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PROJECTING CANADIAN PRAIRIE RUNOFF FOR 2041–2070 WITH NORTH AMERICAN REGIONAL CLIMATE CHANGE ASSESSMENT PROGRAM (NARCCAP) DATA[1]

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ABSTRACT: The South Saskatchewan River Basin (SSRB) of Alberta, Canada, is semiarid and under severe water stress due to increasing human demands. We present the first examination of projected changes in SSRB runoff from a large set of North American Regional Climate Change Assessment Program regional climate models (RCMs) plus one Coordinated Regional Climate Downscaling Experiment RCM. We used six different runoff estimation methods: total surface and subsurface runoff (total runoff), surface runoff, and four estimations based on Budyko functions. Most RCM estimations showed substantial biases and distribution differences when compared to observed data; thus bias correction was necessary. Total runoff was the best of the six variables in modeling observed runoff for each of the four SSRB subbasins. Projected total runoff for 2041–2070 shows a geographic gradient in the SSRB, with possible drying in the southern Oldman River subbasin and possible increased runoff in the northernmost Red Deer River subbasin. A shift to an earlier spring peak in runoff and drier late summer, with a need for increased irrigation, should be expected. In a first examination of the important question of projected changes in interannual variability, we show increasing magnitude. This result further adds to adaptation challenges over the course of this century in this basin, which is already largely closed to further allocation.

(KEY TERMS: aridity index; climate change; Coordinated Regional Climate Downscaling Experiment (CORDEX); North American Regional Climate Change Assessment Program (NARCCAP); runoff; South Saskatchewan River Basin.)

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INTRODUCTION

While the economy of Alberta, Canada, is powered by hydrocarbons, it vitally depends on water that is derived mostly from the Rocky Mountain snowpack (Schindler and Donahue 2006). The sustainable use of Alberta's freshwater supplies and its economic life rely upon a solid understanding of climatic and hydrologic variability and the province's ability to adapt to climate change. Alberta faces major freshwater challenges caused by a growing population, typically accelerating economic growth, and a changing climate. Nowhere in Canada are these issues more insistent than in the South Saskatchewan River Basin (SSRB), in southern Alberta (Figure 1). Water

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supplies in the SSRB are under serious pressure, with three of its four subbasins closed to new water allocations following the approved water management plan for the SSRB in 2006 (Alberta Environment 2006). Canada's most extensive irrigation system is located in southern Alberta (67% of Canada's irrigated agricultural land) and it relies upon mountain snowpack. This natural storage is augmented by ~50 reservoirs (McGee et al. 2012; Statistics Canada 2017). Therefore, there is great concern about the near-future status of these surface freshwater supplies.

To address this concern, the *South Saskatchewan River Basin Adaptation to Climate Variability Project* brought together water users and managers to explore opportunities to improve water resource resiliency in the SSRB in the face of global warming (Sheer et al. 2013; Alberta Water Portal 2014; Sauchyn et al. 2016). Presented with projections of future hydroclimate, including the most extreme scenarios, plus stakeholder observations, the project participants proposed and evaluated potential risk management and adaption strategies, using the OASIS mass-balance model applied interactively at live modeling sessions

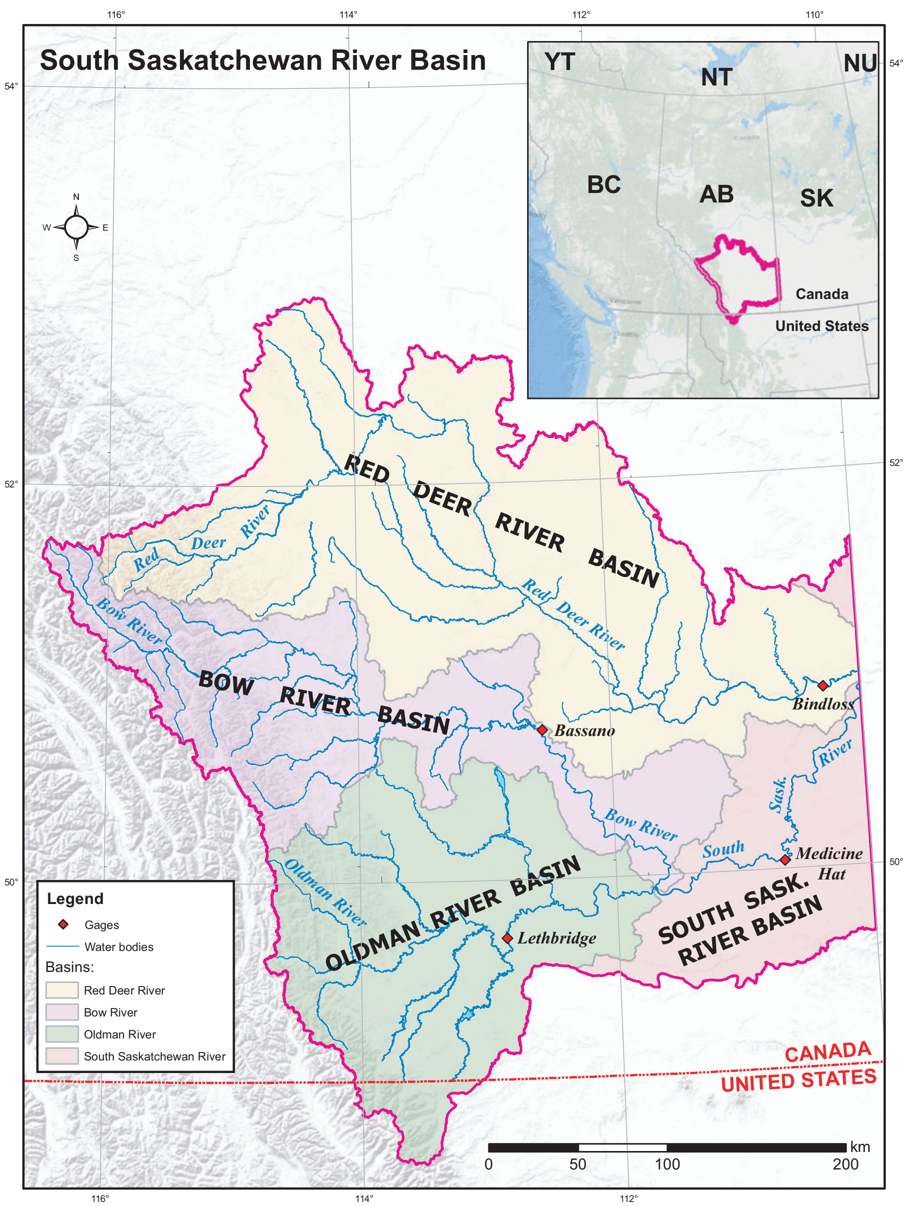

FIGURE 1. Map of the South Saskatchewan River Basin (SSRB), showing the Red Deer, Bow, Oldman, and South Saskatchewan River subbasins in Alberta, together with western North America inset. YT, Yukon; NT, Northwest Territories; NU, Nunavut; BC, British Columbia; AB, Alberta; SK, Saskatchewan.

(Sheer et al. 2013). We provided projections of future SSRB runoff. In this study, we expand on this work to give a detailed set of SSRB runoff projections for 2041–2070, using two different approaches and the output of a large set of current state-of-the-art regional climate models (RCMs).

Our first approach was the direct use of climate model outputs to project future hydrological flows. The direct use of climate model runoff data, rather than the standard approach of running climate model precipitation and temperature data through an off-line hydrologic rainfall–runoff model, has long been a goal of climate modelers (Hirabayashi et al. 2008; Poitras et al. 2011; Sperna Weiland et al. 2012; Nakaegawa et al. 2013). Hydrological models require a large amount of data for their initial calibration. These data might not be available for a given river basin, particularly over a longer time period that is more representative of the actual hydroclimatology than a typical 30-year normal period and also for regional studies covering extensive areas. Also, in the last decade, the important roles that surface hydrology and river flows play in the planetary climate system have been appreciated (Sperna Weiland et al. 2012). To model feedback mechanisms between land surface and atmosphere, climate models incorporate increasingly more complex land surface schemes (LSSs), which are approaching the resolutions and skillfulness of macroscale hydrological models (Hagemann and Gates 2003; Clark and Gedney 2008). Climate model runoff data have been run through river-routing schemes to add another layer of realism (Falloon et al. 2011; Poitras et al. 2011; Sperna Weiland et al. 2012). The runoff term from RCMs has been used to examine projected changes in streamflows in North America (e.g., Sushama et al. 2006; Music and Caya 2007; Music et al. 2009; Poitras et al. 2011). An important step in this approach is examining current state-of-the-art climate models for how well their modeled runoff simulates observed runoff in various regions, to determine whether or not anticipated improvements have finally materialized.

Another approach to producing runoff projections from climate models is through the use of a water balance model with aridity index estimations from Budyko functions (Schreiber 1904; Ol'dekop 1911; Budyko 1948; Turc 1954; Pike 1964). This approach incorporates more widely available energy and precipitation data to estimate less widely available annual surface runoff and evapotranspiration. Using observed climate and hydrometric data, numerous recent studies have calculated mean annual surface runoff in this fashion (Koster and Suarez 1999; Zhang et al. 2001; Sankarasubramanian and Vogel 2003; Potter and Zhang 2009; Donohue et al. 2011; Renner and Bernhofer 2012; Renner et al. 2012). Arora (2002) proposed this approach for a first-order estimate of runoff from climate models, since at that time LSSs had severe known problems in producing observed runoff, whereas available energy and precipitation were modeled more accurately. González-Zeas et al. (2012) developed this approach, proposing its use in large-scale studies in regions where a calibrated hydrologic model is not feasible because of data restrictions. They compared annual runoff calculated using five Budyko functions and direct runoff from RCMs (the European PRUDENCE project) to observed runoff over 338 basins in Spain. They found that runoff calculated according to Schreiber (1904) worked well for this largely semiarid region.

In this paper, we explore in the water-stressed SSRB, the feasibility of two runoff projection methods: the direct use of runoff outputs, and the hydroclimate formulas based on the water balance calculated using the Budyko functions of Schreiber, Ol'dekop, Budyko, and Turc–Pike (Arora 2002; González-Zeas et al. 2012), both using RCM data from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2007; Mearns et al. 2009) and the Coordinated Regional Climate Downscaling Experiment (CORDEX), to represent SSRB hydrologic flows. To the best of our knowledge, this is the first use of the output of a large ensemble of RCMs, with their superior resolution of topographic complexity and finer scale atmospheric dynamics, in exploring the hydrologic response of the SSRB to global warming. First, we use direct RCM runoff and runoff calculated from the water balance model to estimate SSRB runoff under current hydroclimate conditions and compare these results to observed data to determine the procedure that produces the best fit for this region. This is done with a view of applying these results more widely in the subhumid Canadian Prairies where calibration data can be scarce. Then, using the best of these projection methods with bias correction, we then project annual runoff for 2041–2070 for the SSRB (Figure 1) to examine changes in mean annual and monthly runoff and changes in their variability. In particular, any projected changes in runoff variability, an important and unstudied question, are vital for climate change adaptive planning, as considered by the *South Saskatchewan River Basin Adaptation to Climate Variability Project* (Sauchyn et al. 2016).

Area of Study

The study area is the Alberta portion of the SSRB (Figure 1), comprised of four subbasins: the Oldman, Bow, and Red Deer subbasins, together with the portion of the downstream South Saskatchewan River subbasin that is contained within Alberta. The river basin has a diverse topography, with the Canadian Rocky Mountains to the west (elevation 3,500 m), which slope through the foothills to the low-relief steppes of Palliser's Triangle in the east (elevation 600 m). The rivers arising in the mountains are fed by high-elevation snowpack, which is their principal water source, except for the Red Deer which arises in the foothills of the Rockies. Their annual hydrographs show a strong peak at the end of May or early June from spring snowmelt. Summer convective storms can cause further minor peaks later. There are minor glacial contributions to the Oldman and Bow Rivers. Annual runoff varies over the subbasins, with 0.56 mm/day for the Oldman River subbasin, 0.52 mm/day for the Bow River subbasin, 0.11 mm/day for the Red Deer subbasin, and 0.35 mm/day for the South Saskatchewan River subbasin proper. The subbasin drainage areas are comparable in size, with the largest being the Red Deer (77,850 km^2), followed by those of the Oldman (27,533 km^2), Bow (25,278 km^2), and South Saskatchewan (13,189 km^2). There is a steep climatic gradient, with high precipitation and low temperatures in the mountains, and semiarid conditions and high summer temperatures on the plains, e.g., Lake Louise in the mountains has a mean annual temperature of 0.2°C, mean total precipitation of 544 mm, and subarctic (Dfc) Köppen climate classification, vs. Medicine Hat on the plains with a mean temperature of 6.1°C, mean total precipitation of 323 mm, and semiarid continental Köppen climate classification BSk.

METHODS AND DATA

RCM and Instrumental Hydrologic Data

We used NARCCAP RCM data from a set of nine runs driven by a suite of global climate models (GCMs) over a domain spanning most of the United States (U.S.) and Canada (NARCCAP. Accessed January 2016, http://www.narccap.ucar.edu/about/index.html) (Table 1). The higher resolution of RCMs, vs. that of GCMs, offers greater topographic complexity and allows finer scale atmospheric dynamics to be simulated, thereby providing a more adequate method of producing the information needed for regional impact studies (Poitras et al. 2011; Barrow and Sauchyn 2017). We used nine nested RCM/GCM combinations (Table 1). Two other RCM/GCM pairs — WRFGccsm and WRFGcgcm3 — had too much missing data.

TABLE 1. The nine North American Regional Climate Change Assessment Program (NARCCAP) regional climate model–global climate model (RCM/GCM) pairs used in this study.

	Driving GCM				
RCM	**ccsm**	**cgcm3**	**gfdl**	**hadcm3**	**Acronym for RCMgcm pair**
CRCM	×	×			CRCMccsm, CRCMcgcm3
ECP2			×		ECP2gfdl
HRM3			×	×	HRM3gfdl, HRM3hadcm3
MM5I	×			×	MM5Iccsm, MM5Ihadcm3
RCM3		×	×		RCM3cgcm3, RCM3gfdl

Notes: Names of RCMs: CRCM, Canadian RCM; ECP2, Experimental Climate Prediction Center Regional Spectral Model; HRM3, Hadley Regional Model 3; MM5I, MM5 — PSU/NCAR Mesoscale Model; RCM3, RCM version 3. Names of GCMs: ccsm, Community Climate System Model; cgcm3, Third-Generation Coupled GCM; gfdl, Geophysical Fluid Dynamics Laboratory GCM; hadcm3, Hadley Centre Coupled Model version 3.

NARCCAP produced runs for a historical simulation period of 1971–2000 and for a future period of 2041–2070. The NARCCAP GCM runs were all part of the Phase 3 of the Coupled Model Intercomparison Project (CMIP3) (Meehl et al. 2007; IPCC 2013). The GCMs have been forced for the 21st Century by the Special Report on Emissions Scenarios (SRES) A2 high emissions scenario (Nakicenovic et al. 2000). Given recent emissions of greenhouse gases at a rising rate (WMO 2014), A2 is increasingly the most realistic emission scenario. Control simulations with these GCMs were also produced for the current (historical) period and these were used to drive the RCMs for the baseline simulation period of 1971–2000. All the NARCCAP RCMs have a spatial resolution of 50 km.

We also included one run of the Canadian RCM version 4 (CRCM4) RCM with a spatial resolution of ~25 km (Laprise et al. 2003; de Elía et al. 2008). It was nested within the Canadian Earth Systems Model version 2 (cesm2) (Government of Canada. Accessed January 2016, http://www.cccma.ec.gc.ca/data/canrcm/CanRCM4/index_cordex.shtml). cesm2 was forced for the 21st Century by RCP8.5 (a later generation high emissions pathway comparable to the SRES A2 scenario) (Meinshausen et al. 2011). This gave 10 RCM runs in total. The CRCM4cesm2 run is actually a part of CORDEX (Giorgi et al. 2009), the successor to NARCCAP, using the most recently developed models.

For the actual river flow data, we used naturalized river flows from the Oldman River at its mouth; the Bow River at Bassano, Alberta, the most downstream gauge in the contributing area of the Bow River Basin (further downstream is noncontributing); the Red Deer River at Bindloss, Alberta (the most downstream gauge just before the Red Deer joins the

South Saskatchewan); and the South Saskatchewan River at the border between Alberta and Saskatchewan. These naturalized records were generated by Alberta Environment and Parks hydrologists, by adding in water abstractions, reservoir level changes, and evaporation to recorded flows. These naturalized records are referred to as the actual or observed runoff (R_{obs}) for the rest of this paper. R_{obs} was calculated by dividing actual flow by drainage basin area. Ten kilometer-gridded ANUSPLIN data were used for observed air temperature and precipitation (McKenney et al. 2011).

Methods to Generate Annual SSRB Subbasin Runoff

First, we examined how well the direct outputs of the RCMs captured SSRB river flows. We determined how well total surface and subsurface runoff or "total runoff" (R_{mrro} — the RCM variable mrro) and surface runoff (R_{mrros} — the RCM variable mrros) compared to R_{obs} and its annual cycle over 1971–2000 for each of the four subbasins. We also examined whether runoff estimated using the water balance model and four Budyko functions, i.e., Budyko, Ol'dekop, Schreiber, and Turc, can be used as estimators of R_{obs} as suggested by Arora (2002) and González-Zeas et al. (2012). We then determined which of these six RCM runoff estimates was the best single method for modeling SSRB subbasin runoff. Each RCM calculates R_{mrro} and R_{mrros} differently, with CRCM4 including a fairly complex version of the Canadian Land Surface Scheme (Diro et al. 2014). Each RCM domain is partitioned into its own grid cell pattern. For each of the 10 RCM runs, and for each of the four subbasins, we identified the grid cells centered within the subbasin (e.g., Figure S1). To estimate the annual runoff using R_{mrro} or R_{mrros} for each subbasin, we directly averaged the three-hourly R_{mrro} or R_{mrros} data for each water year (October–September) over all the RCM grid cells within the subbasin, avoiding interpolation (González-Zeas et al. 2012). This total averaged output over the subbasin is directly comparable to the naturalized total water year discharge of the subbasin. In practice, at least eight grid cells were contained within each subbasin, an important consideration for accuracy (Rodenhuis et al. 2011). We used units of runoff and precipitation of mm/day.

Surface runoff on an annual time scale can be estimated using catchment water balance with the aridity index calculated by Budyko functions (Arora 2002). The mean value of annual surface runoff (R) is calculated from the water balance as $R = P - \mathrm{ET} - \Delta S - D$, where P is annual precipitation, ET is annual actual evapotranspiration, ΔS is the change in soil moisture and snow storage, and D is recharge to groundwater. We make the common assumption that ΔS and D are very small in nonglaciated regions over an annual time scale (Zhang et al. 2001). On the semiarid Canadian Prairies,

TABLE 2. Budyko functions $F(\phi)$ used to calculate the evapotranspiration/precipitation ratio.

Author and name	Budyko function $F(\phi)$
Schreiber (1904)	$1 - e^{-\phi}$
Ol'dekop (1911)	$\phi \tanh(\phi^{-1})$
Budyko (1948)	$[\phi \tanh(\phi^{-1})\,(1 - e^{-\phi})]^{0.5}$
Turc (1954), Pike (1964)	$\frac{1}{\sqrt{0.9+\left(\frac{1}{\phi}\right)^2}}$

$$R \approx P - \mathrm{ET} = P(1 - \mathrm{ET}/P) \approx P(1 - F(\phi)), \quad (1)$$

where $\phi = \mathrm{PET}/P$ is the aridity index, PET is potential evapotranspiration, and $F(\phi)$ is a Budyko function. The four Budyko functions used in this study are shown in Table 2.

For calculation of PET, we used Hargreaves method (Hargreaves and Samani 1982):

$$\mathrm{PET} = 0.0023\mathrm{conv}(T_{\mathrm{mean}} + 17.8)(T_{\max} - T_{\min})0.5R_{\mathrm{A}}, \quad (2)$$

where PET is in mm/day, T_{mean} is the mean temperature in °C, T_{max} is the maximum temperature in °C, T_{min} is the minimum temperature in °C, R_A is the solar radiation in the upper part of the atmosphere in MJ/m^2 day, and conv = 0.4082 m^2 mm/MJ. We used Equations (1) and (2) and NARCCAP and CRCM4 data to produce annual runoff variables derived from the aridity indices for each SSRB subbasin for 1971–2000. We used the RCM variables *pr* for P, *tas* for T_{mean}, *tasmax* for T_{max}, *tasmin* for T_{min}, and *rsdt* for R_A. To produce annual subbasin runoff, we again averaged annual runoff from all RCM grid cells whose centers fell within the subbasin watershed. We refer to the four Budyko function-derived annual runoff variables as the Schreiber, Ol'dekop, Budyko, and Turc runoff variables (R_{Sch}, R_{Old}, R_{Bud}, and R_{Turc}). To determine how well the water balance approach works in the SSRB, we also drove the Budyko functions with observed ANUSPLIN temperature and precipitation data.

We then evaluated how well the six RCM-derived runoff variables modeled the observed four subbasin flows using quantitative indicators of goodness of fit: a bias metric and the Kolmogorov–Smirnov (KS) test (Conover 1980). The bias reveals a model's tendency to overestimate or underestimate one variable and quantifies the model's systematic error. We calculated the bias for each of the six runoff estimates and each of the four subbasins and all 10 models by

$$\text{Bias} = \frac{\overline{S} - \overline{O}}{\overline{O}}, \tag{3}$$

where $\overline{S}$ denotes the mean of the RCM-derived runoff variable over 1971–2000, and $\overline{O}$ denotes the mean of the observed total annual subbasin runoff R_{obs}. We compared cumulative density functions (cdfs) of the six annual mean runoff variables, R_{mrro}, R_{mrros}, R_{Sch}, R_{Old}, R_{Bud}, and R_{Turc}, to cdfs of the observed subbasin runoff for the 10 RCM/GCM pairs and the four SSRB subbasins to determine which runoff variable most closely modeled R_{obs}. We used KS tests at the 0.05 significance level to test the difference between the cdfs of the actual and RCM-derived runoff.

We also examined how well R_{mrro} and R_{mrros} modeled monthly R_{obs} of each SSRB subbasin. We calculated hydrological regime curves, each of which consisted of the 30-year average mean monthly runoff, obtained for all 12 months individually for 1971–2000 for the observed subbasin runoff and for R_{mrro} and R_{mrros} from each of the 10 RCM/GCM pairs. In addition to plots of the regime curves, we used the Nash–Sutcliffe efficiency (NSE) coefficient to evaluate the goodness of fit of the 30-year average monthly values of the R_{mrro} regime curves to the corresponding observed values (Nash and Sutcliffe 1970).

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}, \tag{4}$$

where i represents the 12 months, S_i represents R_{mrro} for a given RCM/GCM pair, O_i is the observed mean monthly runoff, and $\overline{O}$ is the observed annual subbasin runoff. An NSE coefficient ranges from minus infinity (a very poor model) to 1 (a perfect model). In practice, an NSE coefficient of greater than zero shows that a model is worthwhile.

These three statistics were used to determine the best estimation method of present-day runoff in the SSRB. Once the best estimation method was identified, we used 2041–2070 RCM data to infer future SSRB runoff. There was one last processing step; bias correction of both the 20th Century simulated and 21st Century projected raw RCM results in order to simulate realistic regional hydrology (Christensen et al. 2008; Ashfaq et al. 2010; Chen et al. 2011; Teutschbein and Seibert 2012). We used the quantile–quantile (QPPQ) mapping approach (Hughes and Smakhtin 1996; Boé et al. 2007), which is currently the best practice (Teutschbein and Seibert 2012), to bias correct the mean daily runoff (annualized). From this procedure, we obtained the bias-corrected mean daily flows for each year and for each of the 10 RCM runs for both the projected future and simulation periods. We then examined changes in mean runoff and variance between 1971–2000 and 2041–2070 for the best runoff estimator using t-tests and F-tests. We also bias-corrected monthly simulated and projected R_{mrro} in order to examine projected shifts in runoff to earlier in the year as warming occurs (Stewart et al. 2004, 2005). We again used QPPQ mapping to bias correct, pooling monthly R_{mrro} values over the 30 years for the smoothed empirical cdfs.

RESULTS AND DISCUSSION

RCM Temperature and Precipitation Results

Comparison of the mean monthly temperatures produced by the 10 RCMs for the historical period 1971–2000 to those from the same time period from ANUSPLIN data for the entire SSRB showed that the models captured the annual temperature cycle well in the SSRB (Figure 2a). These temperature results are similar to those reported by Mearns et al. (2012) for their U.S. Great Plains region with the NARCCAP simulation runs, except that most RCMs showed a pronounced cold bias in our region vs. a strong warm bias in their region. Comparison of the mean monthly precipitation produced by the 10 RCMs for the historical period to that from the same time period from ANUSPLIN data showed that the models are much less able to simulate the correct amount and timing of precipitation in this basin (Figure 2b). Eight RCMs overestimated summer precipitation (MM5Iccsm and CRCMccsm were the exceptions). All RCMs overestimated winter precipitation (except for CRCM4cesm2). The general wet bias in the SSRB (0.34 mm/day) is in contrast to the drier bias shown by the NARCCAP models over the adjacent U.S. Great Plains (Mearns et al. 2012).

All RCMs showed increased warming in 2041–2070 relative to 1971–2000 (Figure S2a), with a mean increase of 3.0°C in July and a mean increase of 2.5°C in January. The overall mean increase over all the months and RCMs is 2.5°C, with a range of −0.3 to 5.5°C. Precipitation showed a mean increase of 0.07 mm/day in January and a mean increase of 0.11 mm/day in July. Precipitation changes were more variable, with the models typically showing increases in some months but declines in others (Figure S2b). There was a weak tendency to have more precipitation in winter and spring and less in the last half of the year, which could prove challenging for agriculture.

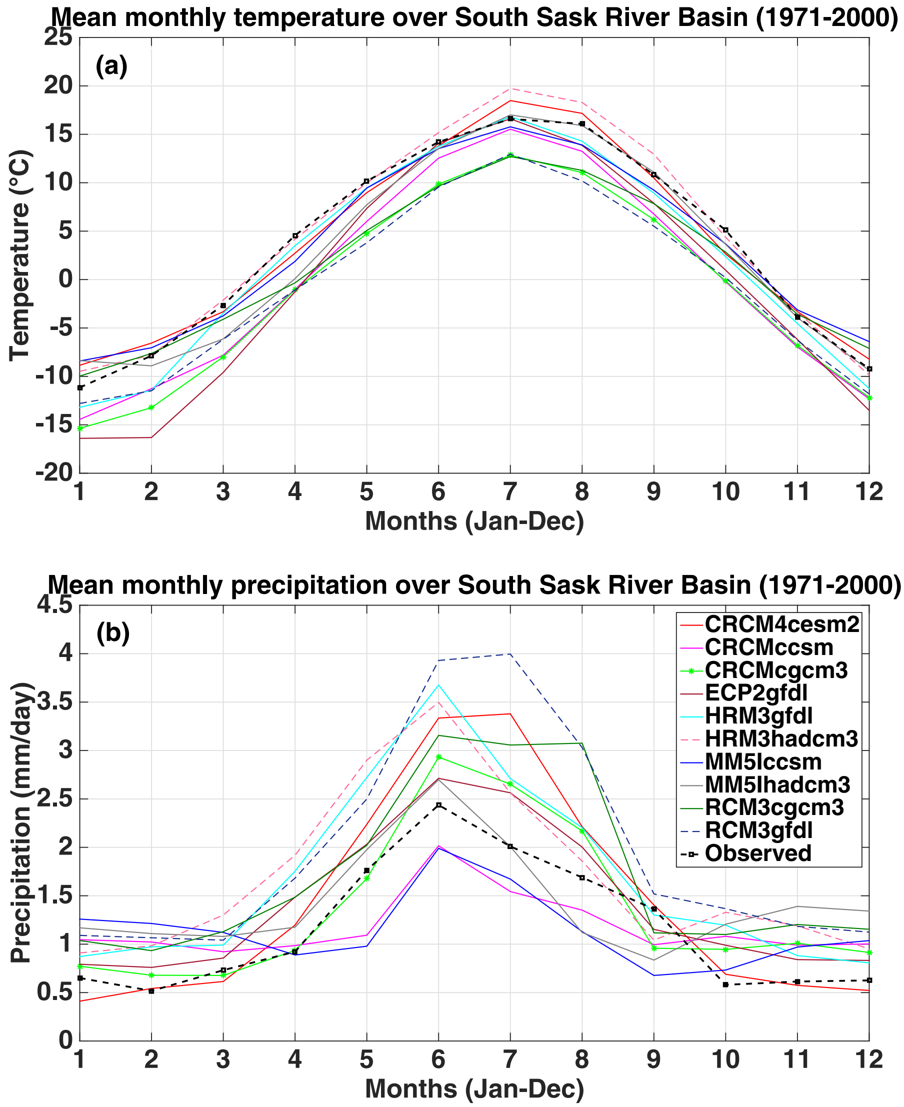

FIGURE 2. Mean monthly plots of (a) temperature (°C) and (b) precipitation (mm/day) for the SSRB restricted to Alberta for the 10 RCMs. The observed temperature and precipitation ANUSPLIN data are from McKenney et al. (2011). The acronyms of the RCMs are defined in Table 1. Legend of (b) also applies to (a).

Determination of the Best Runoff Estimation Method

According to the bias and KS statistics comparing the simulated 20th-Century runoff to R_{obs}, R_{mrro} was the best of the six runoff variables in modeling R_{obs} for each of the four SSRB subbasins (Figures 3 and S3). R_{mrro} had the lowest absolute value of the bias statistic in 45% of the 40 cases (four subbasins, each modeled by 10 RCMs), and the second lowest absolute bias in an additional 28% of the cases (Figure 3). The bias was much greater for the Red Deer subbasin for almost all the RCMs. With R_{mrro}, there was a consistent positive bias toward more runoff than observed for HRM3gfdl, HRM3hadcm3, MM5Ihadcm3, RCM3cgcm3, and RCM3gfdl. Also, R_{mrro} had the lowest KS statistic in 60% of the 40 cases, and hence had the best fit, and the second lowest KS statistic in an additional 23% of the cases (Figure S3). Even though the simulated historical R_{mrro} typically had the lowest KS statistics of the six runoff estimates, it mostly was significantly different at the 0.05 level from R_{obs}, hence bias correction was necessary to use it further. According to the bias and KS statistics, R_{mrros} was the second best estimator. Otherwise, one of the Budyko function-based estimates was the best runoff estimator, with none of them being particularly good, including R_{sch}, which was recommended by MacMahon et al. (2011) and which González-Zeas et al. (2012) found to work well in Spain. Driving the Budyko functions with observed ANUSPLIN temperature and precipitation data showed that this approach does not work particularly well in the SSRB

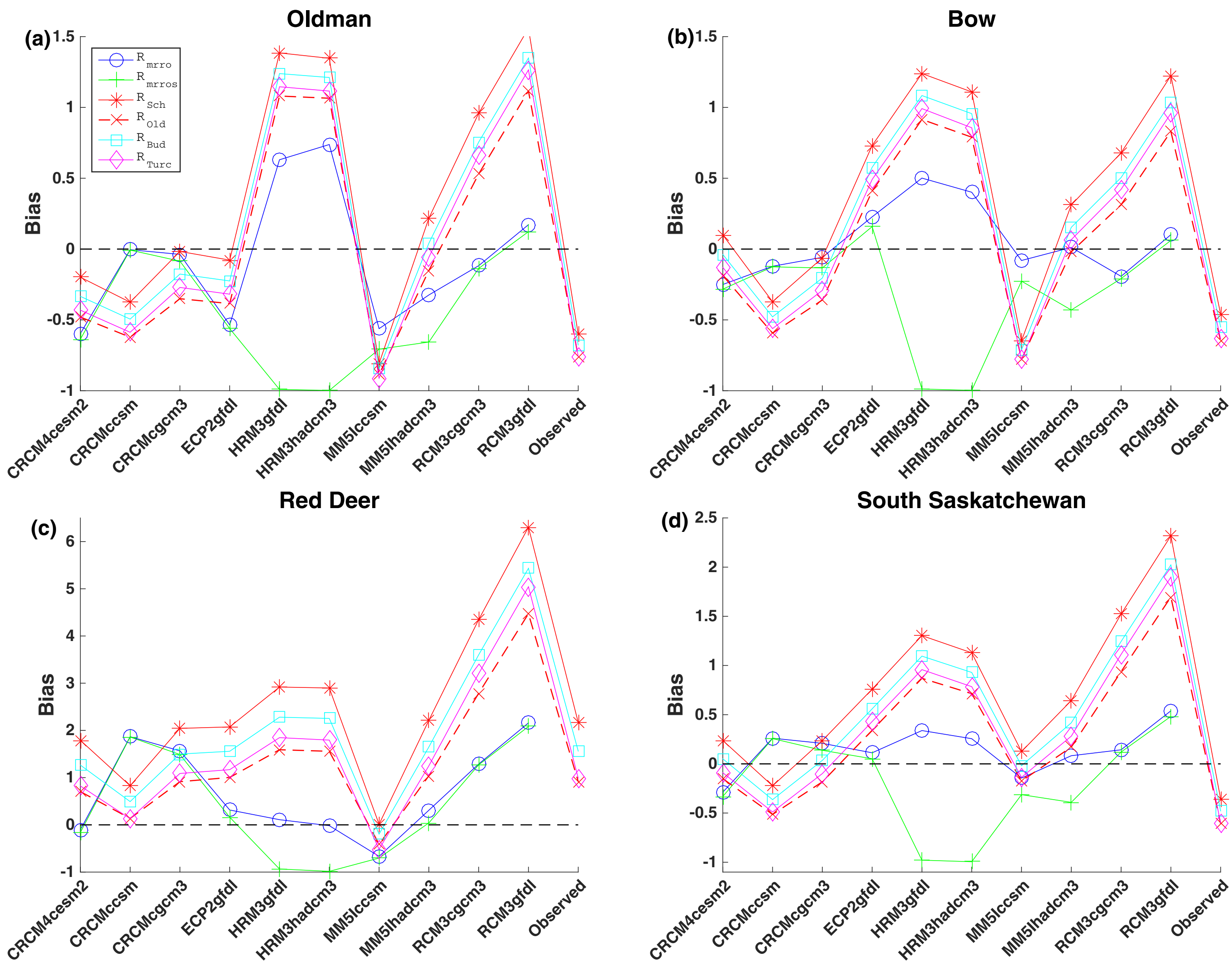

FIGURE 3. Goodness of fit indicators (bias statistics) obtained for total runoff (R_{mrro}), surface runoff (R_{mrros}), and the four Budyko function-based runoff estimates (R_{Sch}, R_{Old}, R_{Bud}, R_{Turc}) for the nine NARCCAP and one Coordinated Regional Climate Downscaling Experiment (CORDEX) RCM simulations for the (a) Oldman River subbasin, (b) Bow River subbasin, (c) Red Deer River subbasin, and (d) South Saskatchewan River subbasin contained within Alberta. The black dashed line denotes zero bias. The acronyms of the RCMs are defined in Table 1. The legends for (b–d) are the same as that of (a). Observed denotes the bias statistics of the Budyko functions driven by observed ANUSPLIN climate data.

with even instrumental data, with R_{mrro} almost always having better bias and KS statistics (Figures 3 and S3). We also bias-corrected RCM historical temperature and precipitation using QPPQ mapping and observed ANUSPLIN data, and used these bias-corrected data to drive the Budyko functions and still obtained poor results in comparison to R_{mrro} (Figures S4 and S5). Contrastingly, González-Zeas et al. (2012) found that in Spain using the PRUDENCE RCMs, R_{mrro} usually performed worse than runoff estimated using a Budyko function. Hence, either the hydroclimatologies of the semiarid regions of southern Alberta and Spain are sufficiently different that the runoff modeling results of one cannot be applied to the other and/or the LSSs of the NARCCAP RCMs are more advanced and accurate than those of PRUDENCE models.

Some RCMs gave total annual simulated runoff R_{mrro} that was closer to R_{obs} than the others (Figures 3 and S3). According to the bias and KS statistics, CRCMcgcm3, MM5Ihadcm3, RCM3cgcm3, and RCM3gfdl produced annual R_{mrro} that was reasonably close to R_{obs} for most, but not all, subbasins. On the other hand, HRM3gfdl had the greatest errors, consistently producing too much runoff, R_{mrro}, in all subbasins.

SSRB Annual Runoff Projection Results

Because R_{mrro} was the best of the six runoff estimates according to the bias and KS statistics, we projected it into the future for 2041–2070 to determine what changes in runoff average and variance should be expected in each SSRB subbasin. The projected average total surface runoff R_{mrro} showed a weak geographical pattern, with slight drying to the south and increasing moisture to the north for 2041–2070 (Figure 4a and Table 3). For the Oldman River subbasin, HRM3gfdl showed a significant decline and the nine other RCMs showed no significant changes. For the Bow River subbasin, CRCM4cesm2 showed a significant increase, ECP2gfdl showed a significant decline, and the other eight RCMs showed no significant changes. For the Red Deer River subbasin, CRCM4cesm2, CRCMcgcm3, HRM3hadcm3, and RCMcgcm3 showed significant increases, and the other six RCMs showed no significant changes. For the South Saskatchewan River subbasin proper, CRCM4cesm2 showed a significant increase, and the other nine RCMs showed no significant changes. This is summarized by the multi-model means, which showed only a significant increase for the Red Deer River subbasin and no significant changes for the others. CRCM4cesm2 consistently showed increasing average R_{mrro} for all subbasins except Oldman.

This study's results should be placed in the context of other SSRB streamflow projections produced using GCMs to drive physically based hydrologic models or LSSs (i.e., Lapp et al. 2009; Shepherd et al. 2010; Larson et al. 2011; MacDonald et al. 2011; Kienzle et al. 2012; Tanzeeba and Gan 2012; Islam and Gan 2015). Lapp et al. (2009) coupled the CMIP3 hadcm3 GCM with the hydrological WATFLOOD model to produce future SSRB flow scenarios, under the A2 emissions scenario. They found projected annual flow decreases in all rivers (an average decline of −7%) when comparing 2040–2069 mean projected data to 1961–1990 baseline data. Similarly, Shepherd et al. (2010) drove the physical hydrological models MTCLIM, SNOPAC, and RIVRQ with statistically downscaled data from six CMIP2 and CMIP3 GCMs to project SSRB tributaries, for 2005–2055 under the A2 scenario. They projected considerably declining summer flows, while projecting increasing winter and early spring flows, with a decline in annual discharge of −3% over 2005–2055. Also finding further drying, Larson et al. (2011) and MacDonald et al. (2011) projected decreases in spring flows from snowmelt for the 21st Century for various SRES scenarios, using delta-method downscaled GCM data as inputs into the hydrological models SIMGRID (which modeled spring runoff from snowpack) and GENESYS (which modeled snowpack), in the St. Mary River watershed of Montana and Alberta. The delta-method applies monthly changes from GCM data to observed climate data (typically from 1961 to 1990) and hence cannot examine projected changes in climate variability (MacDonald et al. 2011). Since mountain snowpack provides much of the total annual discharge in these headwaters, projected declining spring meltwater volumes are consistent with projected declines in annual discharge. Tanzeeba and Gan (2012) projected decreases in future SSRB annual and summer streamflow and snow water equivalent, despite projected precipitation increases, using a LSS MISBA driven by delta-method downscaled GCM data as inputs into the hydrological model over a range of SRES scenarios. Importantly, they found that the projected evaporation increase due to a warmer climate would offset the precipitation increases. Islam and Gan (2015) drove MISBA with delta-method downscaled GCM data with added ENSO variability to also project declining SSRB flows. It is not just physical hydrological models and LSSs which show drying in the southern SSRB, St. Jacques et al. (2010) and St. Jacques et al. (2013) used a statistical downscaling method based on modeling streamflow by climate oscillations to show declining projected flows in the Oldman subbasin and the SSRB proper for the 21st Century.

Our higher resolution RCM results showed a more nuanced and detailed picture of a geographical gradient with wetting in the northernmost Red Deer subbasin and weak drying in the southernmost Oldman subbasin, than the above coarser resolution GCM-based results. Our results are consistent with the more nuanced results of Poitras et al. (2011), who using runoff from a single RCM (CRCM4) run through WATroute river-routing projected declining flows in the headwaters of the Oldman and Bow subbasins, but increasing flows downstream at the mouths. They used a different driving GCM, cgcm3.1, vs. our cesm2, but we found similar results. Hence, this suggests that the use of higher resolution RCMs adds expected valuable refinement to our comprehension of near-future SSRB runoff changes, and provides an improvement over earlier GCM-based hydrological modeling.

Our contrasting result of increasing projected runoff from four of the NARCCAP RCMs for the Red Deer River subbasin is consistent with projected increased discharge of the Cline River, a tributary of the North Saskatchewan River Basin, just to the north of the Red Deer subbasin (Kienzle et al. 2012). It is also consistent with the Poitras et al. (2011) projection of increased flows in the North Saskatchewan and Athabasca River Basins.

It is expected that interannual hydroclimate variability will increase with global warming as the atmosphere's water-holding capacity, and therefore its

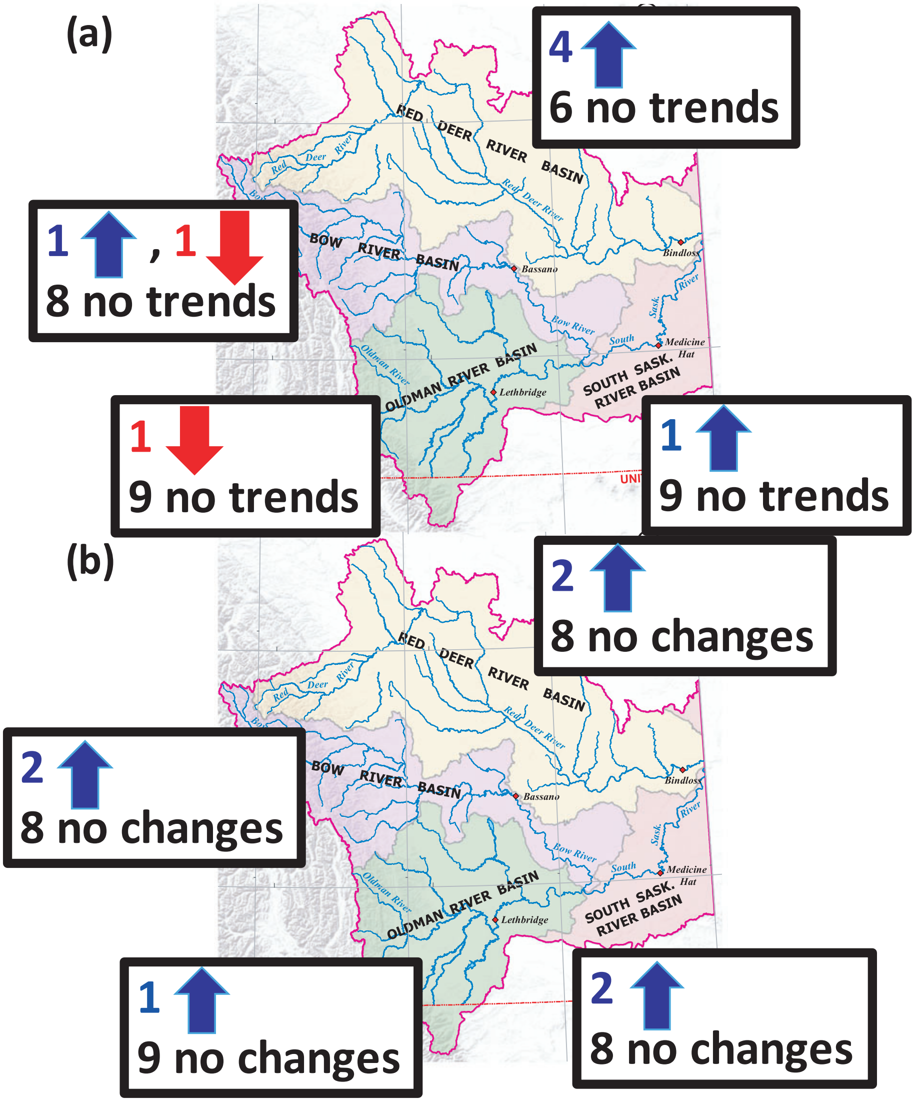

FIGURE 4. Summary of projected significant changes (at the $p \leq 0.05$ level) by 2041–2070 relative to 1971–2000 in the SSRB by subbasin according to: (a) trends in total runoff R_{mrro} and (b) changes in interannual variability of R_{mrro}. Down arrows denote significantly declining runoff or variability; up arrows denote significantly increasing runoff or variability.

evapotranspiration and precipitation potential will increase which in turn promotes increased variability (IPCC 2013). The projected variance of total surface runoff R_{mrro} showed a weak increasing pattern (Table 3 and Figure 4b). For the Oldman River subbasin, MM5Ihadcm3 showed a significant increase in variance of R_{mrro} and the other nine RCMs showed no significant changes. For the Bow River and South Saskatchewan River subbasins, CRCM4cesm2 and MM5Ihadcm3 projected a significant increase in interannual R_{mrro} variance, as did CRCM4cesm2 and HRM3gfdl in the Red Deer subbasin. For Bow, South Saskatchewan, and Red Deer subbasins, the remaining eight RCMs showed no significant changes in interannual R_{mrro} variability. Only CRCM4cesm2, HRM3gfdl, and MM5Ihadcm3 projected significantly increased variance in R_{mrro}. The multi-model mean R_{mrro} projected significantly increased interannual variability for the Bow River and Red Deer subbasins. The other two subbasins had nonsignificantly increased interannual variability according to the multi-model mean R_{mrro}.

There is concern among SSRB stakeholders that hydroclimate variability could increase with global warming (Sheer et al. 2013; Sauchyn et al. 2016). Unfortunately, almost all previous studies projecting SSRB streamflow or runoff (i.e., Lapp et al. 2009; Larson et al. 2011; MacDonald et al. 2011; Kienzle et al. 2012; Tanzeeba and Gan 2012; Islam and Gan 2015) used delta-method downscaled GCM data to drive their physical hydrological models. The simplistic delta-method approach is not able to capture

TABLE 3. Percent change in average and variance of total surface runoff R_{mrro} for the SSRB between 2041–2070 and 1971–2000 for the nine NARCCAP models and one CORDEX model, together with that of the multi-model mean (mm mean).

	RCM/GCM pair										
	CRCM4cesm2	CRCMccsm	CRCMcgcm3	ECP2gfdl	HRM3gfdl	HRM3hadcm3	MM5Iccsm	MM5Ihadcm3	RCMcgcm3	RCM3gfdl	mm mean
Percent change in average											
Oldman R_{mrro}	7.8	7.3	−3.5	−9.0	**−14.3**	6.3	−7.7	5.3	6.3	−2.1	−0.4
Bow R_{mrro}	***13.6***	4.0	0.5	**−13.3**	−7.5	5.8	−1.5	11.6	5.6	−1.4	2.7
Red Deer R_{mrro}	***34.1***	7.8	***14.4***	7.1	15.1	***16.5***	4.9	11.4	***15.3***	10.9	***14.1***
South Saskatchewan R_{mrro}	***17.5***	6.5	1.6	−12.6	−8.1	5.6	−3.8	11.4	7.8	−1.8	2.4
Percent change in variance											
Oldman R_{mrro}	86.9	65.9	−4.9	22.5	35.4	2.5	−27.5	***206.7***	−18.5	−36.9	48.6
Bow R_{mrro}	***135.4***	−3.0	−46.2	4.7	103.2	7.2	−20.3	***213.9***	−40.8	−13.6	***142.3***
Red Deer R_{mrro}	***130.0***	−9.1	−31.4	63.6	***172.7***	−18.2	50.0	72.7	−38.6	100.0	***121.4***
South Saskatchewan R_{mrro}	***128.8***	14.9	0.0	−0.4	79.5	−4.8	−30.3	***286.0***	−28.3	−35.1	85.5

Notes: Significant changes at the 0.05 level are shown in bold, underlined font for significant declines, and italic for significant increases.

possible changes in the variance of the driving climate variables from the GCMs; therefore, projected changes in streamflow variance could not be examined when using it. Our method of directly examining R_{mrro} from the RCMs does not suffer from this drawback. St. Jacques et al. (2013) did not report variance results, even though their method allowed them to examine this. Islam and Gan (2015) acknowledged this drawback when using the delta-method, which they tried to remedy by adding in observed ENSO variability from the climate normal period of 1961–1990. However, their innovative approach cannot model any changes in ENSO variability caused by anthropogenic climate change, which certainly is possible. Hence, our result of likely increasing interannual R_{mrro} variability in the SSRB fills an important gap in our knowledge and confirms stakeholders' concerns that they face the challenge of increasing hydroclimate variability.

SSRB Monthly Runoff Results

We had monthly runoff values for only R_{mrro} and R_{mrros} and not for R_{Sch}, R_{Old}, R_{Bud}, and R_{Turc}, because these methods produced only annual values. Because surface runoff R_{mrros} declines unrealistically to near-zero values during the cold season (results not shown), we did not use it further, and instead concentrated on monthly total runoff R_{mrro}. QPPQ bias correction greatly improved the accuracy of monthly simulated runoff estimates. For all subbasins, the NSE coefficients showed significant model improvement after bias correction (Figure S6).

Plots of bias-corrected mean monthly total runoff R_{mrro} for the 10 RCMs for the four SSRB subbasins show that the main late spring–early summer runoff peak occurs roughly one month too early in the year in the simulated historical data in the Oldman and South Saskatchewan subbasins and at the right time in the Bow and Red Deer subbasins (Figure 5). However, late summer runoff declines more steeply than it should in the Oldman, Bow, and South Saskatchewan subbasins and to lower values than those observed in all four subbasins, even after bias correction (although this problem is significantly improved by bias correction, results not shown). This is an unsurprising result, given that the LSSs in these RCMs lack river-routing. All upper subbasins have a summer–early fall secondary peak flow in the observed data in response to precipitation from summer convective systems. Most RCMs struggled to produce this secondary runoff peak. However, CRCM4cesm2 and HRM3gfdl did a reasonable estimation of this secondary peak in the Red Deer subbasin. Summer convective systems are poorly

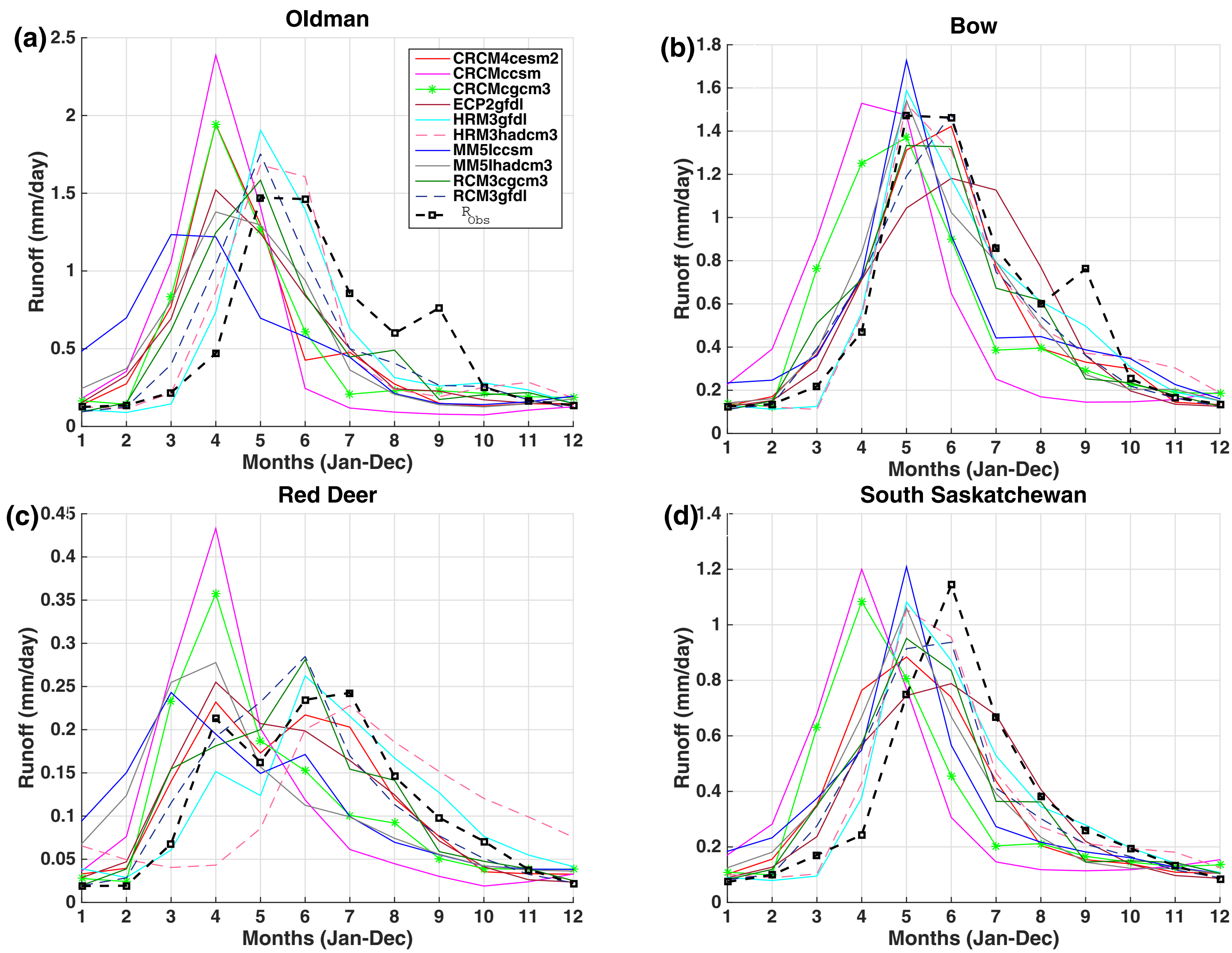

FIGURE 5. Mean monthly plots of total runoff R_{mrro} (mm/day) for the bias-corrected SSRB subbasins for the 10 RCMs for 1971–2000: (a) Oldman River subbasin, (b) Bow River subbasin, (c) Red Deer River subbasin, and (d) South Saskatchewan River subbasin contained within Alberta. The legends for (b)–(d) are the same as that of (a). The acronyms of the RCMs are defined in Table 1.

modeled in NARCCAP RCMs and even in the CORDEX RCM because the resolution of these up-to-date RCMs is still too coarse to adequately capture these fine-scale processes, on the order of 1 km in diameter, that generate summer precipitation on the northern Great Plains. These results are comparable to NARCCAP's problems with seasonal precipitation peaks in other localities, i.e., the U.S. Rocky Mountains (Wang et al. 2009; Mearns et al. 2012).

Plots of the differences in bias-corrected R_{mrro} between 1971–2000 and 2041–2070 for the four subbasins show that almost all RCMs projected increased R_{mrro} in winter and early spring, followed by sharp declines in late spring and early summer (Figure 6). This shows the advance of the spring snowmelt to earlier in the year as the climate warms, together with increased winter runoff as snow changes to rain and midwinter thaws occur more frequently. This is an expected result already evident in the observed hydrometric data (Stewart et al. 2005), and also present in model projections (Stewart et al. 2004; Lapp et al. 2009; Shepherd et al. 2010; Poitras et al. 2011; Kienzle et al. 2012; Tanzeeba and Gan 2012). One RCM, HRM3gfdl, projected a shift to a later spring peak for the three upper subbasins, but it was an outlier. For the rest of the year, the RCMs projected either no changes or no consistent changes in R_{mrro}. The projected earlier spring peak and the corresponding earlier summer runoff decline will result in less water available for irrigation in late summer. With increased summer temperatures, evapotranspiration should also increase, and hence demand for irrigation. These two factors will provide challenges for adapting local agriculture to a warming climate.

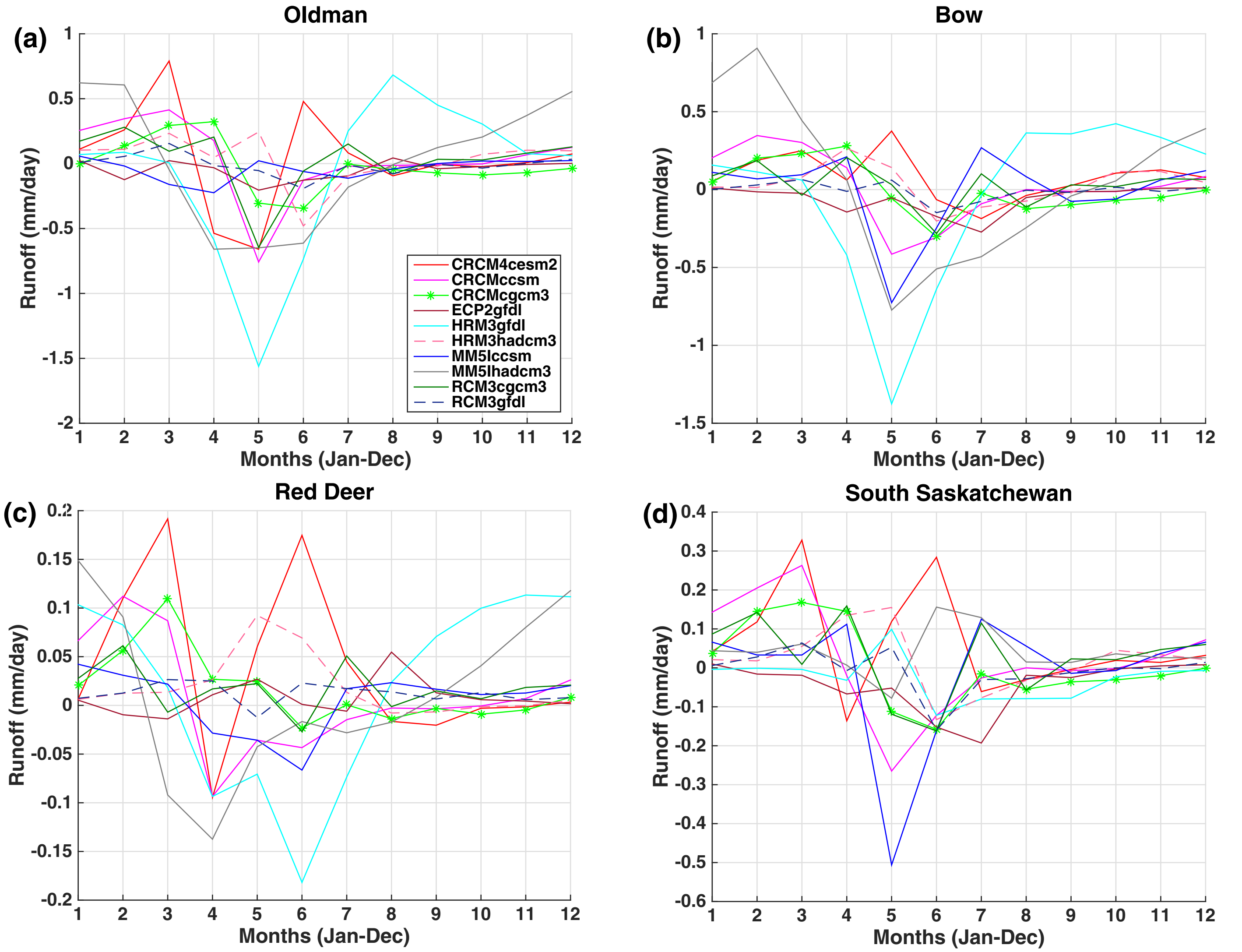

FIGURE 6. Plots of the differences of the bias-corrected mean monthly total runoff R_{mrro} (mm/day) between 1971–2000 and 2041–2070 for the four SSRB subbasins for the 10 RCMs: (a) Oldman River subbasin, (b) Bow River subbasin, (c) Red Deer River subbasin, and (d) South Saskatchewan River subbasin contained within Alberta. The legends for (b)–(d) are the same as that of (a). The acronyms of the RCMs are defined in Table 1.

CONCLUSIONS

In this study, we present, to the best of our knowledge, the first examination of projected changes in SSRB runoff using a large suite of RCMs from NARCCAP and CORDEX. We used six different runoff estimation methods: total surface and subsurface runoff (total runoff), surface runoff, and four estimations based on Budyko functions. Most models showed substantial biases and significantly different distributions of runoff estimations from those of the observed data (Figures 3 and S3), thus bias correction was necessary. Hence, using RCMs for 21st-Century projections critically depends on the magnitude of regionally projected climate changes and if the bias correction also holds in the future (which is important because the bias correction can be of greater magnitude than the projected changes). Our results suggest that not all this large river basin will respond in the same way to global warming. There is a geographic gradient: with possible drying in the southern Oldman River subbasin and possible increased runoff in the northernmost Red Deer River subbasin. The shift to an earlier spring runoff peak and drier late summer, with a consequent need for increased irrigation, should be expected, as has been found by other researchers. In a first examination of the important question of projected changes in interannual variability, projected R_{mrro} showed increasing interannual variability of runoff. This result further adds to adaptation challenges over the 21st Century in this basin, already largely closed to further surface water allocation. This study highlights the importance of preparatory stakeholder discussions, such as that of the *South Saskatchewan River Basin Adaptation to Climate Variability Project*, to better plan cooperative water resource management.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: A CRCM4 grid map, plots of the differences between projected and simulated temperature and precipitation, KS statistics, Budyko function results using bias-corrected climate data and NSE coefficients.

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