GCM used in the TAR were summarized as monthly changes in mean state variables (for example, near-surface temperature and precipitation) with respect to the 1961–1990 baseline climate normal. The Fourth Assessment Report (AR4) the SRES scenarios were again used to force the most recent generation of GCMs, which feature improvements in grid resolution and process treatment but no fundamental advances comparable to the inclusion of ocean dynamics in FAR and TAR (IPCC 2007). The projected global average temperature change by the end of the twenty-first century ranged from 1.4 to 5.8°C in TAR and 1.1 to 6.4°C in AR4.

The projections of these relatively coarse resolution GCMs have been used to drive land surface hydrology models to estimate the potential impact of climatic change on hydrology in mid-latitude regions such as California (e.g., Lettenmaier and Gan 1990; Brekke et al. 2004; Knowles and Cayan 2004; Maurer 2007) and the Europe (e.g., Middelkoop et al. 2001; Etchevers et al. 2002; Beniston et al. 2003; Zierl and Bugmann 2005). This paper focuses on the potential effect of climate change and mountains by assessing hydrologic sensitivities of regional scale river basins on either side of the Rocky Mountains of western Canada to: the Athabasca River Basin (ARB) of Alberta, and the Fraser River Basin (FRB) of British Columbia. Because of the Rocky Mountains, these basins experience quite different climate and thus contain different vegetation: boreal forest in the ARB and coniferous forest in the FRB.

2 Study basins

The ARB is of key interest mainly because of its multi-billion dollar, oil sands industry at Fort McMurray. The basin area of ARB is 133,000 km^2 and its main channel length is about 1,154 km (Kellerhals et al. 1972). ARB has a continental climate with daily mean temperature dropping below freezing between mid-October and early April. Typical temperatures are −20°C in January and 17°C in July. June to October are the wet months, with an average total precipitation of about 300 mm, while winter and spring only experience about 150 mm of precipitation in an average year. Coniferous, mixed wood and deciduous forests are the dominant vegetation especially in the upland areas (elevation ranging from 350 to 850 m) and willow brush, shrubs, black spruce and sphagnum moss dominate the often poorly drained lowland areas. For lowland dominated by muskeg, interflow tends to constitute of a significant component of the sub-surface runoff (Golder Associates 2002). Dominant surficial soils are glacial soils (silt, clay and sands), glaciolacustrine soils (clay loam to heavy clay) and glaciofluvial soils (sandy loam to sands) (Fulton 1995).

Natural watersheds in many parts of ARB are characterized by peat soils that vary from 0.3 m (upland) to over 1 m (lowland). Upland watersheds typically have ground slopes of 0.5% or more, while lowland areas typically have average slope less than 0.5%. Lowland areas normally have thick peat soils with a near-surface groundwater table. As a result, a significant amount of runoff (e.g., could be more than 70%) from lowland watersheds occurs as interflow through deep peat, or muskeg, irrespective of the sub-soil types (Golder Associates 2002).

The Fraser River Basin (FRB) is the principal river of British Columbia (BC), Canada. Rising in the Rocky Mountains and flowing northwest through the Rocky Mountain Trench to Prince George, the Fraser River then turns south and west to Vancouver where it flows into the Strait of Georgia 1,370 km from its headwaters and draining an area of 230,000 km^2. The river contains the chief spawning grounds in North America for the Pacific salmon and logging is important along the upper course. The Fraser delta, the most fertile agricultural region of BC, contains the largest concentration of people in Western Canada.

The FRB lies between the Coast and Rocky Mountain ranges. As a result, the basin valley is quite dry with an average annual precipitation between 300 and 500 mm. The upper reaches of the basin, in the Rocky Mountains, are by far the wettest, averaging 1,500 mm of precipitation annually. Average January temperatures vary from −15°C in the northern, mountainous regions to 0°C at the mouth. In June, temperatures range from 20°C in the interior to 10°C in the high mountains. The FRB is heavily forested, with coniferous forests dominating the Western regions, and mixed forests in the Eastern regions. There is also significant agriculture along FRB's main channel. The upper reaches of the Nechako River is regulated by Kennedy Dam, affecting 6.7% of the river basin area and 2.6% of the FRB's mean annual flow. Surficial soils are dominated by glacial till deposits in the interior plateau and alpine rock outcrops along the eastern and western boundaries of the basin. The region surrounding the confluence of the Nechako and Fraser Rivers is dominated by fine grained glaciolacustine deposits (Fulton 1995).

3 Research methodology

The Interactions between the Soil–Biosphere–Atmosphere (ISBA) model of Meteo France (Noilhan and Planton 1989) modified by Kerkhoven and Gan (2006) for the hydroclimatic conditions of western Canada (known as MISBA) was used to simulate the hydrology of the ARB and FRB. MISBA was forced by climate scenarios projected by selected general circulation models (GCM) described below and downscaled to the regional scale to simulate the future water supply under the impact of climate change. From the results, the projected impact of climate change were assessed using statistics such as annual flow means and variances, seasonal flow means and variances, peak flows, low flows, goodness-of-fit statistics, flow duration curves, and frequency analysis.

The meteorological datasets used were Meteorological Survey of Canada's Global Environmental Multiscale Model (GEM) forecast archive, and ERA-40 historical reanalysis data developed by the European Centre for Mid-range Weather Forecasts (ECMWF). All land use data was derived from the Ecoclimap dataset (Masson et al. 2003). Basin characteristics, such as areal extent and the drainage network, were derived from the 6 arc-second (approximately 200-m resolution) Digital Elevation Model (DEM) of the Peace-Athabasca River basin and the 3 arc-second (approximately 100 m) Shuttle Radar Topography Mission (SRTM) DEM.

Attempts to quantify hydrologic sensitivities (or uncertainties) in the ARB and FRB and their tributaries under the potential impact of climate change can be very challenging because the consequences are decades away, associated uncertainties are many and are often unpredictable, and GCMs are a simplified version of nature with a coarse spatial resolution, and so are prone to errors at regional scales. The simulated runoffs are subjected to possible errors caused by uncertainties in the model structure of MISBA, which is also a simplified version of nature, hydrologic and topographic data errors, and most importantly, uncertainties associated with projected future emission/climate scenarios. As a means to assess uncertainties to model results, and to obtain a sense of realistic possible changes induced by climatic warming in the hydrologic signals of the ARB and FRB, projections of climate change of seven major GCMs (Japan's CCSRNIES, Canada's CGCM2, Australia's CSIROMk2b, Germany's ECHAM4, the USA's GFDLR30, the UK's HadCM3, and the USA's NCARPCM) driven under four SRES climate scenarios (A1FI, A2, B1, and B2) over three 30-year time periods (2010–2039, 2040–2069, 2070–2099) were used in this study.

Given the relatively coarse resolution of the ERA-40 reanalysis data ($2.5^\circ \times 2.5^\circ$), the data were adjusted with respect to the higher resolution GEM forecast archive ($0.329^\circ \times 0.500^\circ$) using a simple statistical approach. The ECMWF and GEM data sets overlap each other from September 1995 to August 2001. For this period, the differences in monthly temperature, humidity, pressure, wind speed, precipitation, and radiation values between each ECMWF point and its surrounding GEM points were calculated. These differences were then applied to the entire ECMWF data set.

The basic assumption is that the time series at each ECMWF grid point is representative of the climate of all the areas located within each grid. Incorporating the higher resolution GEM data in this way can correct for biases in latitude and elevation as well as any systematic biases in the ECMWF data. This method is similar to the one used for historical flows in the ARB (Kerkhoven and Gan 2006). However, instead of adjusting the ECMWF data for each GEM point, the ECMWF data is adjusted to match the basin area weighted average of the surrounding GEM points. The final simulations are therefore still run at the 2.5° scale. This is therefore an assimilation scheme rather than a downscaling scheme. This approach was taken in order to reduce the time required to conduct all 54 simulations in each river basin while incorporating most of the additional information that the GEM archive provides: mainly temperature and precipitation biases produced by using a single grid point to represent climate conditions over a large area.

The SRES GCM scenarios predict the monthly change in near-surface air temperature and precipitation for three 30-year time periods (2010–2039, 2040–2069, 2070–2100) with respect to a historical 30-year period (1961–1990). These predicted changes were used to adjust the historical ERA-40 data to produce new meteorological datasets for each future time period.

4 Discussion of results

MISBA, driven by ERA40-GEM data, was used to simulate a number of SRES climate scenarios for the Athabasca and Fraser River basins. The predicted changes to mean monthly temperature and precipitation from seven GCM models (CCSRNIES, CGCM2, CSIROMk2b, ECHAM4, GFDLR30, HadCM3, and NCARPCM) for four SRES climate scenarios (A1FI, A21, B11, B21) over the 1961–1990 base period were used to adjust the ERA40-GEM temperature and precipitation over three 30-year time periods: 2010–2039 (early twenty-first century), 2040–2069 (mid twenty-first century), and 2070–2099 (late twenty-first century). Results are available from all seven GCMs for the A2 (fragmented world) and B2 (local sustainability) scenarios, but only the HadCM3 and CCSRNIES models have provided results for the A1FI (fossil fuel intensive) and B1 (global environmental emphasis) scenarios. In total, 18 future climates scenarios were run for each 30-year period (two A1FI predictions, seven A2 predictions, two B1 predictions, and seven B2 predictions) for a total of 54 simulations for each of the two river basins, ARB and FRB.

4.1 Athabasca River basin (*ARB*)

The historic reconstruction of streamflows in the ARB was conducted by Kerkhoven and Gan (2006). In general, the predicted future streamflows were more sensitive to the GCM used than the scenario selected. However, most of the GCMs predict continuing decreases in average, maximum, and minimum flows over the next 100 years. A summary of the GCM predictions for annual temperature and precipitation changes in the ARB is shown in Fig. 1a. The GCMs generally predict an increase in both temperature and precipitation. HadCM3 is the wettest, ECHAM4 is the driest, CCSRNIES is the warmest, and CGCM2's predictions fall in the middle. Changes in predicted runoff are weakly correlated with precipitation changes. However, the

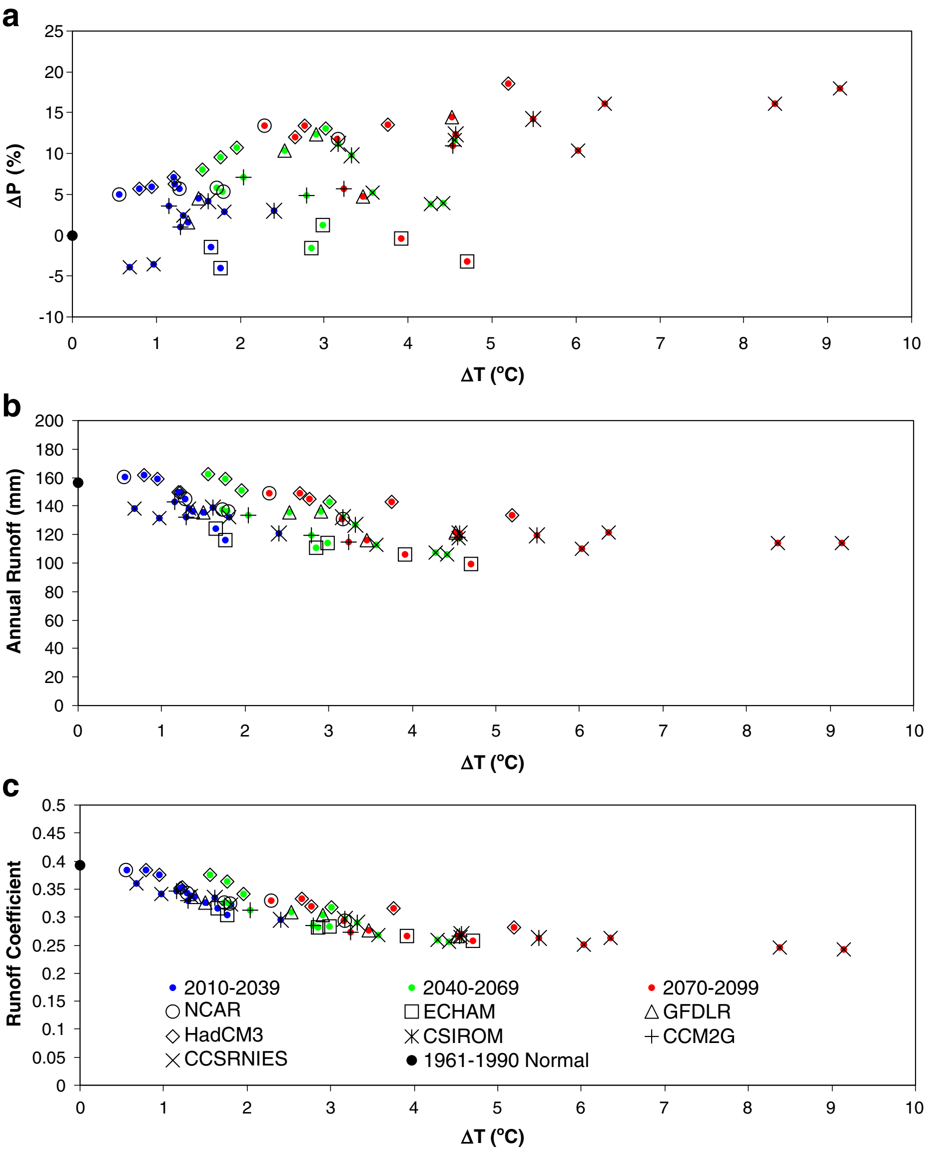

Fig. 1 Changes in **a** annual precipitation (ΔP), **b** annual runoff, and **c** runoff coefficient against changes in annual temperature (ΔT) in the Athabasca River Basin predicted by SRES climate scenarios

MISBA model predicts that all these GCM scenarios lead to decreased streamflow by the end of the twenty-first century, and two-thirds of the scenarios predict stream flows to decline by over 20% (Fig. 1b). Even though the precipitation is mostly projected to increase (Fig. 1a), the runoff coefficient seems to be strongly correlated with changes in temperature such that for every degree of temperature rise, the runoff coefficient drops by about 8% (Fig. 1c). In other words, the hydrologic response of ARB is more sensitive to the projected temperature changes than to the projected precipitation changes.

As can be seen in Fig. 2, where the four enveloping curves indicate the three time periods of the 2020s, the 2050s, and the 2080s and the predictions of the wettest GCM in the ARB (HadCM3), the mean annual snowpack in the basin is strongly correlated with mean annual flow. With the exception of the HadCM3 GCM (which is by far the wettest in December and January) the scenarios predict a strong decrease in the snow pack over the twenty-first century resulting in less water available for spring snowmelt runoff. This reduction in snow pack is primarily due to increases in winter temperatures that result in less snow accumulation and increased evaporation loss, which could offset a projected increase in precipitation. The correlation between winter precipitation (December–January) and maximum snow pack ($R = +0.345$) is much lower than the correlation between winter temperature (December–January) and maximum snow pack ($R = -0.800$). This behaviour is consistent with the findings of paleo-climatologic research in the Peyto Glacier basin on the western slopes of the Alberta Rocky Mountains (Demuth and Keller 2006; Luckman 2006) where the extent of the glacier was found to be much more sensitive to declines in winter snowfall than increases in temperature.

Figure 3a shows the mean daily stream flow predictions for the 1961–1990 baseline and the A2 scenario from three GCMs for the last 30 years of the twenty-first century. The baseline hydrograph exhibits two distinct peaks. The first is associated with snowmelt freshets in the lowlands and the second is associated with snowmelt in

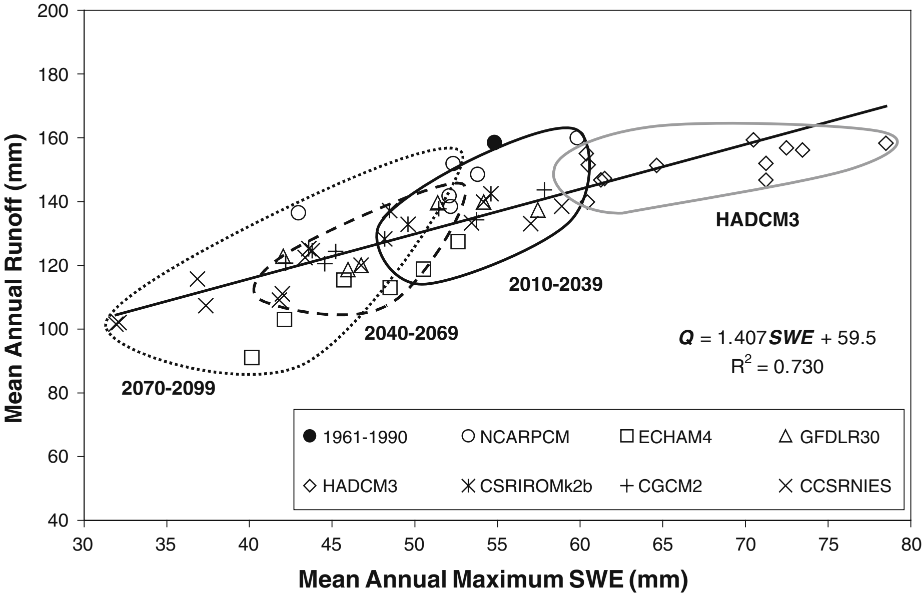

Fig. 2 Mean annual runoff verses mean annual maximum Snow Water Equivalent (*SWE*) in the Athabasca River Basin

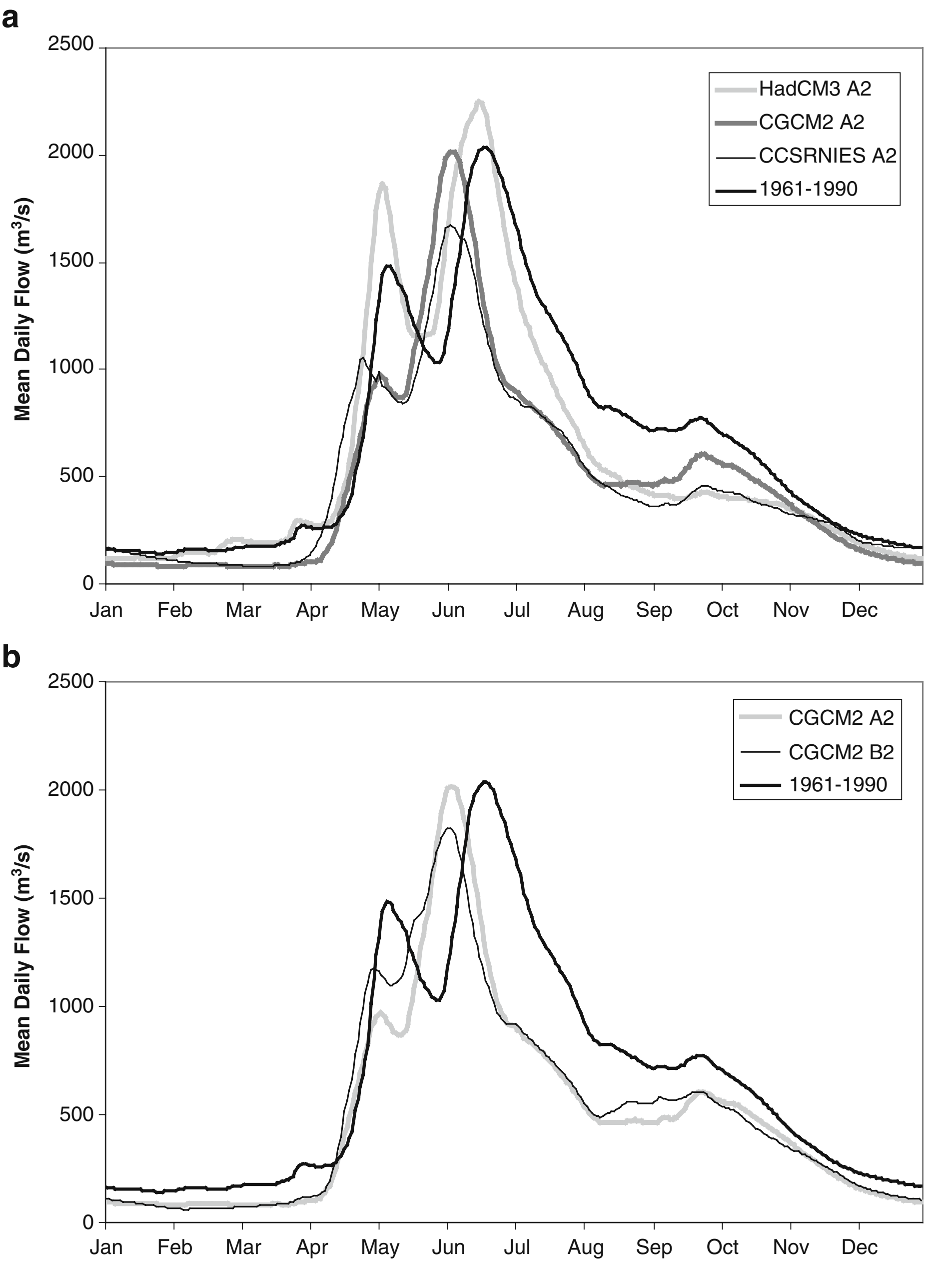

Fig. 3 Mean daily flow rates for 2070–2099 for **a** A2 Climate Scenarios and **b** CGCM2 climate scenarios and historical flow rates for the 1961–1990 climate normal in the Athabasca River Basin

the mountainous southwest. The GCMs tend to predict snowmelt freshets to occur approximately 10 to 15 days earlier than during the historical baseline, and with the exception of the wet HadCM3 model, the amplitude of the lowlands freshet decreases significantly. All the GCMs predict significant declines in flows from June through November, and most predict significant declines in flows in February and March.

Given that among the GCMs' results, CGCM2's are representative of a median simulation for ARB, the mean daily streamflow for the CGCM2 scenarios were examined (Fig. 3b). Both scenarios depict very similar patterns with streamflows becoming progressively smaller as the century progresses. The lowland snowmelt event becomes weaker and the mountain snowmelt comes earlier until the two-peak behaviour disappears. These results are representative of the general tendency of streamflows to vary more between different GCMs within the same emissions scenario than between different emission scenarios from the same GCM, which likely implies that uncertainties associated with climate scenarios are more related to GCMs than the assumed emissions.

In both cases, mean annual flows are predicted to decrease by almost 25% by the last third of the twenty-first century. The high flow season also becomes much shorter. Historically, in an average year ARB stream flows could be expected to stay over 1,000 m^3 s^{-1} for nearly 5 months from late April until mid-August. For both climate scenarios, CGCM2 predicts a high flow season that lasts less than 2 months from early May to mid-June.

In terms of mean annual flow by the end of the twenty-first century, the ECHAM4 A2 scenario predicted the largest decrease at −36.6%, while HadCM4 and NCAR

Table 1 Changes in flow statistics for Athabasca and Fraser River Basins from 2070–2099 with respect to the 1961–1990 climate normal under 18 combinations of GCM model and SRES emission scenarios

Model	SRES scenario	% Change in					
		Athabasca river basin (ARB)			Fraser river basin (FRB)		
		Mean annual flow	Maximum annual flow	Minimum annual flow	Mean annual flow	Maximum annual flow	Minimum annual flow
NCARPCM	A2	−16.4	−11.7	−33.6	−7.3	−35.2	−5.6
	B2	−5.0	10.0	−17.6	0.8	−24.4	−3.5
ECHAM4	A2	−36.6	−12.4	−57.5	−2.1	−24.5	−35.3
	B2	−32.5	−10.4	−56.9	1.6	−18.7	−20.9
GFDLR30	A2	−22.3	−6.4	−53.6	−0.2	−37.5	−14.3
	B2	−26.1	−4.5	−47.5	1.0	−26.6	−7.1
HadCM3	A1FI	−14.7	1.3	−36.2	9.6	−19.4	−36.1
	A2	−8.9	8.1	−25.8	3.2	−16.1	−29.7
	B1	−7.6	4.8	−22.9	7.7	−18.5	−14.5
	B2	−5.0	10.5	−18.3	−1.2	−23.5	−24.8
CSIROMk2b	A2	−23.7	−5.9	−50.9	4.9	−36.0	−10.3
	B2	−22.8	−3.1	−50.2	−0.7	−36.2	−7.0
CGCM2	A2	−24.8	−6.1	−45.6	−7.2	−36.5	−18.2
	B2	−26.6	−8.5	−47.7	−8.8	−32.8	−12.8
CCSRNIES	A1FI	−27.0	−10.3	−34.0	−1.6	−33.9	−22.6
	A2	−27.3	−7.7	−36.8	0.9	−33.9	−20.5
	B1	−29.5	−17.9	−50.6	−5.8	−34.2	−14.9
	B2	−22.0	−9.8	−52.8	−2.9	−36.2	−4.6
Mean		−21.1	−4.4	−41.0	−0.5	−29.1	−16.8
Median		−23.3	−6.3	−46.6	−0.5	−33.4	−14.7

B2 predicted the smallest decrease at −5.0% (Table 1). As expected (Fig. 1a), the average change in annual flow by 2070–2099 was −21.1%. The HadCM3 and NCARPCM consistently predicted the highest flow rates, while the ECHAM4 predicted the lowest. In terms of mean annual maximum flow, the CCSRNIES B2 scenario predicted the largest decrease at −17.9%, while HadCM4 B21 predicted the largest increase at +10.5%. The average change in annual maximum flow by 2070–2099 was −4.4%. In terms of mean annual minimum flow, the climate scenarios usually predicted changes ranging from −7.6 to −57.5%, with an average predicted change of −41.0%.

Under the terms of the Lower Athabasca Management Plan (Alberta Environment 2007), which is scheduled to be updated by 2011, cumulative consumptive water withdrawals from the Athabasca River below Fort McMurray are limited to 8 m^3 s^{-1} when winter flows fall below the historic 95% exceedence flow, which ranges between 100 m^3 s^{-1} and 110 m^3 s^{-1} from December to February. Active, approved, and proposed water licenses along this reach of the Athabasca total 6 m^3 s^{-1}, 10 m^3 s^{-1}, and, 14 m^3 s^{-1}, respectively, as of December 2007 (Pat Marriott, Alberta Environment, personal communication, 2007). The SRES climate scenarios suggest that the mean minimum annual flow will drop from the current 138 m^3 s^{-1} to averages of 111 m^3 s^{-1}, 90 m^3 s^{-1}, and 81 m^3 s^{-1} by the 2020s, 2050s, and 2080s, respectively. Industrial operations in the Lower Athabasca, which typically expect to continue operations for the next 25 to 50 years, could therefore face water shortages far more often than once every 20 years for much of their future operational lifespan. Given that most of these operations do not currently include accommodations for significant water storage, the newer operations with their lower licence priority under Alberta water law could suffer extended slowdowns far more often than an analysis of historic flows would suggest, although this risk is currently partially mitigated by annual water sharing agreements between the major industrial users of water.

4.2 Fraser River basin (*FRB*)

As a first step, the ERA-40 re-analysis data was used to simulate historical river flows at the Fraser River at Hope gauging station from 1 September 1957 to 31 August 2001. Initial results showed that the low resolution of the ERA-40 data is highly problematic for the mountainous Fraser basin. Precipitation on the windward side of the Rocky Mountains is much higher than that on the leeward side. However, the ERA-40 data set cannot distinguish these differences. Precipitation is consistently overestimated when the nearest ERA-40 point is on the windward side and underestimated when it is on the leeward side. In the case of the preliminary simulations, the western part of the basin was subjected to coastal precipitation patterns. This resulted in runoff patterns that did not match those observed in the basin. Figure 4a is a typical example of the observed and simulated hydrographs. The two hydrographs fit poorly ($R^2 = 0.001$).

Next, the assimilation scheme used for the ARB was applied to produce a new meteorological data set (ERA40-GEM) to simulate stream flows of the Fraser River at Hope, BC from September 1957 to August 2001. Figure 4b shows a typical example of the observed and simulated daily hydrographs. The incorporation of the GEM data significantly improves the results ($R^2 = 0.40$ versus 0.001 before the adjustment). The most notable improvement is the reduction on the size of the

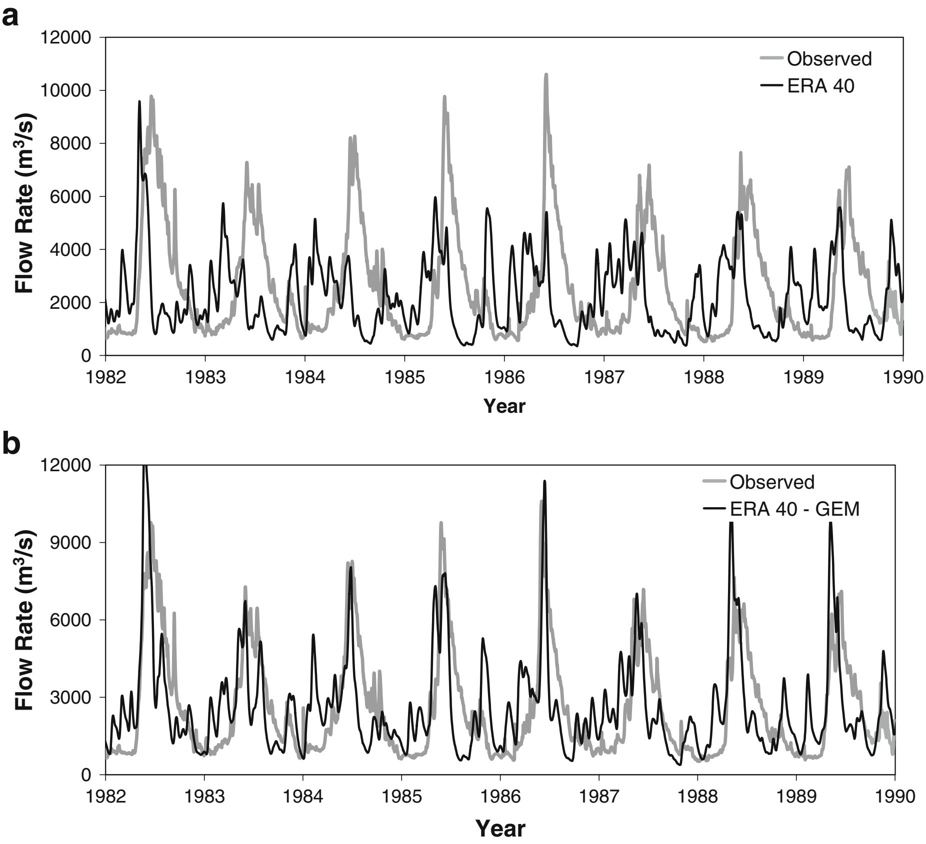

Fig. 4 Observed and simulated hydrographs for Fraser River at Hope, **a** ERA40 simulation and **b** ERA40-GEM simulation

anomalous winter runoff events and much better simulation of the spring runoff peaks. Some of the error can be attributed to FRB being a regulated river basin and the methodology described here cannot account for the regulated effects of man on FRB and the Nechako Rivers.

Figure 5 shows the observed ERA40-GEM simulated mean annual flow, minimum annual flow, and maximum annual flow frequency plots for the Fraser River at Hope. The simulations reproduce the annual variation in mean flow very well and, to a lesser extent, the minimum annual flow except for the flows of high return periods. With the exception of three excessive peak flows in 1967, 1971 and 1974 the annual maximum flow series is also well reproduced. The simulations also tend to improve in later years when better data became available to construct the ERA40 data set.

Figure 6 shows the observed and the ERA40-GEM simulated 365 day moving average flow rate of the Fraser River at Hope. The early significant discrepancy before 1964 can be attributed to a combination of model spin up, particularly the time required to build up snow packs in the mountains, and systematic biases in the ERA40 data set. After 1964, the simulation reproduces the annual variations in stream flow very well for the wet and dry periods both in terms of timing and

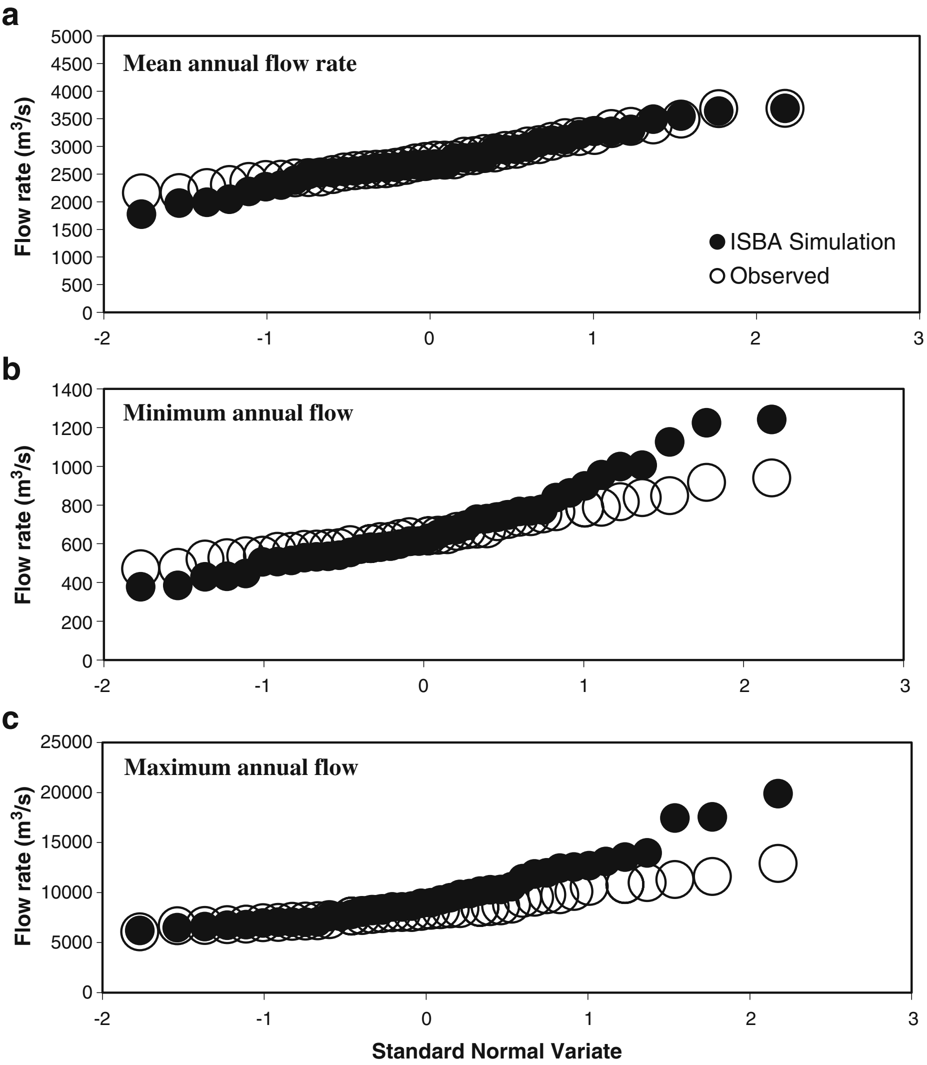

Fig. 5 Observed and ERA40-GEM simulated frequency plots for the Fraser River at Hope, **a** mean annual flow rate, **b** minimum annual flow rate, and **c** maximum annual flow rate

severity ($R^2 = 0.80$, after 1964). This demonstrates that MISBA can reproduce the large-scale behaviour of the FRB.

Although these historical simulations are not as accurate as for the ARB (see Section 4.1), Figs. 5 and 6 shows they are of sufficient accuracy to produce meaningful results from the SRES climate scenarios. Figure 7a is a plot of the predicted changes in annual precipitation and temperature in the FRB based on the results from the GCM scenarios. On average, the scenarios predict average temperature increases of 4.0°C and precipitation increases of 8.4% in the FRB over the next 100 years. All the GCMs predict increasing temperatures and precipitation in the basin throughout

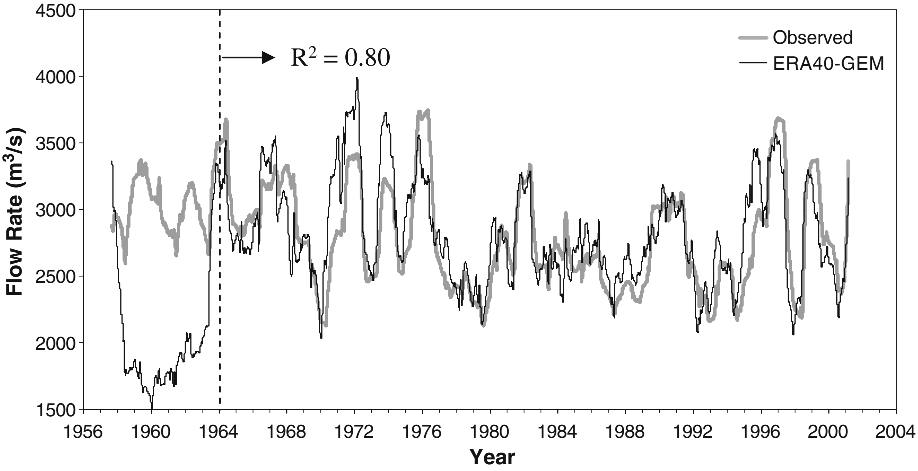

Fig. 6 Observed and ERA40-GEM 365-day moving average flow rates for the Fraser River at Hope

the next century; however the magnitude of these increases varies widely between models. Generally, for the A2 and B2 scenarios, CCSRNIES predicts the largest temperature increases (+5 to +7°C) and NCARPCM the smallest temperature increases (+2.2 to 3.2°C) by the end of the twenty-first century. CCSRNIES, CSIROMk2b, and GFDLR30 consistently predicted the largest increase in the precipitation of the FRB (+9 to 14% by the end of the century) and CGCM2 the least increase (+0.5 to 3.5% by the end of the century).

The seasonal variations in these changes also vary widely between models. For the A2 scenarios, the NCARPCM, CCSRNIES, and CSIROMk2b models predict the bulk of the warming to occur in the winter months (November to February); the CGCM2 model predicts most of the warming to occur in the spring (March to May); and the HadCM3 and ECHAM4 models predict most of the warming to occur in the summer (July to September). Only the GFDLR30 model predicts warming to occur relatively evenly over the year. Most of the models predict that the largest increases in precipitation will occur in the winter months with moderate decreases occurring in the summer.

These scenarios generally predict small to moderate changes in mean annual flow in the FRB by the end of the twenty-first century, with all 18 scenarios predicting changes within ±10% of the historical mean annual flow, with an average change in annual flow of –0.5%. As the wettest GCM, HadCM3 A1FI and B1 scenarios produced the largest increases (+9.6% and +7.7%, respectively) while only CGCM2 consistently predicted decreased annual flow rates (–7.2% for A2 and –8.8% for B2). The other models tended to predict small positive or negative changes. All 18 scenarios, however, predicted declines in the mean annual maximum and minimum flow rates, with maximum flows declining by an average of 29% and minimum flows declining by an average of 17%.

Figure 7b shows the predicted mean annual flow rate and annual precipitation. As was the case in the ARB, changes in annual flow under climate change scenarios are weakly correlated with changes in precipitation. Figure 7b also shows the enveloping curves for each 30-year simulation. The increased spread is a reflection

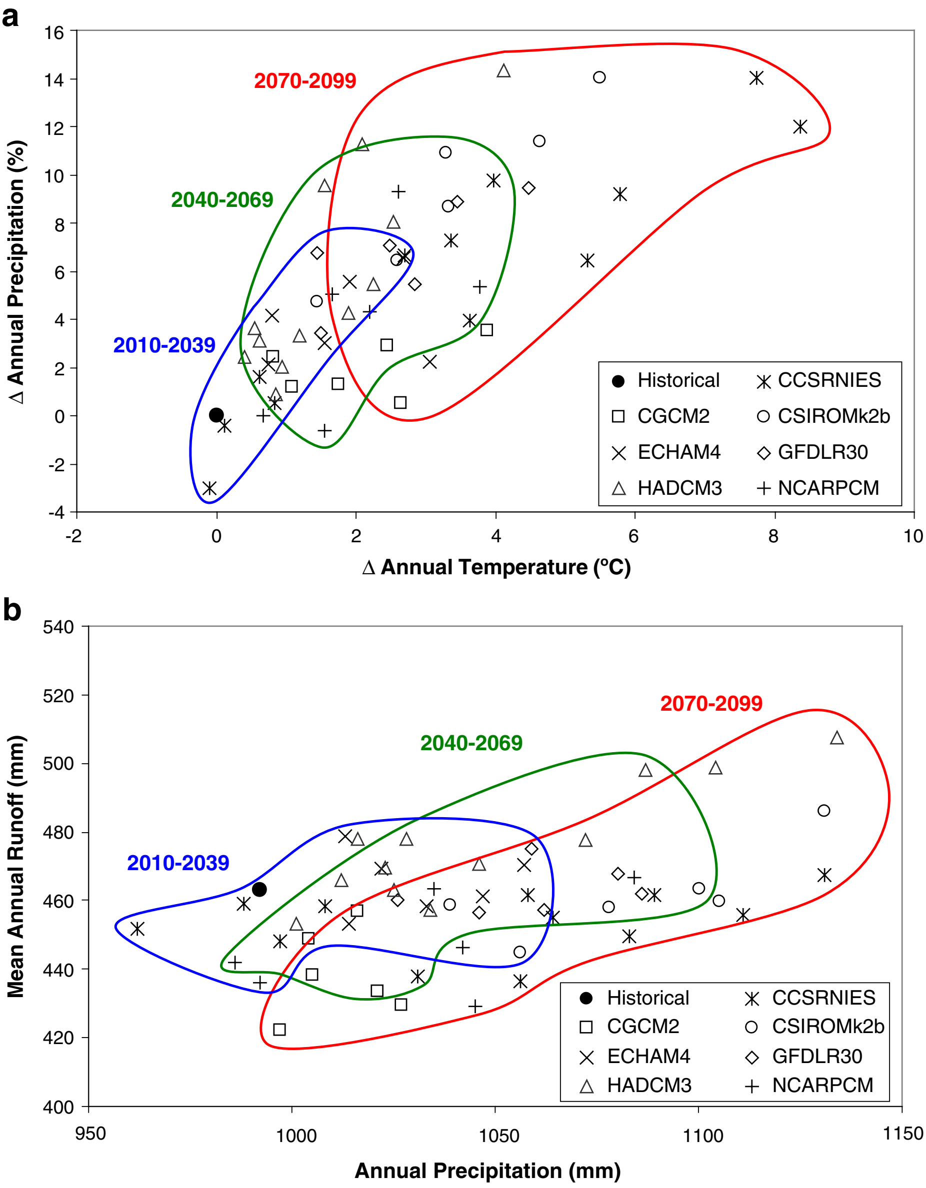

Fig. 7 Projected **a** temperature and precipitation changes and **b** mean annual runoff changes relative to the historical 1961 to 1990 baseline in the Fraser River Basin according to 18 SRES climate scenarios. The *blue*, *green*, and *red curves* envelope the 2010–2039, 2040–2069, and 2070–2099 simulations respectively

of increasing differences between the individual GCMs and the different climate scenarios; however, inter-GCM variation appears to dominate. Overall, the projected annual precipitation tends to increase with time even though the spread between GCMs also increases with time. However, changes to the mean annual runoff are relatively modest compared to precipitation, and as a whole, the predicted mean annual flow marginally decreases with time mainly because the projected increase in evaporation loss due to a much warmer projected climate marginally offsets the projected increase in precipitation.

Figure 8 is a plot of the mean monthly flow rates in the FRB for 2070 to 2099 predicted by the seven GCMs for the four SRES climate scenarios. All the scenarios show a similar earlier onset of spring snowmelt in the annual flow pattern, differing primarily in the magnitude of the shift, and a decrease in peak flows during spring and early summer. Mean monthly flows increase during the winter and early-spring months (November to April) and decrease from the late-spring to the fall (May to October). HadCM3 is the only model to predict relatively minor changes in seasonal flow patterns.

Figure 9a shows that all climate scenarios predict a decrease in the mean annual maximum snow pack in the FRB with temperature increases over the century. The smallest decreases are predicted by HadCM3, which is one of the cooler GCMs but it still shows summer warming. For the other GCM scenarios, the general tendency towards warmer winters more than offsets increases in winter precipitation, resulting in an overall decreased snowpack.

Figure 9b shows large decreases in the mean annual maximum snow pack with increasing winter (November to March) temperature, which offsets the predicted increases in winter precipitation. For example, three scenarios predicted the mean winter temperature to rise above 0°C by the end of the century from the historical −5.6°C, resulting in a large shift away from winter snowfall to rainfall, causing MISBA to predict higher than historical flows during winter months at the expense of lower flows during spring and summer months.

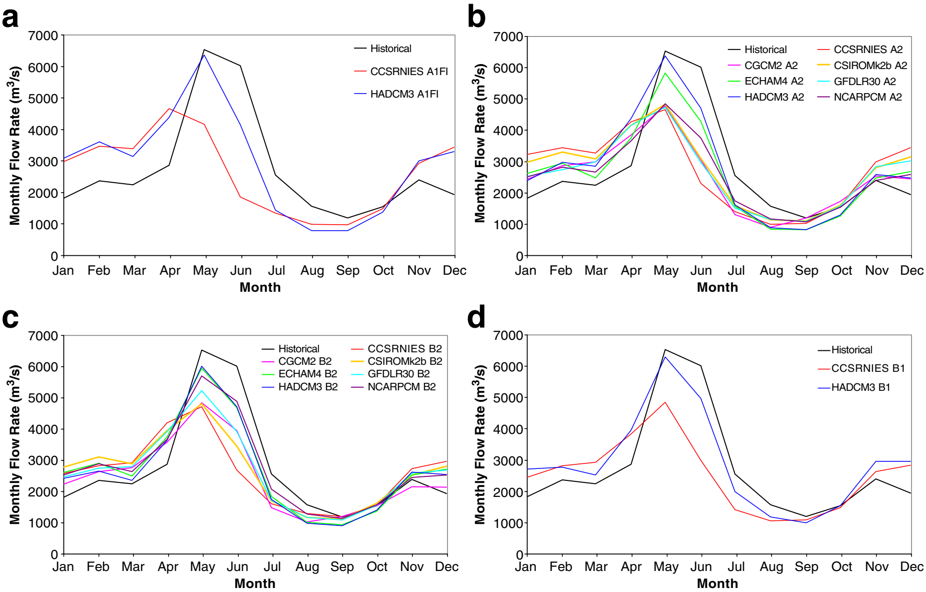

Fig. 8 Mean monthly flows in the Fraser River at Hope for the 1961–1990 (historical) and various climate scenarios: **a** A1FI, **b** A2, **c** B2, and **d** B1 for 2070–2099

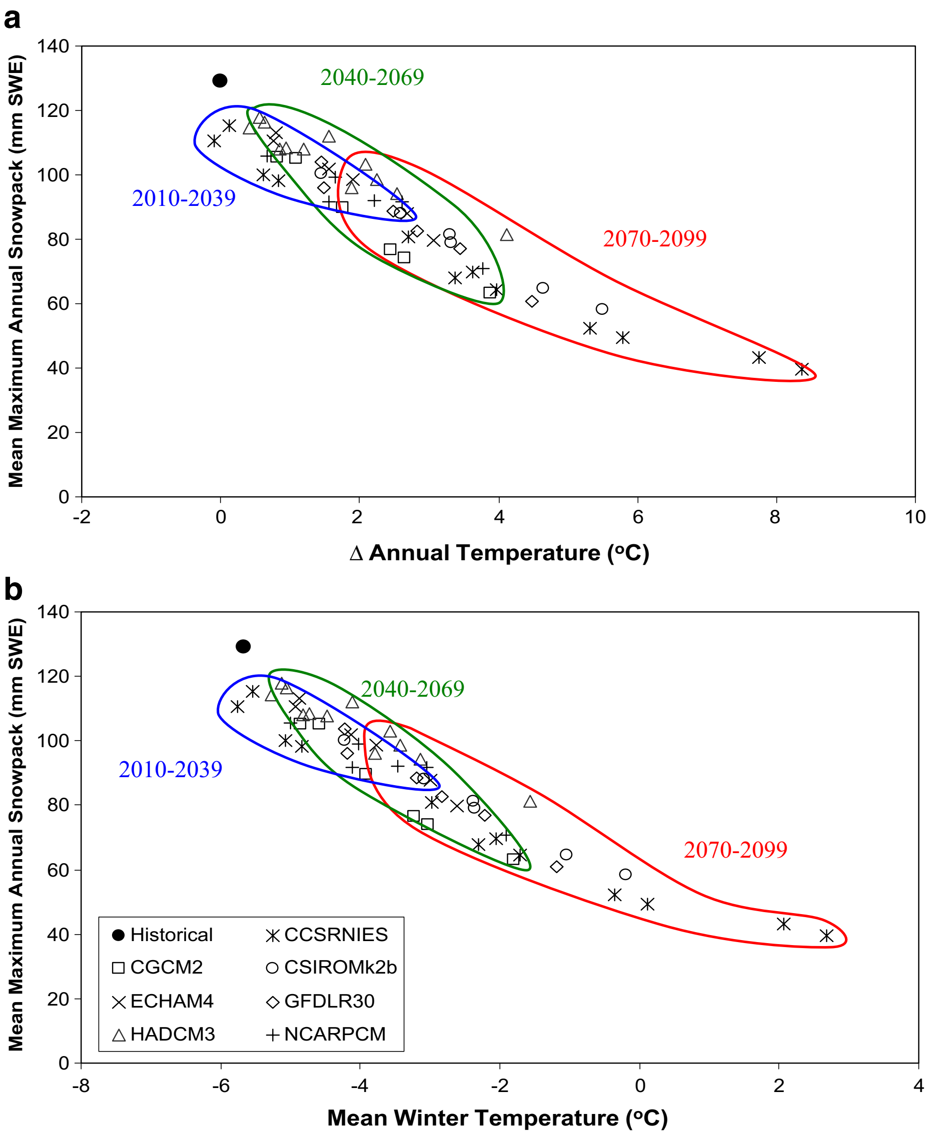

Fig. 9 Mean annual maximum snow pack in the Fraser River Basin versus **a** change in mean annual temperature and **b** mean winter temperature. The *blue*, *green*, and *red curves* envelope the 2010–2039, 2040–2069 and 2070–2099 simulations respectively

Figure 10a shows a general decline in the mean annual maximum flow rate in the FRB with a decreasing mean annual maximum snow pack. However, this decline in the mean annual maximum flow could stop, as can be seen in the CCSRNIES case in the 2080s, which exhibits mean snow packs less than 60 mm of Snow Water Equivalent (SWE). In these cases, the amplitude of the spring freshet declines

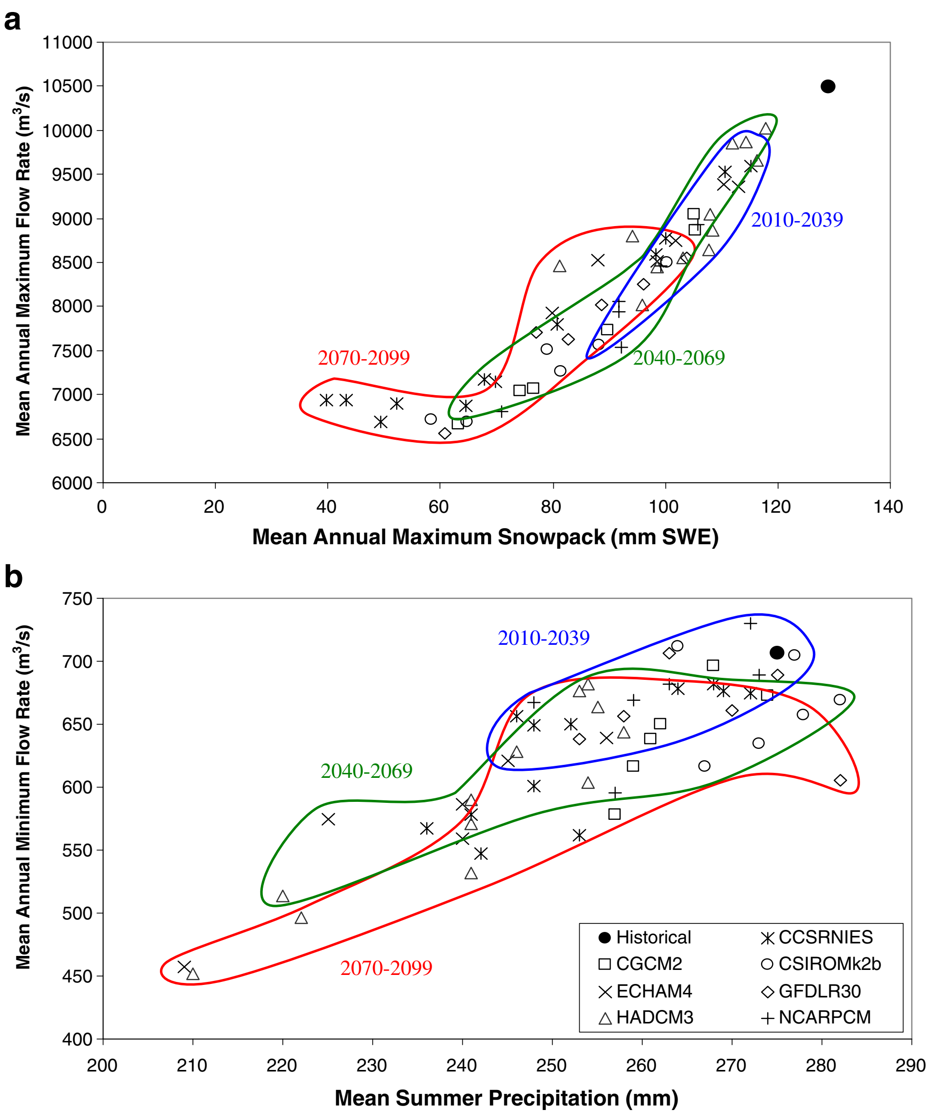

Fig. 10 **a** Mean annual maximum flow versus and mean annual snow pack and **b** mean annual minimum flow rate versus mean summer precipitation in the Fraser River Basin. The *blue*, *green*, and *red curves* envelope the 2010–2039, 2040–2069 and 2070–2099 simulations respectively

significantly because of a combination of increased winter flows and decreased late spring (May and June) flows (Fig. 8).

Simulated annual minimum flows in the FRB show strong correlation with summer precipitation, and both tend to decline for all 18 scenarios (Fig. 10b) by the end of the century. However, differences in the predicted extent of this decline vary widely, ranging from as little as −3.5% (NCARPCM B2) to as much as −36.1% (HadCM3 A1FI).

4.3 Generalized equations between runoff, precipitation and temperature

For the ARB and FRB, generalized equations relating mean annual runoff and mean annual minimum and maximum flows to mean annual rainfall, mean annual snowfall and changes to mean annual winter and summer temperature were developed using a variation of the Shuffled Complex Evolution algorithm (Nelder and Mead 1964; Duan et al. 1992, 1993) (see Figs. 11 and 12). The optimized relationships for the ARB are,

$$Q_{mean,ARB} = 0.276 P_{rain} \exp(-0.00612 \Delta T_s) + 0.604 P_{snow} \exp(-0.165 \Delta T_w) \tag{1}$$

$$Q_{\min,ARB} = 0.186 P_{rain} \exp(-0.00181 \Delta T_s) + 0.654 P_{snow} \exp(-0.304 \Delta T_w) \tag{2}$$

$$Q_{\max,ARB} = 4.25 P_{rain} \exp(0.0396 \Delta T_s) + 12.4 P_{snow} \exp(-0.0719 \Delta T_w) \tag{3}$$

For the FRB the relationships are,

$$Q_{mean,FRB} = 0.347 P_{rain} \exp\left(-0.0227 \Delta T_s\right) + 0.600 P_{snow} \exp\left(-0.0398 \Delta T_w\right) \tag{4}$$

$$Q_{\min,FRB} = 1.22 P_{rain} \exp(-0.0987 \Delta T_s) + 0.104 P_{snow} \exp(-0.388 \Delta T_w) \tag{5}$$

$$Q_{\max,FRB} = 3.71 P_{rain} \exp(0.0747 \Delta T_s) + 16.8 P_{snow} \exp(-0.130 \Delta T_w) \tag{6}$$

where Q_{mean} is the mean annual runoff in mm, Q_{min} and Q_{max} are the mean annual minimum and maximum flow in m^3/s, P_{rain} and P_{snow} are the mean annual rainfall and snowfall in mm, and ΔT_s and ΔT_w are the changes in mean annual summer and winter temperature from the 1960–1990 baseline in °C, respectively. The correlations between these equations and the modelled results are high (R^2 values range from 0.82 to 0.94). The relatively small fraction of the hydrologic behaviour that cannot be explained by these equations can be attributed to the spatial and seasonal variability of temperature and precipitation patterns across the scenarios.

Many of the coefficients are similar for both basins, except for the coefficients for P_{rain} and P_{snow} for minimum flows. The temperature coefficients in these equations show that flow rates in both basins are more sensitive to changes in winter temperature than changes in summer temperature, suggesting that increased sublimation of the snow pack has a greater impact on the stream flows in both basins than increases in summer evapotranspiration. This can be best explained by the fact that an exposed snow surface can continually sublimate at the potential rate while a surface soil quickly dries out in the absence of sustained rainfall. Changes in winter temperature therefore have much more time to produce large reductions in water storage than changes in summer temperature, as is evident in the larger winter temperature coefficients for minimum than for average and maximum flows. In order for snowfall to contribute to minimum flows, snowmelt must enter the near-surface water table and persist for several months since minimum flows usually occur in months with little or no snowmelt. Since increasing winter temperatures result in

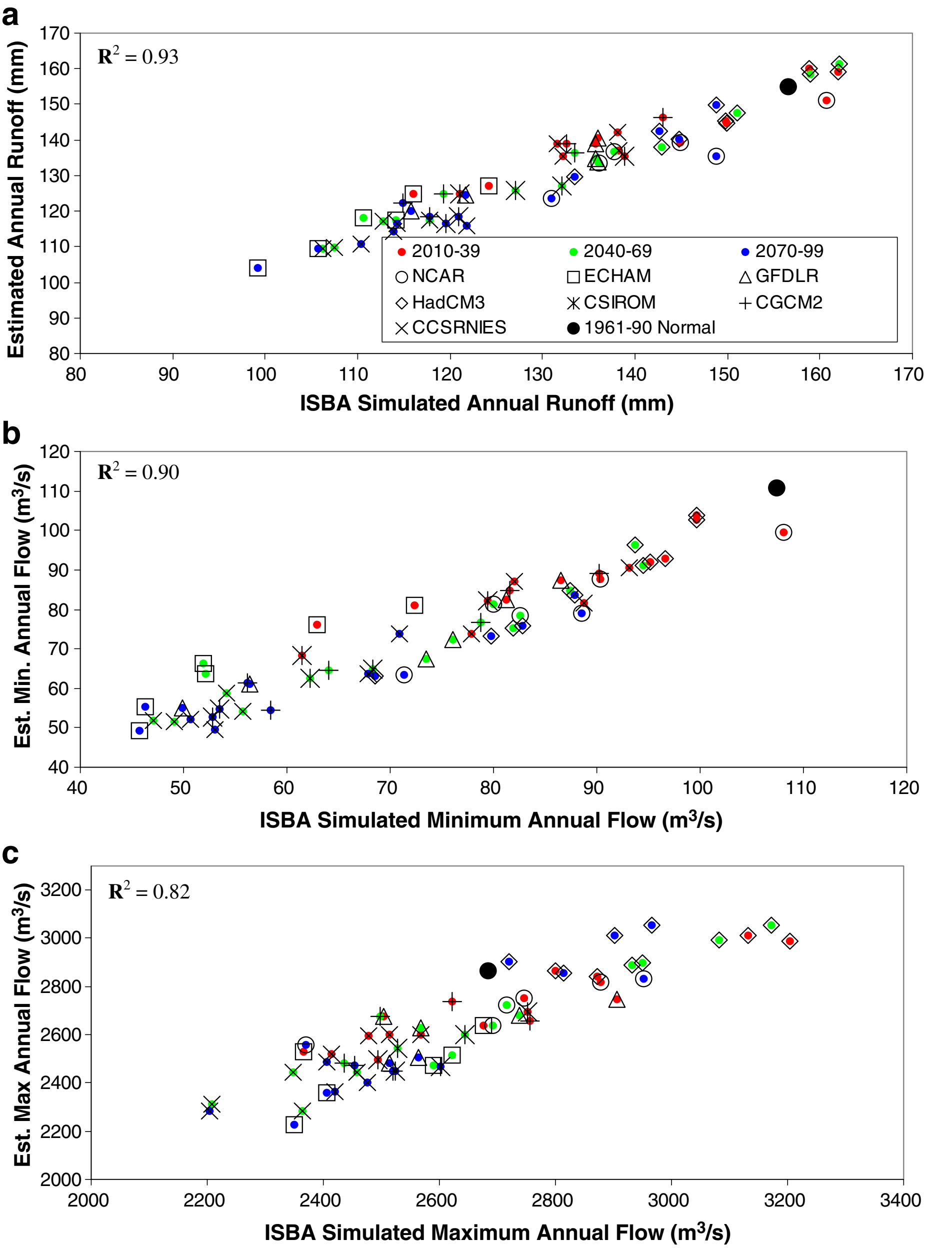

Fig. 11 Generalized relationships in the Athabasca River Basin between mean annual runoff, mean annual minimum flow, and mean annual maximum flow; and precipitation and temperature changes

both smaller snow packs and earlier snowmelt it becomes exceedingly difficult for snowfall to contribute to minimum flows because more time will have elapsed since melting occurred and the initial contribution will be smaller.

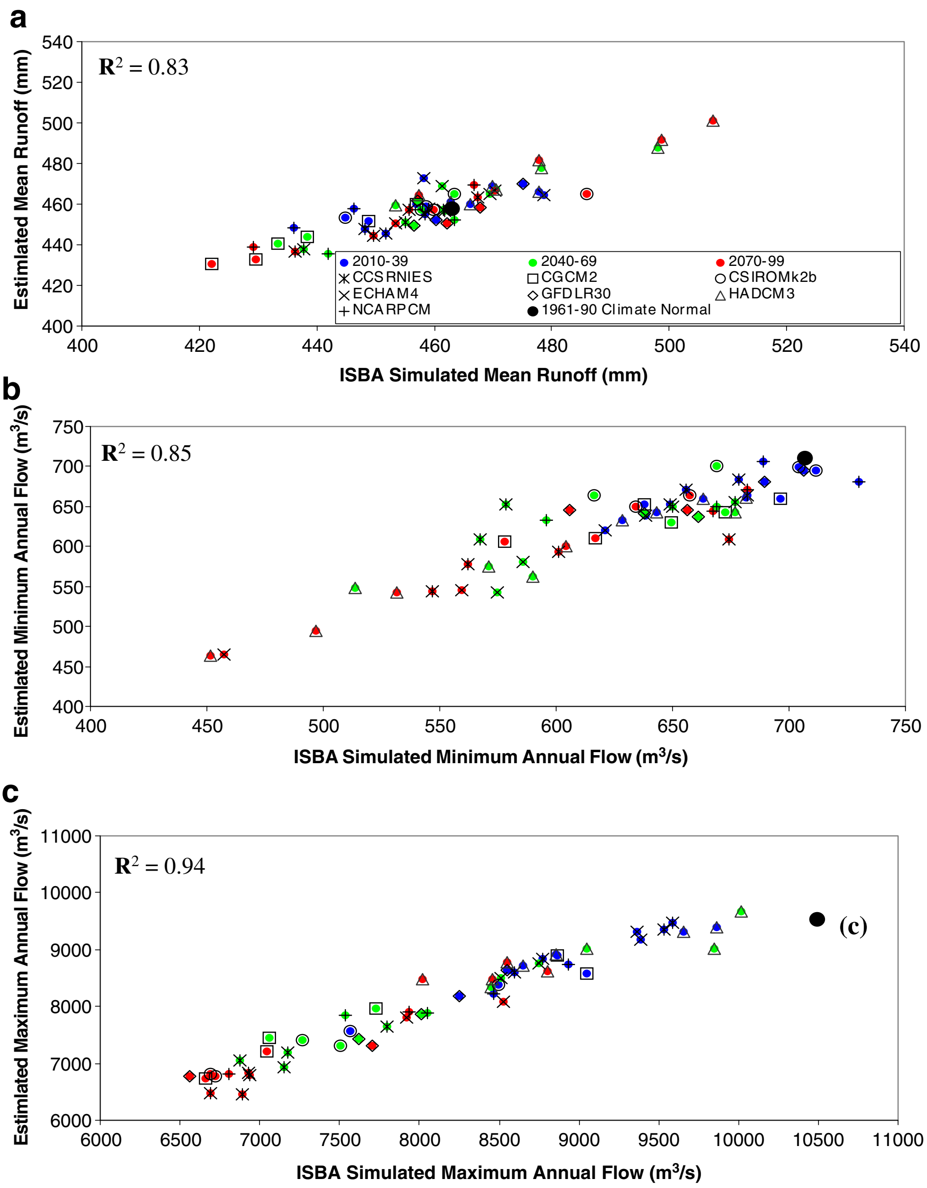

Fig. 12 Generalized relationship in the Fraser River Basin between mean annual runoff, mean annual minimum flow, and mean annual maximum flow; and precipitation and temperature changes

All the temperature coefficients are negative in both basins, except for summer temperature in the maximum flow equations. This reflects the importance of evaporation and sublimation losses for mean and minimum flows, which are sensitive to hydrologic processes at seasonal time scales. In the case of maximum flows, the temperature coefficient is positive because evaporation is generally less under humid conditions and so not as important as the increase in rainfall rates (P_{rain}) associated with increased temperatures.

The rainfall coefficients for mean annual and maximum flows are also similar in both basins. In the case of mean annual flows, under historical climate conditions, approximately 60% of annual snowfall contributes to streamflow, while the rainfall contribution is about 35% in the FRB and 28% in the ARB. Similarly, in both basins the contribution of snowfall to maximum flows is much higher than that of rainfall, although large differences in the temperature coefficients reduce this effect as the climate warms.

Fundamental differences in the hydrologic responses of the FRB and ARB are reflected in differences in the coefficients of these equations. Under historical conditions, precipitation that falls as rain in the ARB is less likely to leave the basin as streamflow compared to the FRB. In the FRB, a unit of rainfall generally produces about 25% more runoff than a unit of rainfall in the ARB because rainfall is more likely to fall on wet soils in the FRB, which is wetter than in the ARB, and so it produces more runoff in an average year. This is especially true in the plains regions of the ARB where summer rains often fall on very dry soils and produce little runoff relative to the precipitation intensity of these events. Annual flow in the ARB is also more sensitive to changes in winter temperatures because snowpacks have more time to sublimate before the melting occurs. Overall, the proportional influence of P_{snow} over P_{rain} for the ARB is higher than for the FRB, especially for the minimum flows (compare Eqs. 2 and 5). Furthermore, as expected, the influence of P_{rain} and P_{snow} in both basins are the strongest for the maximum flows and weakest for the minimum flows.

The two basins differ in their sensitivities to rainfall and snowfall on the minimum flow rates, which reflects the long-term storage of water in the surface water table, since this is the only water source that can consistently supply water to a river during periods with little rainfall, either due to a general lack of precipitation or during cold winter months. In the ARB, minimum flows are mostly supplied by the spring snowmelt, while in the FRB they are more dependent on summer rains. In the absence of rapid river ice freeze-up events, low flows in the ARB usually occur in the late winter, almost a full year after the previous snowmelt. Because this water must persist for such a long period in order to maintain late winter flows, the basin is very sensitive to sublimation losses as much of this water would otherwise recharge the soil making it easier for summer rainfall to maintain soil groundwater storage for the winter. In the wetter FRB, summer rainfall has a much better chance of recharging any moisture deficit that may have occurred due to a low winter snowpack and so summer evaporation is much more important than in the ARB.

5 Summary and conclusions

The potential effects of anthropogenic climatic change on streamflows of two regional river basins in western Canada, Athabasca and Fraser River Basins, were estimated by applying the projections of seven GCMs under four SRES emission scenarios of IPCC over three 30-year periods in the twenty-first century to the ERA-40 re-analysis dataset adjusted with the higher-resolution GEM data. For both basins, the GCMs project average increases in temperature and precipitation of approximately 5°C and 10%, respectively, although the GCM precipitation projections show far more variation in the FRB than in the ARB. Despite this similar change in climate, the simulated streamflow responses in the two basins show different sensitivities to precipitation and temperature change, partly because of the Canadian Rocky Mountain separating the two river basins, giving rise to warmer and more humid climate in the FRB than in the ARB.

In the ARB, mean annual flows are expected to decline as the shortened snowfall season and increased sublimation together lead to a decline in the spring snowpack. Although the wettest scenarios predict mild increases in annual runoff in the first half of the century, all GCM and emission combinations predict large declines by the end of the twenty-first century with an average change in annual runoff, mean maximum annual flow and mean minimum annual flow of −21%, −4.4%, and −41%, respectively.

The climate scenarios in the FRB present a less clear picture of future streamflows in the twenty-first century. All 18 GCM projections suggest mean annual flows in the FRB could change by ±10% with eight projections suggesting increases and 10 projecting decreases in mean annual flow. The primary reason for this contrast with the results for the ARB is the FRB's much milder climate. Under the warmest scenarios, much of the FRB is projected to become warmer than 0°C for most of the calendar year, resulting in a decline in the amplitude of the FRB's characteristic snow fed annual hydrograph response. Given that FRB is also much wetter than ARB, the FRB is not as dependent on winter snowfall because the shift to winter rains happens at a wetter time of year in the FRB and so these rains are more likely to produce runoff than in the ARB. The decline in the amplitude of the snow melt flood wave in the FRB also results in a large decline in the average maximum flow rate as summer rainfall events build upon reduced baseflow because of the shift in winter precipitation.

The impact of climatic change on the mean annual minimum flow in the FRB is much more varied than in the ARB due to FRB's sensitivity to summer rainfall and the relatively high variance between GCMs for the summer rainfall. Apparently there are great disagreements between climate scenarios projected by different GCMs on how global increases in temperature are manifested in regional precipitation changes. For example, HadCM3 predicts dramatic increases in precipitation under the A2 emissions scenario in the Arctic regions of North America and large decreases in Central America and northern South America, while CGCM2 predicts much milder changes in these regions (Fig. 13). CGCM2 also predicts wetter conditions along the Pacific Coast of the United States and drier conditions along the Atlantic Coast, while HADCM3 predicts the opposite.

Overall, the generalized equations relating annual mean, minimum and maximum flows to changes in rainfall, snowfall, winter temperature and summer temperature show that flow rates in both basins are more sensitive to changes in winter temperature than summer temperature (partly due to the greater impact of increased sublimation of the snowpack than increased summer evaporation from the soil) and that the contribution of snowfall to maximum flows is much higher than the contribution of rainfall.

Our study shows that differences in the projected predictions of future temperature and precipitation of different GCMs at regional spatial scales are likely the most important factor limiting the application of GCM model output to future water

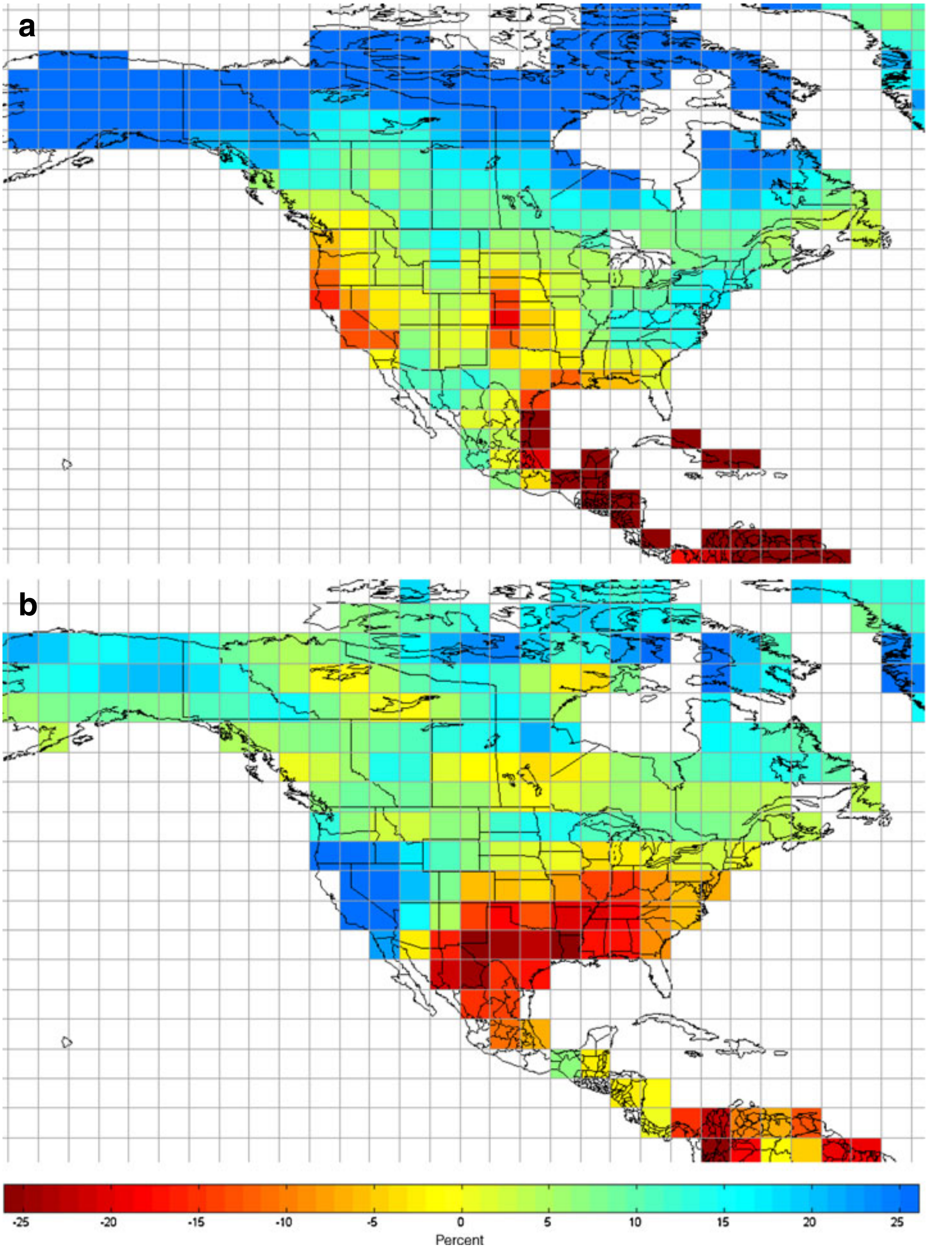

Fig. 13 Projected changes in annual precipitation over North America for 2070–2099 with reference to the 1961–1990 climate normal according to the **a** HadCM3 A2 and **b** CGCM2 A2 scenarios (Taken from Canadian Climate Impacts and Scenarios (CCIS) Project)

management and planning under the potential impact of climate change. However, even though many key hydroclimatic variables show much variation between different GCMs by the end of the twenty-first century, the models consistently predict similar seasonal changes in flow patterns, due primarily to temperature induced phase shifts from snow to rain. These changes include the earlier onset of snowmelt, a decline in the amplitude of the snowmelt flood wave, a reduction in flow during summer months, and declines in flows during low flow months.

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