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Potential future climate effects on mountain hydrology, stream temperature, and native salmonid life history

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Abstract: Native salmonids of western North America are subject to many environmental pressures, most notably the effects of introduced species and environmental degradation. To better understand how native salmonids on the eastern slopes of the Canadian Rocky Mountains may respond to future changes in climate, we applied a process-based approach to hydrologic and stream temperature modelling. This study demonstrates that stream thermal regimes in western Alberta, Canada, may only warm during the summer period, while colder thermal regimes during spring, fall, and winter could result from response to earlier onset of spring freshet. Model results of future climate impacts on hydrology and stream temperature are corroborated by an intercatchment comparison of stream temperature, air temperature, and hydrological conditions. Earlier fry emergence as a result of altered hydrological and thermal regimes may favour native westslope cutthroat trout (*Oncorhynchus clarkii lewisii*) in isolated headwater streams. Colder winter stream temperatures could result in longer incubation periods for native bull trout (*Salvelinus confluentus*) and limit threatened westslope cutthroat trout habitat.

Résumé : Les salmonidés indigènes de l'ouest de l'Amérique du Nord sont assujettis à de nombreuses pressions ambiantes, notamment les effets d'espèces introduites et de la dégradation de l'environnement. Afin d'établir une meilleure compréhension de la réaction possible des salmonidés indigènes sur le versant est de Rocheuses canadiennes aux changements climatiques futurs, nous avons appliqué une approche axée sur les processus à la modélisation de l'hydrologie et de la température des cours d'eau. L'étude démontre que les régimes thermiques des cours d'eau dans l'ouest de l'Alberta (Canada) pourraient ne se réchauffer que durant la période estivale, alors que des régimes thermiques plus froids au printemps, à l'automne et en hiver pourraient découler du devancement des crues printanières. Les résultats de la modélisation des impacts climatiques futurs sur l'hydrologie et la température des cours d'eau sont corroborés par la comparaison de la température des cours d'eau, de la température de l'air et des conditions hydrologiques dans différents bassins versants. L'émergence devancée des alevins découlant de la modification des régimes hydrologiques et thermiques pourrait favoriser la truite fardée versant (*Oncorhynchus clarkii lewisii*) dans des cours d'eau d'amont isolés. La diminution des températures hivernales des cours d'eau pourrait se traduire par de plus longues périodes d'incubation pour l'omble à tête plate (*Salvelinus confluentus*) indigène et limiter l'habitat de la truite fardée versant, une espèce menacée. [Traduit par la Rédaction]

Introduction

Native salmonids appear to have a competitive advantage over non-native species only within specific thermal and nutrient regimes (Rasmussen et al. 2010; Warnock and Rasmussen 2013). Therefore, changes in thermal conditions within a stream can result in physiological or behavioral responses in aquatic organisms and reduced habitat availability for native species (Poole and Berman 2001; Wenger et al. 2011). Native westslope cutthroat trout (WCT; *Oncorhynchus clarkii lewisii*) and bull trout (BT; *Salvelinus confluentus*) are restricted in their current spatial distribution relative to their historical range because of the introduction of non-native species and environmental degradation (Rasmussen et al. 2010; Wenger et al. 2011). The majority of the current range of WCT and BT is restricted to mountain catchments (Behnke 2002). Therefore, high elevation mountain streams provide critical refugia for these species (Paul and Post 2001) given that these streams exhibit thermal and nutrient regimes best suited to native salmonids.

Previous studies have shown that human-induced atmospheric warming will alter hydroclimatic regimes in mountain regions across western North America (Barnett et al. 2008). Expected changes include earlier spring snowmelt (Mote et al. 2005; Stewart 2009; MacDonald et al. 2011), reductions in late season streamflow (St. Jacques et al. 2010), increased drought (Pederson et al. 2010; Sauchyn and Bonsal 2013), and subsequent increased human demand on water resources (Schindler and Donahue, 2006). Stream thermal regimes are likely to respond to changes in hydroclimatic regimes (Cristea and Burges 2010), as the capacity for streams to store heat is inversely proportional to volume (Poole and Berman 2001; Webb et al. 2003). Degradation of thermal habitat as a result of anthropogenic and natural disturbance, coupled with competition from introduced species, will likely further reduce habitat availability for native salmonids in the Rocky Mountains (Meyer et al. 1999; Isaak et al. 2012*a*; Isaak et al. 2012*b*; Jones et al. 2013). Therefore, it is important to understand how hydrologic and thermal regimes of mountain streams will respond to climate change.

Predicting climate change effects on stream temperature is complicated by numerous interactions between a stream and its surrounding environment. For example, recent work describing the stream temperature contributions of surface–subsurface exchange (Leach and Moore 2011), bed temperature (Guenther et al. 2012), riparian cover (Groom et al. 2011), and catchment-scale

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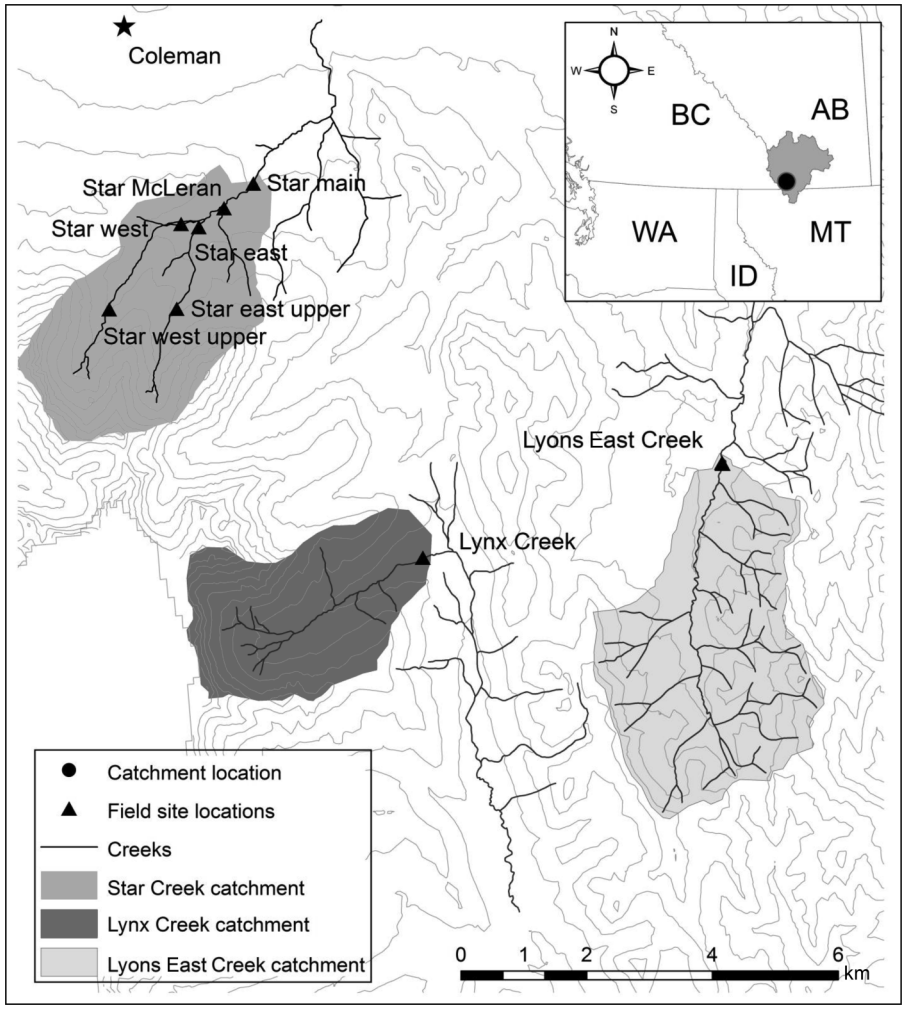
Fig. 1. Star Creek watershed and study area location in the Oldman River watershed, southwestern Alberta, Canada.



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moisture conditions (MacDonald et al. 2013) demonstrate the challenge in quantifying their response to changing environmental conditions. These interactions are also difficult to quantify at spatial and temporal scales relevant to management decision making. Therefore, studies often use correlations among air temperature, stream temperature, and sometimes streamflow for stream temperature predictions rather than solving complex heat budgets (Mohseni et al. 2003; van Vliet et al. 2011). Although predictions using air–stream temperature correlations are useful, they do not describe the influence of key stream temperature drivers (Johnson 2003). Furthermore, decreasing stream temperature trends over recent decades suggest stream thermal response to climate change may be poorly understood (Arismendi et al. 2012).

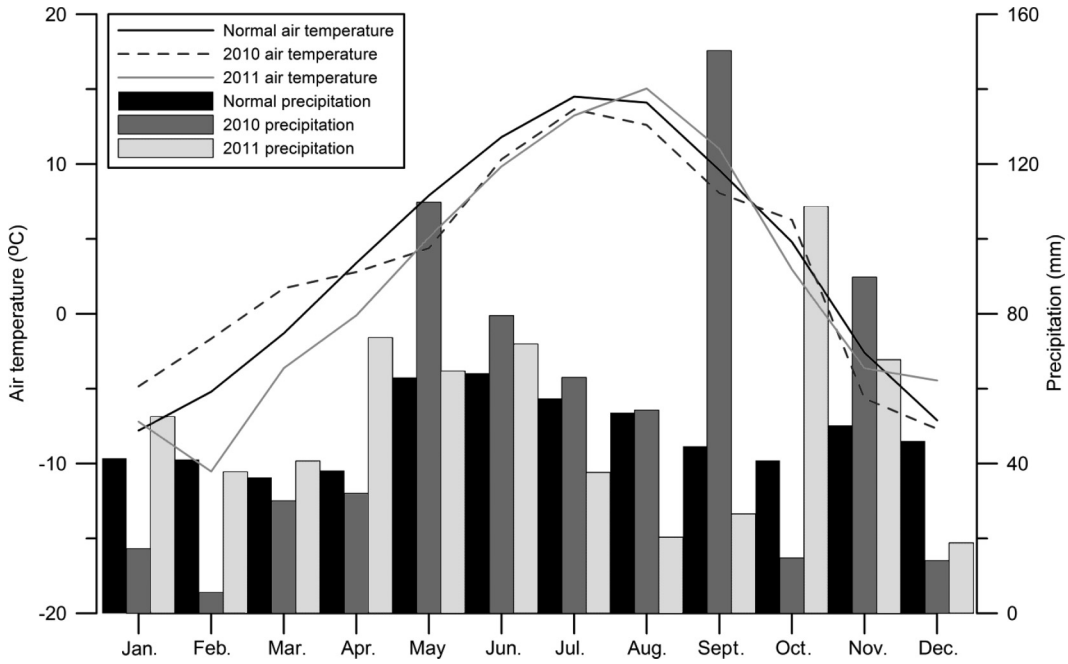
Process-based modelling can provide key insights into the mechanisms affecting stream temperature and also into subsequent salmonid life-history response to future climatic conditions (Johnson 2003). We used a field study coupled with a process-based modelling approach to evaluate the hydrological and thermal sensitivity of a headwater stream to future climate scenarios. We also assessed potential WCT and BT incubation period changes, as this life-history stage is highly sensitive to thermal and hydrological regimes (Beacham and Murray 1990; Baxter and McPhail 1999). Our objectives were to (*i*) define which seasons were most sensitive to a range of future climate scenarios, where the criteria for sensitivity were changes in streamflow and stream temperature, and (*ii*) determine the response of WCT and BT incubation periods and the timing of fry emergence.

Study area

This study primarily uses data collected at Star Creek, a headwater tributary of the Crowsnest River, Alberta (Fig. 1), which is typical habitat for native WCT and is representative of BT habitat. Star Creek has an estimated groundwater contribution to total streamflow of 68% (Silins et al. 2009), flowing from a step–pool channel to an intermediate pool–riffe/step–pool channel type (Montgomery and Buffington 1997). The Star Creek catchment ranges in elevation from 1475 to 2631 m. The mean channel slope in Star Creek is 5% with dominantly cobble substrate. The mean bankfull channel width is 3.0 m, with a mean wetted width of 2.6 m. Riparian cover is dominated by lodgepole pine (*Pinus contorta*), with willow (*Salix* spp.) and alder (*Alnus* spp.) comprising the subcanopy.

Data were also collected from study sites at Lyons East and Lynx creeks (Fig. 1) to conduct an intercatchment comparison of stream temperature (T_s; °C), air temperature (T_a; °C), and total stream discharge (Q; $m^3 \cdot s^{-1}$) patterns. Although surface–subsurface interactions can be controlled by catchment-scale geomorphology (Baxter and Hauer 2000), the T_s, T_a, and Q comparisons among Star, Lynx, and Lyons East creeks provide context for potential salmonid habitat response as a result hydroclimatic change. Lyons East Creek has streamflow contribution from shallow

Fig. 2. Mean monthly air temperature and total precipitation for 2010 and 2011at Star Main (1504 m) relative to the 1971–2000 normal at Coleman (1341 m).



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subsurface water sources, with an estimated 43% of total streamflow from ground water (Silins et al. 2009). It is inhabited primarily by introduced rainbow trout (*Oncorhynchus mykiss*) and is classified as a pool–riffle channel type based on Montgomery and Buffington (1997). The Lyons East catchment ranges in elevation from 1632 to 2639 m, with a mean stream channel slope of 3%, and the stream is dominated by cobble substrate. The mean bankfull channel width is 5.4 m, with a mean wetted width of 2.8 m.

Lynx Creek has an estimated 63% of total streamflow contribution from ground water (Silins et al. 2009) and is habitat for a genetically pure population of WCT (AESRD 2013). The Lynx Creek catchment has an elevation range of 1441 to 2027 m, with a mean stream channel slope of 6%, and is classified as an intermediate pool–riffle/step–pool channel type (Montgomery and Buffington 1997). The dominant substrate is cobble with subdominant gravels. The mean bankfull channel width is 4.7 m and the mean wetted width is 3.5 m. Both Lyons East and Lynx creeks have burned lodgepole pine riparian cover, with willow, alder, and grass subcanopies.

Characterized by a continental climatic regime, the Crowsnest Pass region receives an average of 576.5 mm total precipitation annually (31% of which is snow), with peak precipitation occurring in June (64.1 mm). Normal (1971–2000) mean annual air temperature for the region is 3.5 °C; the warmest month is July (14.5 °C) and the coldest month is January (–7.8 °C; Fig. 2) (Environment Canada 2012). Air temperatures for all months during the study period were within the normal range of values. The 2010 to 2011 period represented a range of precipitation conditions, with 2010 having relatively low fall–winter precipitation and high summer precipitation, while 2011 had primarily above average precipitation during the period from fall to spring, but below average summer precipitation (Fig. 2).

Methods

Data collection

Hydrometeorological stations were installed at two locations within the Star Creek watershed, Star Main and Star West upper (Fig. 1), and measured hourly mean T_a, relative humidity (RH; %), and wind speed (u; m·s^{-1}) at 2 m above the stream bankfull depth. Hourly mean net radiation (Q^*; W·m^{-2}) was also recorded directly over the stream surface at 1 m above bankfull depth. Hourly total precipitation (mm) was measured approximately 10 m from the stream bank at the Star Main site. Hourly mean T_s was measured at five sites within the Star Creek watershed: Star West upper, Star East upper, Star East, Star McLaren, and Star Main (Fig. 1). Hourly mean Q was estimated using stage–discharge relationships at all sites except Star McLaren, where it was estimated using a compound weir. Manual measurements of Q were collected at all stations during periods of high, low, and median Q. Data used for this study were collected from 15 May 2010 to 15 September 2011.

Hourly average T_a, T_s, and Q were measured at Lyons East and Lynx creeks (Fig. 1). Hourly mean Q was measured for the period from 1 January 2011 to 31 December 2011, while T_a and T_s were measured from 1 June 2011 to 31 December 2011. All hourly means and totals were derived from 10 s readings. A detailed description of energy and mass balance data collection procedures is available in MacDonald et al. (2013).

Hydrometeorological model

We applied a coupled approach using the Generate Earth Systems Science input (GENESYS) and Mountain Stream Temperature (MST) models (MacDonald et al. 2009; R.J. MacDonald, S. Boon, and J. Byrne, in review). The GENESYS model has been used in numerous studies to investigate the impacts of climate change on snowpack in mountain catchments (Lapp et al. 2005; Larson et al. 2011; MacDonald et al. 2011, 2012). Daily simulations of hydrometeorological variables were generated using hydrologic response units (HRUs) and a series of process-based modelling routines.

Daily maximum and minimum T_a values were estimated for each HRU using regional T_a lapse rates derived for each month from Parameter–elevation Regressions on Independent Slopes Model (PRISM) normal (1971–2000) data (Daly et al. 2008). For each HRU, daily precipitation estimates were derived using regional

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monthly precipitation lapse rates also derived from the PRISM normal dataset.

A daily hydrological balance was calculated for each HRU during the snow-covered period using

$$\text{(1)} \quad \mathrm{SWE}_{(t)} = \mathrm{SWE}_{(t-1)} + \mathrm{Precip}_{(t)} - \mathrm{Int}_{(t)} - \mathrm{Subl}_{(t)} - \mathrm{IF}_{(t)}$$

where SWE is the snow water equivalent (mm), Precip is simulated daily total rain or snow (mm), Int is canopy interception (mm), Subl is sublimation (mm), IF is infiltration (mm), and t is the time step (days). Soil moisture conditions (SM; mm) were simulated from the onset of snowmelt using

$$\text{(2)} \quad \mathrm{SM}_{(t)} = \mathrm{SM}_{(t-1)} + \mathrm{IF}_{(t)} + \mathrm{Precip}_{(t)} - \mathrm{ET}_{(t)} - \mathrm{Rech}_{(t)} - \mathrm{Run}_{(t)}$$

where ET is evapotranspiration (mm), Run is runoff (mm), and Rech is groundwater recharge (mm) contributing to catchment groundwater storage. To simulate Q, the GENESYS model routes Run using the Muskingum routing method. To estimate the groundwater contribution to total Q (baseflow; $\mathrm{m^3 \cdot s^{-1}}$), an exponential storage–discharge curve was applied.

MST model

Outputs from the GENESYS model used as input to the MST model include T_a, RH, Q, and atmospheric transmissivity (TRANS; %). Simulated daily maximum and minimum T_a were used to estimate hourly T_a with a method developed by Parton and Logan (1981). Hourly T_a estimates were then used to calculate hourly RH values (Glassy and Running 1994). TRANS was estimated using Bristow and Campbell (1984).

The MST model applies previously developed process-based methods (Boyd and Kasper 2003; Leach and Moore 2010; Leach and Moore 2011). T_s values were simulated using temperature response units (TRUs), which apply the same logic as HRUs but represent the physiographic characteristics of a stream. We used hourly mean T_s from Star West upper, Star East upper, and Star McLaren in this simulation to provide the boundary conditions for the model. Advective and heat inputs to the stream were estimated (Boyd and Kasper 2003) for each TRU as

$$\text{(3)} \quad \frac{dT_s}{dt} = -V \cdot \frac{dT_s}{dx} + \frac{(Q^* + Q_h + Q_e + Q_b + Q_{gw} + Q_f)}{C \cdot \rho \cdot \bar{d}}$$

where $\frac{dT_s}{dt}$ is the difference in T_s per unit of time (s). Velocity (V; $\mathrm{m \cdot s^{-1}}$) is estimated as a function of Q, wetted width (WW; m), and wetted depth ($\bar{d}$; m). WW, Q, and $\bar{d}$ data collected from stream surveys on Star Creek were used to derive continuous estimates of $\bar{d}$ for each TRU by applying multiple linear regression (MLR) with WW and Q as predictive variables ($R^2 = 0.64$, RMSE = 0.01, $n = 40$). Continuous WW estimates were derived for each TRU with linear regression, where the predictive variable was Q ($R^2 = 0.48$, RMSE = 0.47, $n = 40$). C is the specific heat of water (4182 $\mathrm{J \cdot kg \cdot °C^{-1}}$), ρ is the density of water (998.2 $\mathrm{kg \cdot m^{-3}}$), and $\bar{d}$ is the mean wetted depth (m) in each TRU. Q^* is net radiation ($\mathrm{W \cdot m^{-2}}$), estimated using Arc GIS 10.0 and Leach and Moore (2010). Q_e is latent heat flux ($\mathrm{W \cdot m^{-2}}$), estimated using a method described in Moore et al. (2005) and Q_h is sensible heat flux ($\mathrm{W \cdot m^{-2}}$), which was determined using Leach and Moore (2010). The bed heat (Q_b; $\mathrm{W \cdot m^{-2}}$) and groundwater (Q_{gw}; $\mathrm{W \cdot m^{-2}}$) fluxes were estimated using Moore et al. (2005), and the heat flux from friction (Q_f; $\mathrm{W \cdot m^{-2}}$) was estimated using Theurer et al. (1984).

T_s was estimated for each TRU and each hourly time step with Euler's method, similar to Leach and Moore (2011):

$$\text{(4)} \quad T_{s_{i+1,t+1}} = T_{s_{i,t}} + \Delta t \cdot \frac{dT_s}{dt}$$

The exposure time (Δt) was determined as the product of stream velocity (V; $\mathrm{m \cdot s^{-1}}$) and TRU length (m), i is the TRU end point, and t is the time step.

To account for mixing of both surface and subsurface water, a mixing model was used:

$$\text{(5)} \quad T_{s_{i,t}} = \frac{T_{s_{i,t}} Q_{i,t} + T_{in_{i,t}} Q_{in_{i,t}}}{Q_{i,t} + Q_{in_{i,t}}}$$

where T_{in} (°C) and Q_{in} ($\mathrm{m^3 \cdot s^{-1}}$) are the temperature and Q values from a tributary or hyporheic exchange flow, respectively (Leach and Moore 2011; Boyd and Kasper 2003). Q values for each TRU were assumed to be proportional to the basin area contributing to the upstream and downstream ends of the TRU, accounting for inflows from tributaries. Hyporheic exchange flow (Q_{hyp}; $\mathrm{m^3 \cdot s^{-1}}$) was calculated using Darcy's Law (Domenico and Schwartz 1990). Calculated Q_{hyp} ranged between 0.4% and 4.7% of total Q per 100 m of stream, which is consistent with other estimates for steep headwater catchments (Wondzell 2011). The temperature of Q_{hyp} was parameterized as mean daily T_s in each TRU based on the assumption that mean daily T_{hyp} can be similar to mean daily T_s of the water column (Arrigoni et al. 2008).

The model verification presented here is for the time period from 15 May 2010 to 15 September 2011, as this is the period when Q^* data were available. T_s, T_a, and Q verifications were also conducted for this time period for standardization of results. The Nash–Sutcliffe (NS) efficiency coefficient, the correlation coefficient (R^2), and root mean square error (RMSE) were used as measures of model performance.

Sensitivity analysis

This study used the "delta" method, which applies absolute mean monthly T_a changes to the observed time series using future T_a predictions (Diabat et al. 2012; Hay et al. 2000). We applied a constant T_a change to the GENESYS model daily time series input for 2010 and 2011. Daily T_a output from the GENESYS model was then downscaled to hourly T_a using Parton and Logan (1981) and used as input to the MST model. Groundwater temperature (°C) used to calculate Q_{gw} (Moore et al. 2005) was adjusted by the same magnitude as T_a; this is based on the assumption that groundwater temperature closely approximates mean annual T_a (Meisner et al. 1988).

We used future T_a estimates from General Circulation Model (GCM)-derived climate change scenarios for the periods from 2039 to 2069 (2050s) and 2070 to 2099 (2080s) in this analysis. These scenarios are from the IPCC Fourth Assessment report (AR4) and are available via the Pacific Climate Impacts Consortium (PCIC). Spatially downscaled T_a predictions were obtained from the Climate WNA high resolution climate data tool version 4.7 (Wang et al. 2012). Climate WNA provides climate output (T_a, precipitation) from climate change scenarios for any point in western North America, enabling elevation-adjusted estimates of future climatic conditions. The mean and standard deviation of monthly change in maximum and minimum T_a for all 20 climate change scenarios available from Climate WNA were used to derive three scenarios for both the 2050s and 2080s, capturing a representative range in plausible future T_a conditions. Scenarios 1, 2, and 3 represent the mean, +1 standard deviation, and –1 standard deviation, respectively (Table 1). We did not apply precipitation changes given that the 2010 to 2011 precipitation at Star Creek represents a range of conditions relative to the 1971–2000 normal at Coleman (Fig. 2), and there is often considerable variation in GCM simulations of future precipitation (Barrow and Yu 2005).

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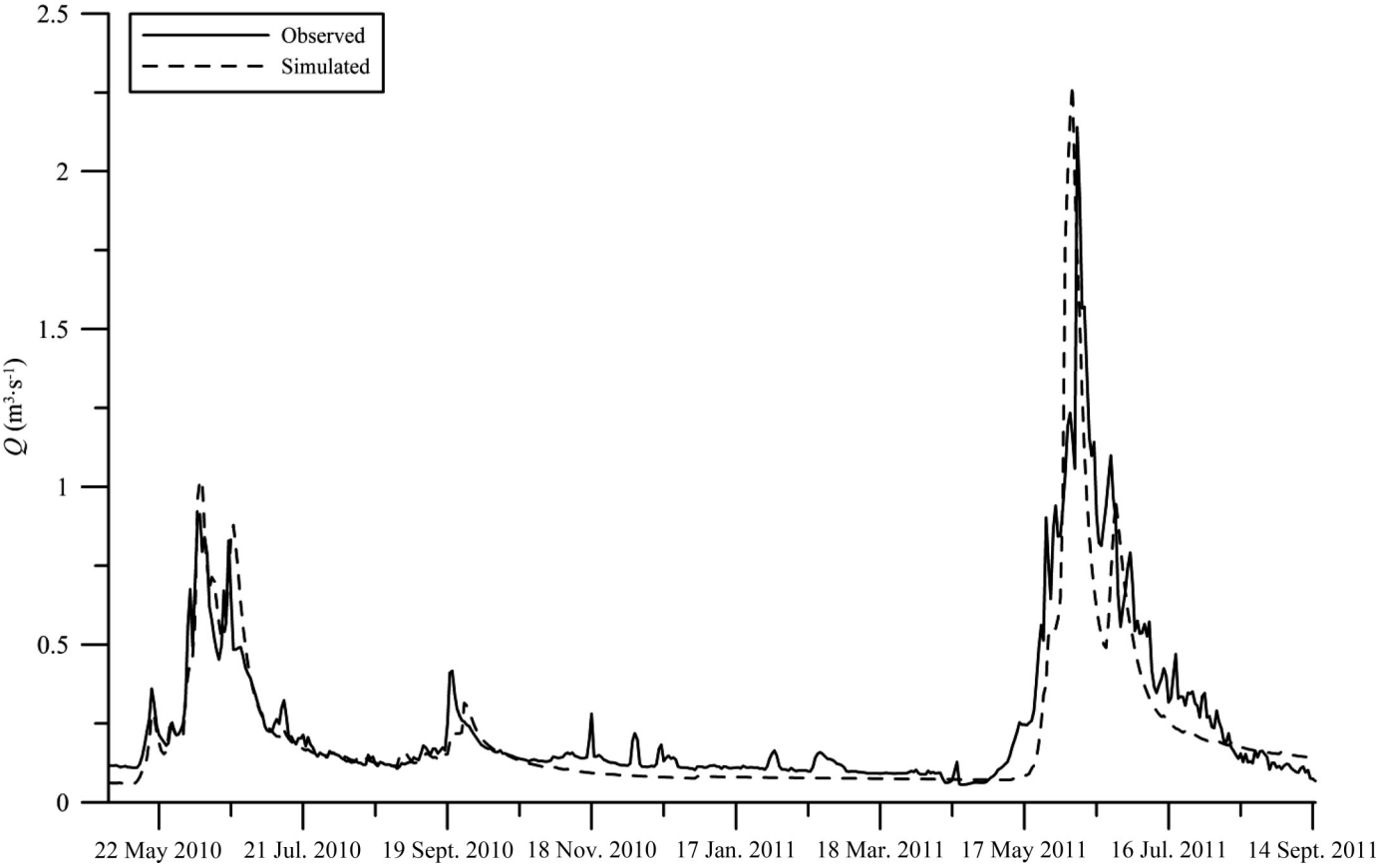
Table 1. Seasonal change in minimum and maximum T_a relative to the 2010–2011 historical period for all three future climate scenarios derived using Climate WNA.

	Spring		Summer		Fall		Winter	
Scenario	ΔMax T_a	ΔMin T_a	ΔMax T_a	ΔMin T_a	ΔMax T_a	ΔMin T_a	ΔMax T_a	ΔMin T_a
2050								
1	1.72	2.05	3.20	3.63	1.81	1.61	−0.54	−0.16
2	2.63	3.01	4.52	4.92	2.83	2.67	0.51	1.01
3	2.83	3.20	4.23	4.68	2.78	2.56	0.59	1.12
2080								
1	0.62	0.91	2.16	2.58	0.84	0.66	1.68	1.43
2	4.11	4.47	6.09	6.43	4.23	3.97	1.89	2.57
3	1.16	1.56	2.96	3.42	1.44	1.38	−0.86	−0.55

Fig. 3. Observed and simulated mean daily Q at Star Main for the period from 15 May 2010 to 15 September 2011.



Changes in the simulated ratio of snow to total seasonal precipitation relative to 2010 and 2011 were quantified for all three scenarios to evaluate the hydrometeorological response to future climate scenarios. Absolute changes in simulated mean daily Q and baseflow, as well as mean, maximum, and minimum daily T_s relative to 2010 and 2011, were calculated for all three scenarios to quantify the hydrological and thermal response to future climate scenarios. Changes in seasonal mean T_s were calculated relative to 2010 and 2011 to quantify interseasonal differences in seasonal T_s response. Absolute WCT and BT incubation period changes were quantified with the cumulative thermal unit (CTU) method, which assumes egg hatching requires a constant number of accumulated thermal units, defined as the mean daily temperature above 0 °C (Beacham and Murray 1990).

Owing to the complexity in determining the timing of WCT spawning, which is related to both Q and T_s (Brown and Mackay 1995), the assumption was made to calculate incubation period for WCT starting at peak spring Q. The date of WCT emergence was estimated based on WCT eggs requiring 300 CTUs after peak Q to hatch (Drinan 2010). The initiation of BT spawning is related to T_s and photoperiod (McPhail and Baxter 1996). We used a standardized date of 21 September because spawning activity in southeastern Alberta typically peaks in late September (Hurkett et al. 2011); this date also provides a reasonable surrogate to account for photoperiod. The date of emergence for BT was estimated based on the assumption that 350 CTU are required after peak Q to hatch (Gould 1987). CTU values of 300 and 350 for WCT and BT, respectively, were used to estimate date of emergence for 2010–2011 as well as all three future climate scenarios in both the 2050 and 2080 periods.

Results

Model verification

Atmospheric variable simulations were assessed at an hourly time step, as this was the temporal resolution required for

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the MST model. Simulated mean hourly Q^* compared well with observed values at Star Main for the period from 15 May 2010 to 15 September 2011 (R^2 = 0.73, RMSE = 58.5, n = 11 736). Mean hourly T_a simulations compared well with observed values at Star Main for the same period (R^2 = 0.75, RMSE = 5.5, n = 11 736).

Simulated mean daily Q compared well with observed mean daily Q for the period from 15 May 2010 to 15 September 2011 (NS = 0.76, RMSE = 0.13, n = 489). The simulated timing of peak Q for both years was within 2 days of observed, with a higher peak Q in 2011. The recession towards baseflow was simulated better in 2010 than in 2011. In 2011 the GENESYS model was not responsive to precipitation events during late summer and early fall. Winter Q events were not simulated as well. However, baseflow was simulated well, with a small negative bias (Fig. 3).

The daily mean, maximum, and minimum of hourly change in T_s from Star West upper to Star Main (ΔT_s; °C) were used to assess model performance for the period from 15 May 2010 to 15 September 2011. The daily mean ΔT_s was simulated well (Fig. 4A; NS = 0.92, RMSE = 0.31, n = 489). The daily maximum ΔT_s was not simulated as well (Fig. 4B; NS = 0.69, RMSE = 1.43, n = 489); however, daily minimum ΔT_s was simulated well (Fig. 4C; NS = 0.93, RMSE = 0.41, n = 489). Over the entire study period, mean daily T_s simulations compared well with observed mean daily T_s (Fig. 5; NS = 0.96, RMSE = 0.30, n = 489). However, simulated mean daily T_s did not compare well with observed T_s during the early spring, where simulated values were consistently positively biased. Simulations were consistently negatively biased during the freshet period from mid-May to mid-June (Fig. 5).

Limitations

- Given that the relationship between T_s and T_a is nonlinear and inapplicable in cold winter periods where ice is present (Mohseni and Stefan 1999), we assumed that the boundary T_s, hyporheic exchange flow temperature, and stream bed temperature conditions remained constant. Since boundary T_s conditions were not shifted to account for long-term shift in mean T_s expected under atmospheric warming (Jones et al. 2013), there is likely a conservative negative bias in T_s predictions during warm summer periods.
- Winter high Q events were not well simulated. This is important as winter T_s is dependent on Q (Power et al. 1999). It is difficult to determine if winter Q events were actually driven by increased Q or if these events are artifacts in the data resulting from increased stream stage from ice formation.
- Consistent errors in historical T_s simulations occur just before and during spring freshet. These errors likely result from the following: (*i*) the processes representing the effects of snow- and ice-melt on T_s were explicitly not accounted for in the MST model; and (*ii*) simulated historical Q is lower than observed during the early spring and higher than observed during freshet. These errors in simulated Q likely resulted in over- and underestimates of T_s of 1 °C during the early spring and freshet periods, respectively.
- Boundary u conditions remained constant. Increases or decreases in u affect Q_e in the MST model. Therefore, changes in u would have affected T_s simulations. Q_e is an important heat flux component (Webb and Zhang 1997); therefore, a model to account for future u changes would be useful.

Sensitivity analysis

The ratio of snow to total monthly precipitation decreased in all three scenarios and in both 2050 and 2080 periods relative to the historical record. The simulated percent change in the ratio of snow to total monthly precipitation was greatest for spring, with

Fig. 4. Scatter plots of observed and simulated maximum (A), minimum (B), and mean (C) daily ΔT_s from Star West Upper to Star Main for the period from 15 May 2010 to 15 September 2011. The line is 1:1.

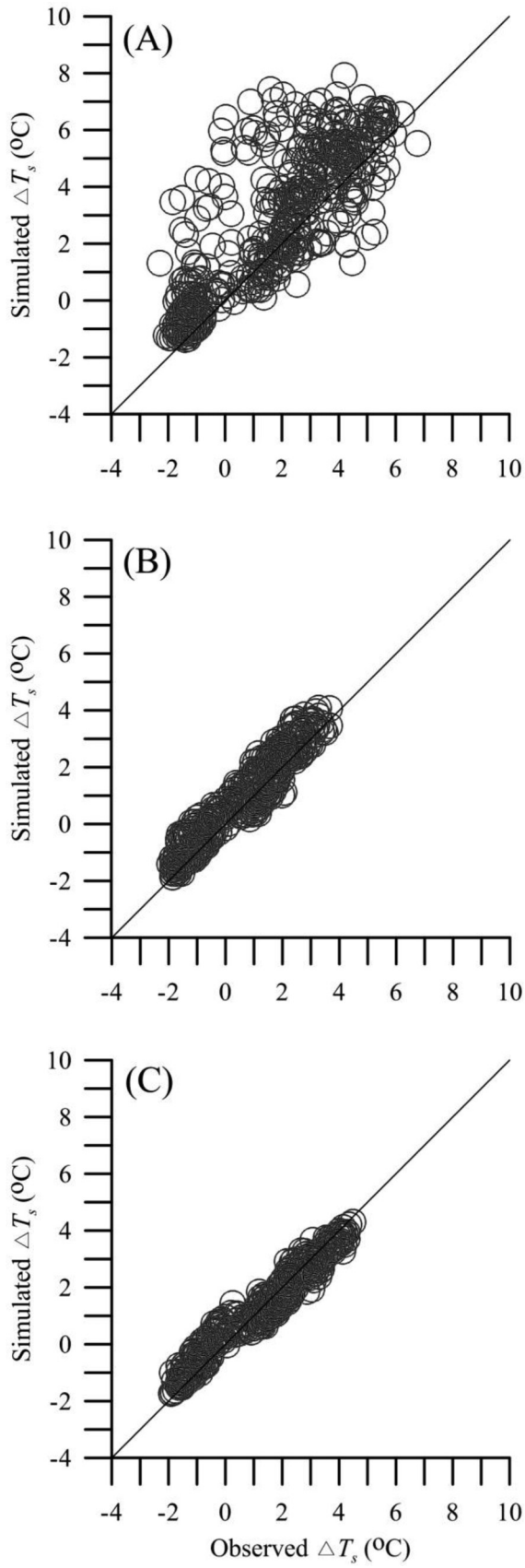
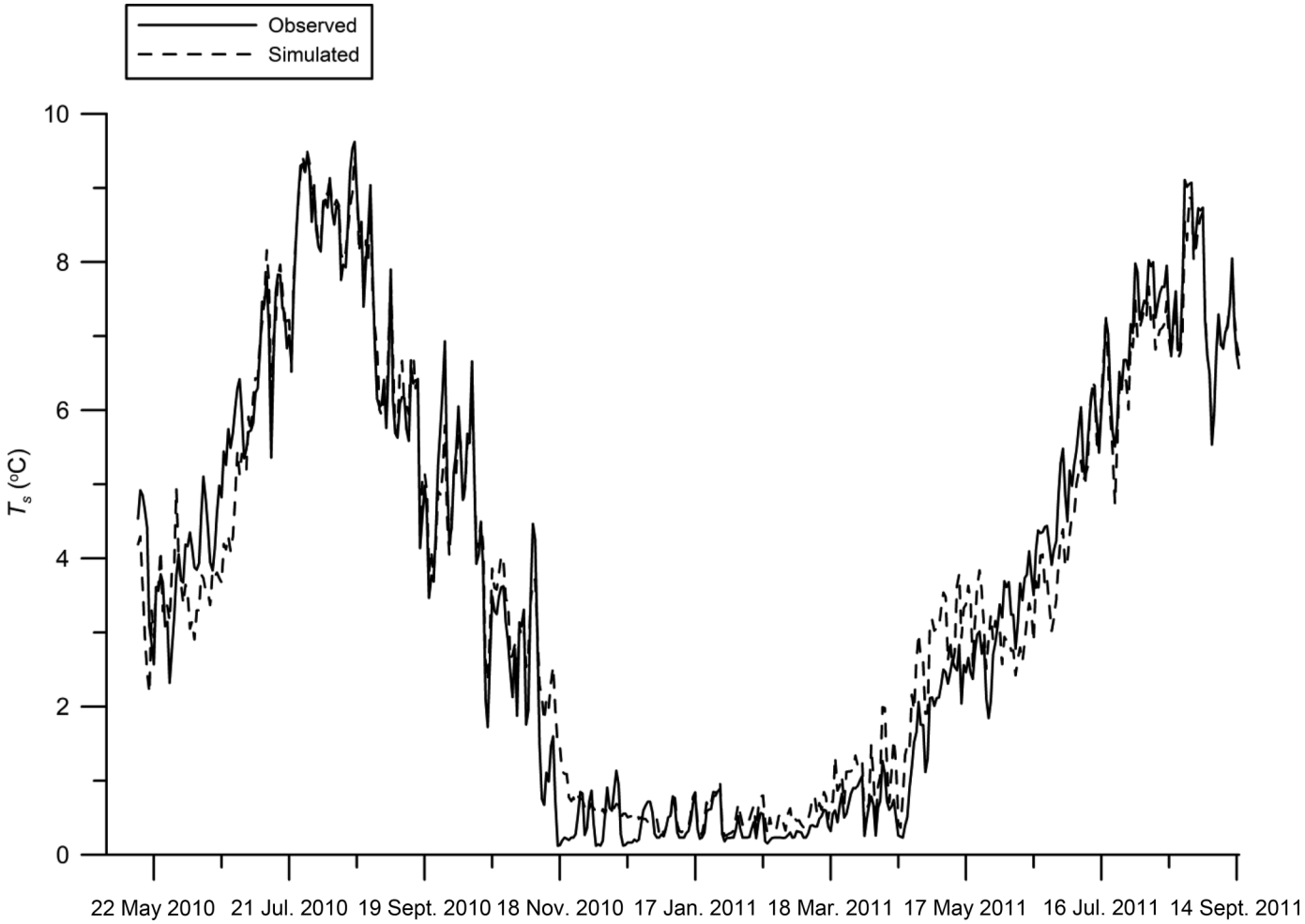


Fig. 5. Observed and simulated mean daily T_s for Star Main from 15 May 2010 to 15 September 2011.



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a maximum 42% decrease in Scenario 2 for the 2080 period. Winter was projected to experience the least amount of change in precipitation phase, with a 6% decrease in Scenario 2 for the 2080 period (Fig. 6).

The greatest difference in simulated Q between all future climate scenarios and the historical (2010 to 2011) period was during the spring, with consistently earlier onset of peak Q (Table 2). The greatest change in overall magnitude of Q occurred in Scenario 2 for both the 2050 and 2080 periods, particularly during June (i.e., peak flows). The largest shifts in peak Q were also estimated for 2010, which had lower historical Q. In all three scenarios, small reductions in late season Q were predicted for both the 2050 and 2080 periods (Figs. 7A and 7C).

Simulated changes in baseflow generally shifted towards the peak occuring earlier in the spring, with lower baseflow in summer, fall, and winter. In all scenarios, the change in peak baseflow did not shift as substantially as the change in peak Q in 2010. However, in 2011 a more consistent shift towards an earlier peak baseflow was predicted. The greatest change in baseflow magnitude was predicted to occur in Scenario 2 for both the 2050 and 2080 periods, where baseflow declined in both early and late seasons relative to the historical period (Figs. 7B and 7D).

Simulated T_s differences coincided with differences in Q for all three scenarios, with variable seasonal responses and greatest absolute change in mean daily T_s, relative to historical T_s, predicted for the spring and early summer in the 2050 and 2080 periods. Overall, the low Q year (2010) had a higher magnitude T_s response relative to the higher Q year (2011). Scenario 2 had the greatest response with a negative change in simulated mean daily T_s for early spring (maximum of –1.45 °C) and a positive change in mean daily T_s for late spring and early summer (maximum of 1.25 °C). The simulated late summer mean daily T_s change was well within the range of modelling error and dominantly positive. The fall–winter change in mean daily T_s was also within the range of modelling error and was negative for all scenarios (Figs. 8A and 8B).

Simulated percent change in mean daily T_s was highest for the winter in all three scenarios and both future time periods. The only positive percent change in mean daily T_s was predicted to occur for the summer period, with negative changes predicted for fall, winter, and spring. Scenario 2 had the highest magnitude of change in simulated mean daily T_s for all seasons (Fig. 9).

The historical incubation period for WCT was estimated to be 53 days in 2010 and 62 days in 2011. The date of emergence for WCT was predicted to shift earlier in the spring and change by a greater magnitude in 2010 (low Q and high T_s change) relative to 2011 (high Q and low T_s change). The 2010 date of WCT emergence was predicted to occur 18 and 19 days earlier in Scenarios 1 and 2, respectively. The 2011 date of WCT emergence was predicted to advance by 11 and 13 days in Scenarios 1 and 2, respectively. WCT emergence was predicted to advance by 4 and 5 days in Scenario 3 for the 2050 and 2080 periods, respectively (Table 3).

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Fig. 6. Percent change in the ratio of snow to seasonal total precipitation relative to the historical period for all three scenarios in the 2050 and 2080 periods.

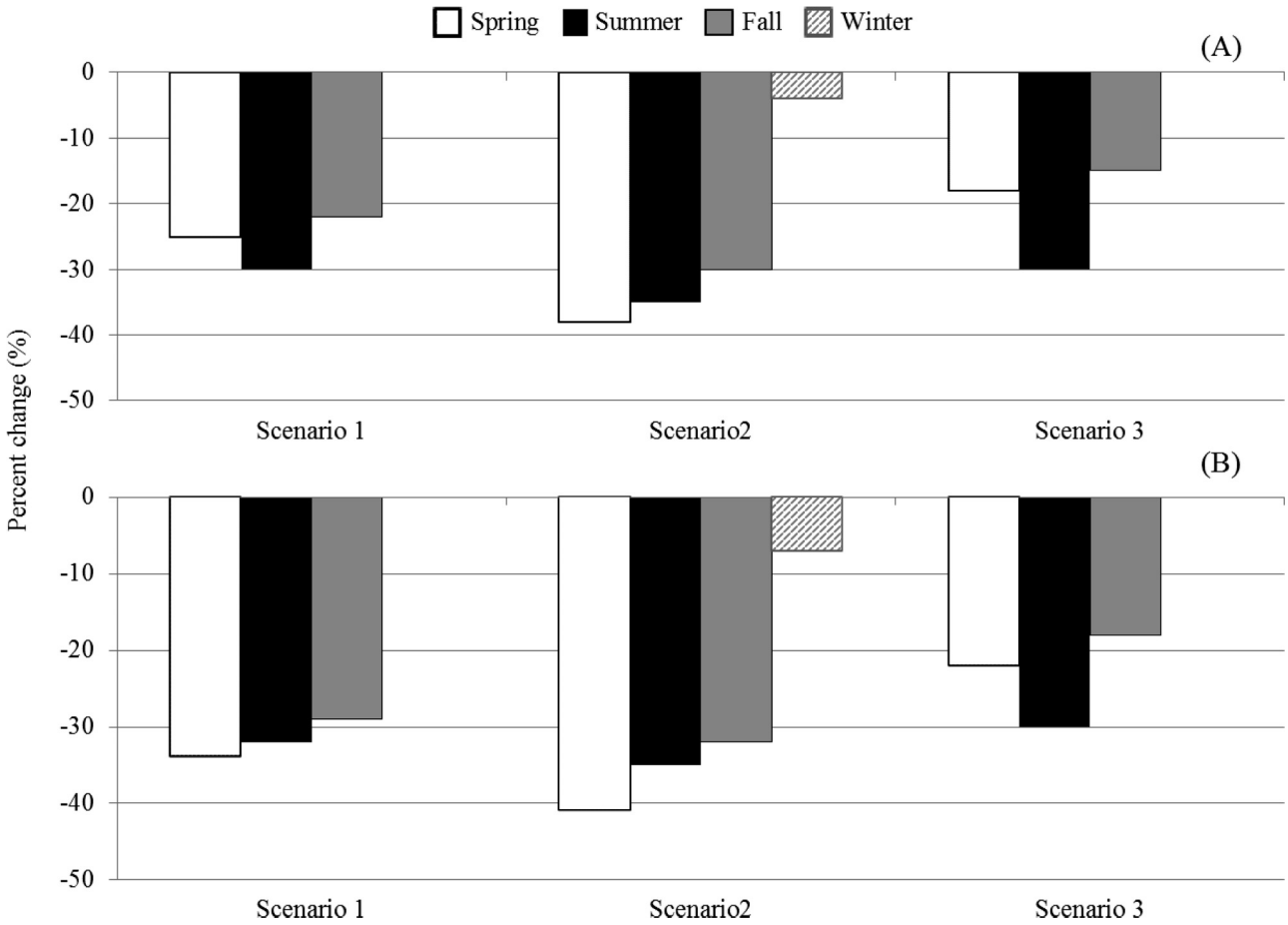

Table 2. 2010 and 2011 date of peak Q for the historical period and all three scenarios for the 2050 and 2080 periods.

	Date of peak discharge	
Scenario	2010	2011
Historical	6 June	6 June
2050		
1	18 May	27 May
2	19 May	25 May
3	3 June	3 June
2080		
1	19 May	25 May
2	18 May	24 May
3	19 May	3 June

The historical incubation period of BT was estimated to be 194 days and was predicted to shift later in the spring in all three scenarios. BT emergence was predicted to occur 15 days later for both the 2050 and 2080 periods in Scenario 1. Scenario 2 was predicted to have the greatest change in BT emergence, occurring 15 and 16 days later in the 2050 and 2080 periods, respectively. BT emergence was predicted to occur 13 and 14 days later for the 2050 and 2080 periods, respectively in Scenario 3 (Table 3).

Intercatchment comparison

Star and Lynx creeks exhibited very similar temporal T_s patterns, with daily mean T_s reaching approximately 10 °C in mid-August and both streams having similar late-season T_s (variable, but >0 °C). Early spring T_s was approximately 1 °C higher in Star Creek relative to Lynx Creek. Q patterns were also similar between Star and Lynx creeks, with peak Q occurring in both streams on 8 June. However, Lynx Creek had higher peak Q and an earlier onset of high Q in the spring. All three creeks had similar T_s patterns in the late fall.

Overall, Lyons East Creek had a substantially different T_s pattern relative to both Star and Lynx creeks, with a higher maximum (15 °C) in August and lower minimum during the winter period (remained stable at 0 °C). Lyons East Creek also had higher diurnal and seasonal range in T_s relative to both Lynx and Star creeks. Lyons East Creek had an earlier onset of spring peak Q (26 May) followed by a more rapid decline towards baseflow conditions from midsummer to winter (Figs. 10A and 10B).

The differences in Q patterns (earlier onset of spring freshet and lower baseflow) between Lyons East Creek and Lynx and Star creeks were similar to those predicted by future climate scenarios in Star Creek (Fig. 7). All three sites had similar T_a patterns, with a slightly lower diurnal T_a range at the Star Creek site during the winter period (Fig. 10C).

Discussion

This study provides a mechanistic perspective on T_s response to future climate scenarios, suggesting changes were largely a function of projected hydrologic shifts in response to earlier

Fig. 7. Simulated mean daily *Q* (A) and baseflow (B) for all three scenarios for the 2050 period. Simulated mean daily *Q* (C) and baseflow (D) for all three scenarios for the 2080 period.

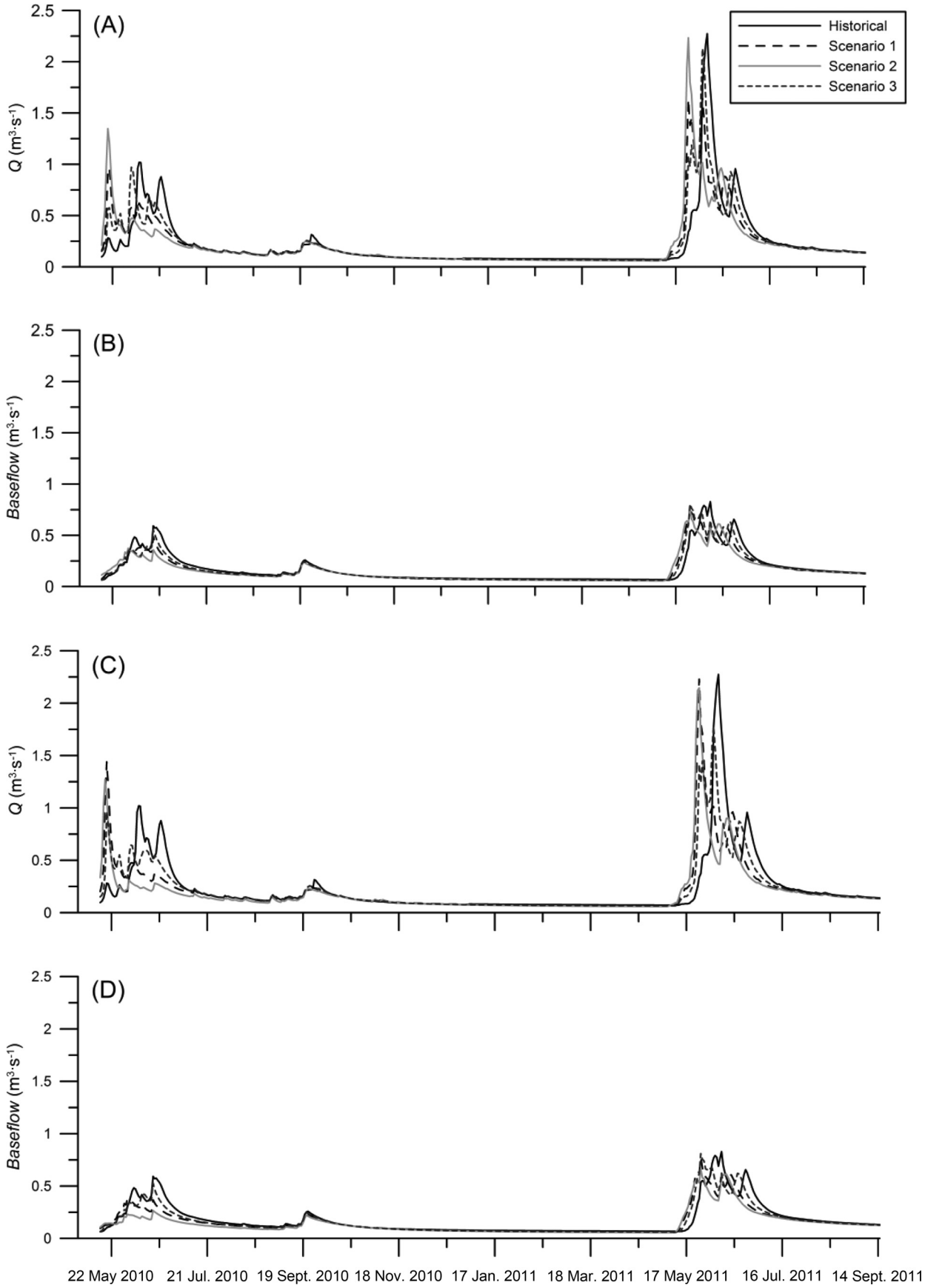

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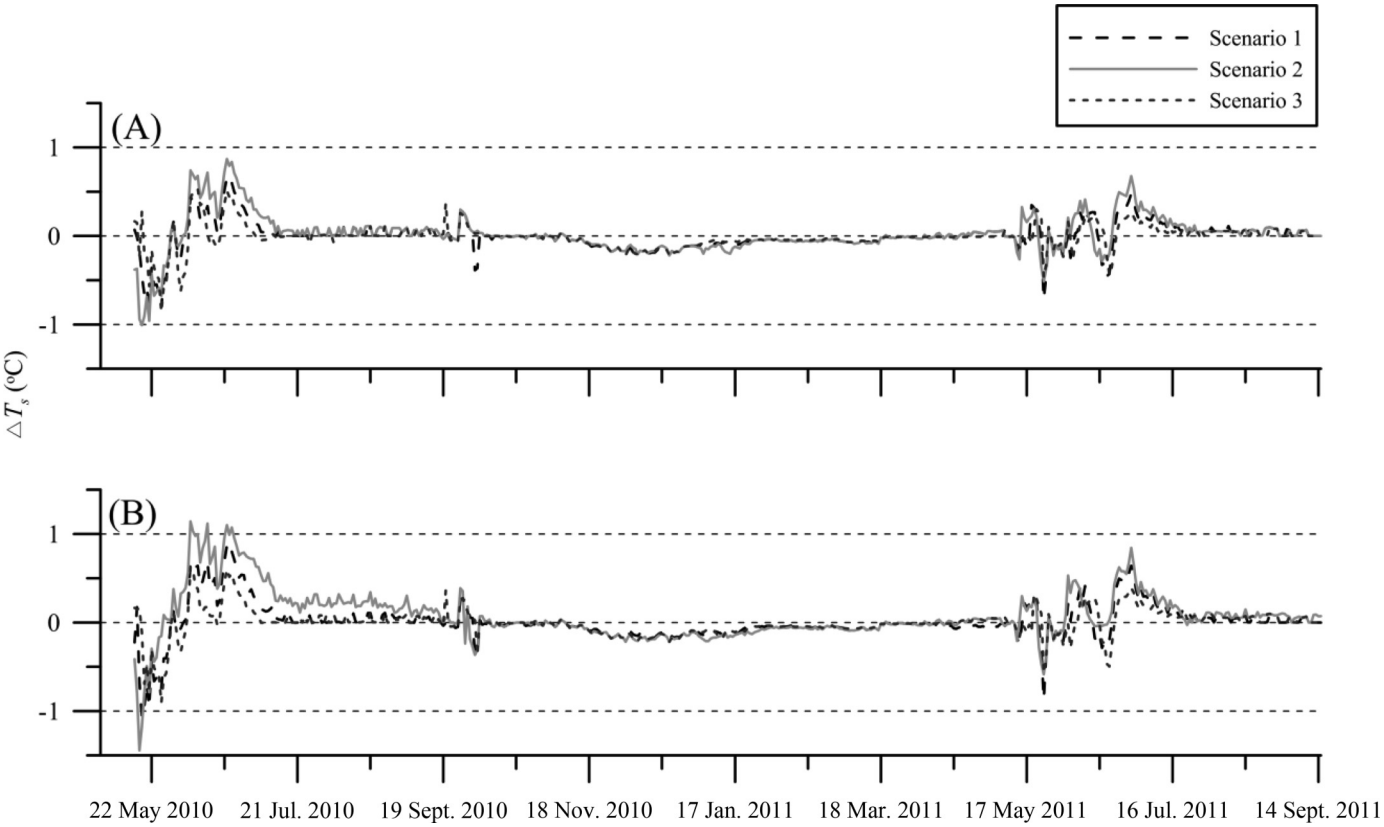
Fig. 8. Simulated change in daily mean T_s relative to the historical period for all three scenarios for the 2050 (A) and 2080 (B) periods.



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onset of spring snowmelt, a trend projected to continue into the future (Stewart, 2009). This finding is similar to previous a study that demonstrated T_s response to climate change was more related Q reductions than to increased T_a (Cristea and Burges 2010). We also demonstrate that T_s and subsequent salmonid incubation responses to future climate scenarios are likely to vary with interannual hydroclimatological conditions, with 2010 having a greater magnitude of Q and T_s response in all scenarios. This study was limited by assumptions made regarding boundary conditions. However, the intercatchment comparison among Star, Lynx, and Lyons East creeks demonstrates that T_s patterns can differ under similar T_a conditions, presenting a conceptual model for how thermal regimes may respond to hydroclimatic change in southwestern Alberta.

Many studies suggest increases in future summer T_s and thermal fragmentation in headwater streams during summer months (Isaak et al. 2012*b*; Isaak and Rieman 2013; Jones et al. 2013). While the approach used in this study likely produced conservative estimates of summer T_s change, our results support Tague et al. (2007). They suggest that groundwater-dominated streams are buffered from summer atmospheric influences. The intercatchment analysis of T_s and Q conditions also supports Tague et al. (2007), demonstrating that Star and Lynx creeks are buffered from atmospheric influences because of high groundwater contribution to total Q. Lyons East Creek had substantially lower groundwater contribution to total Q and therefore was more susceptible to atmospheric influence.

Results of this study do not suggest an increase in winter flooding demonstrated in previous studies (Wenger et al. 2011; Goode et al. 2013). It is likely that the cold, dry continental climate of western Alberta is not as susceptible to increased winter flooding events owing to the fact that the ratio of snow to total monthly precipitation is not projected to change substantially during the winter period. This study suggests that even with increased groundwater temperature in Scenarios 2 and 3, a peak Q shift towards earlier in the spring, resulting in reduced late-season groundwater contribution to total Q (Huntington and Niswonger 2012), is likely to increase T_s sensitivity to the atmosphere. This increased atmospheric sensitivity would likely accelerate in-stream ice formation (Brown et al. 2011) and subsequently decrease winter T_s.

Decreased winter T_s in critical headwater overwintering habitat for WCT is of particular concern given that this species is currently restricted in its range. Headwater groundwater-dominated streams provide this overwintering habitat because of reduced ice formation, tolerable T_s and dissolved oxygen conditions, and relatively stable Q conditions (Jakober et al. 1998; Power et al. 1999). Therefore, decreases in late season Q as a function of earlier onset of spring could result in a winter habitat bottleneck for WCT by reducing the carrying capacity of isolated headwater streams.

WCT are likely less sensitive to changes in climate than BT (Wenger et al. 2011); however, little is known about the potential biological implications of colder spring T_s. Negative trends in spring T_s were observed by Isaak et al. (2012*a*) and attributed to cooler T_a during the same period. Early spring T_s differences between Star and Lynx creeks were not attributed to T_a given that T_a was similar between sites.

While our results suggest earlier timing of WCT emergence in response to an earlier onset of peak Q under all scenarios used, it is unlikely that shifts of this magnitude would result in any biologically significant change in young-of-year WCT size. Based on growth rates obtained from Fraley and Shepard (2005), extending the growing period of WCT by 19 days would result in an additional growth of approximately 4 mm for WCT less than 4 years of

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Fig. 9. Percent difference in mean seasonal T_s for all three scenarios for the 2050 (A) and 2080 (B) periods relative to the 2010 to 2011 study period. For spring and summer comparisons, both 2010 and 2011 data were included.

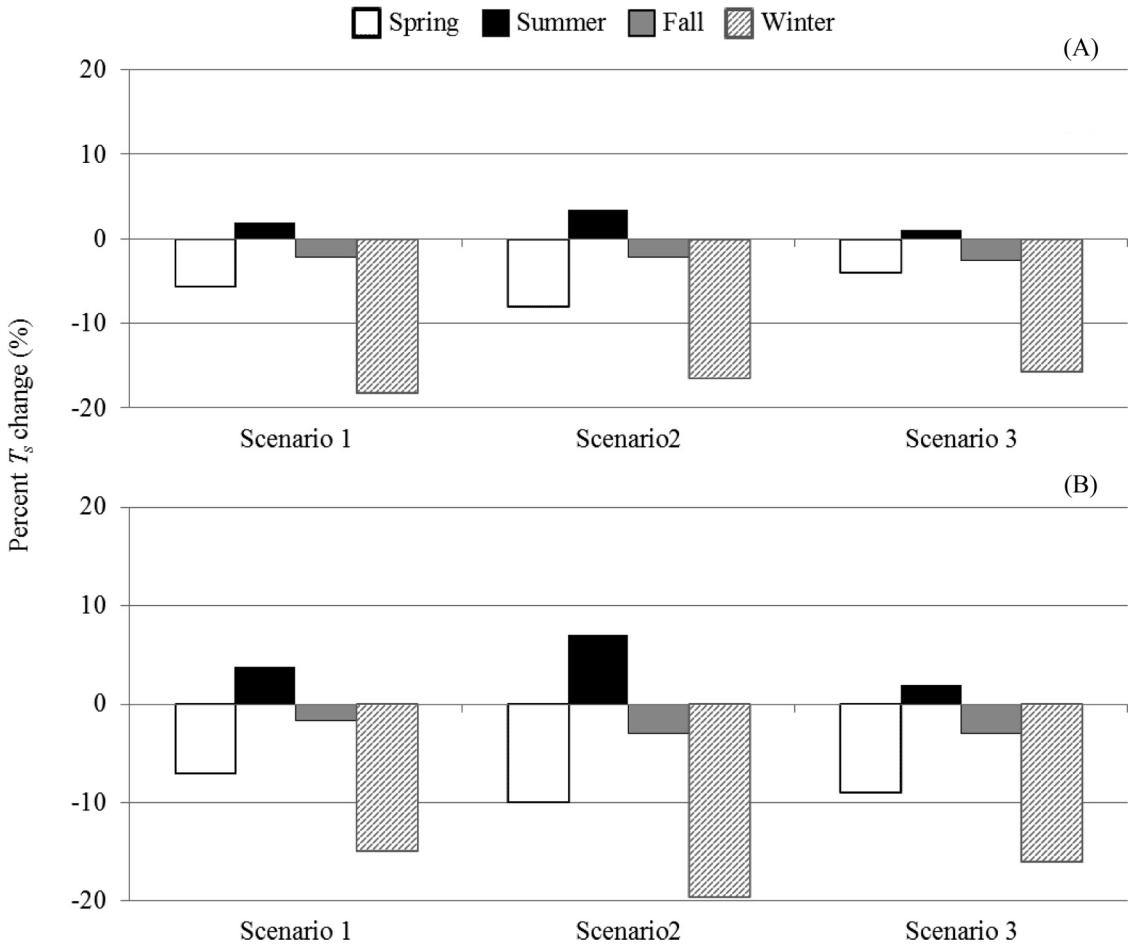

Table 3. Estimated date of westslope cutthroat trout (WCT) and bull trout (BT) fry emergence for the historical period and all three scenarios for the 2050 and 2080 periods.

	Date of emergence		
Scenario	WCT, summer 2010	WCT, summer 2011	BT, early spring 2011
Historical	28 July	7 Augsut	27 March
2050			
1	11 July	28 July	10 April
2	10 July	26 July	10 April
3	24 July	1 August	8 April
2080			
1	11 July	26 July	10 April
2	10 July	25 July	11 April
3	11 July	1 August	9 April

age. Others do suggest, however, that an earlier emergence could increase the survivorship of WCT (Coleman and Fausch 2007), currently limited in their distribution to high elevation portions of catchments, benefiting the species overall. T_s increases in high elevation, nutrient-poor streams are expected to improve the habitat of greenback cutthroat (*Oncorhynchus clarkii stomias*), with the assumption that populations remain isolated from non-native rainbow trout (Cooney et al. 2005). This assumption is important, as hybridization between these species is likely to increase in response to higher T_s (Muhlfeld et al. 2009; Rasmussen et al. 2010).

Thermally stable groundwater-dominated streams provide important BT spawning and incubation habitat by remaining ice-free over the winter period (Baxter and McPhail 1999; Baxter and Hauer 2000). Given the habitat selection specificity of these critical life stages, changes in groundwater-dominated catchments are likely to dramatically affect fall spawning salmonids. Our study suggests that a longer BT incubation period associated with decreased winter Q is possible under future climate scenarios. This demonstrates that independent of reductions in summer habitat (Isaak and Rieman 2013; Jones et al. 2013) and competition with non-native brook trout (*Salvelinus fontinalis*) (Warnock and Rasmussen 2013), BT populations could be affected by longer incubation periods resulting from decreased Q and increased winter ice cover. Therefore, fisheries management strategies should continue to be implemented in Alberta to help preserve the habitat of native BT populations.

This study provides a year-round perspective on the potential impacts of climate change on native salmonid habitat in the Rocky Mountains of southern Alberta using a process-based T_s modelling approach and intercatchment comparison of T_s, T_a, and Q. We demonstrate that stream thermal response to climate change is likely to be variable and that fall-spawning salmonids are likely more susceptible. McCullough et al. (2009) demonstrate that sublethal effects of altered hydrological and thermal regimes on salmonids are particularly important to consider because integrated population-level impacts are poorly understood. Therefore, we suggest that the perceptual model of T_s response to climate change should focus more on process understanding

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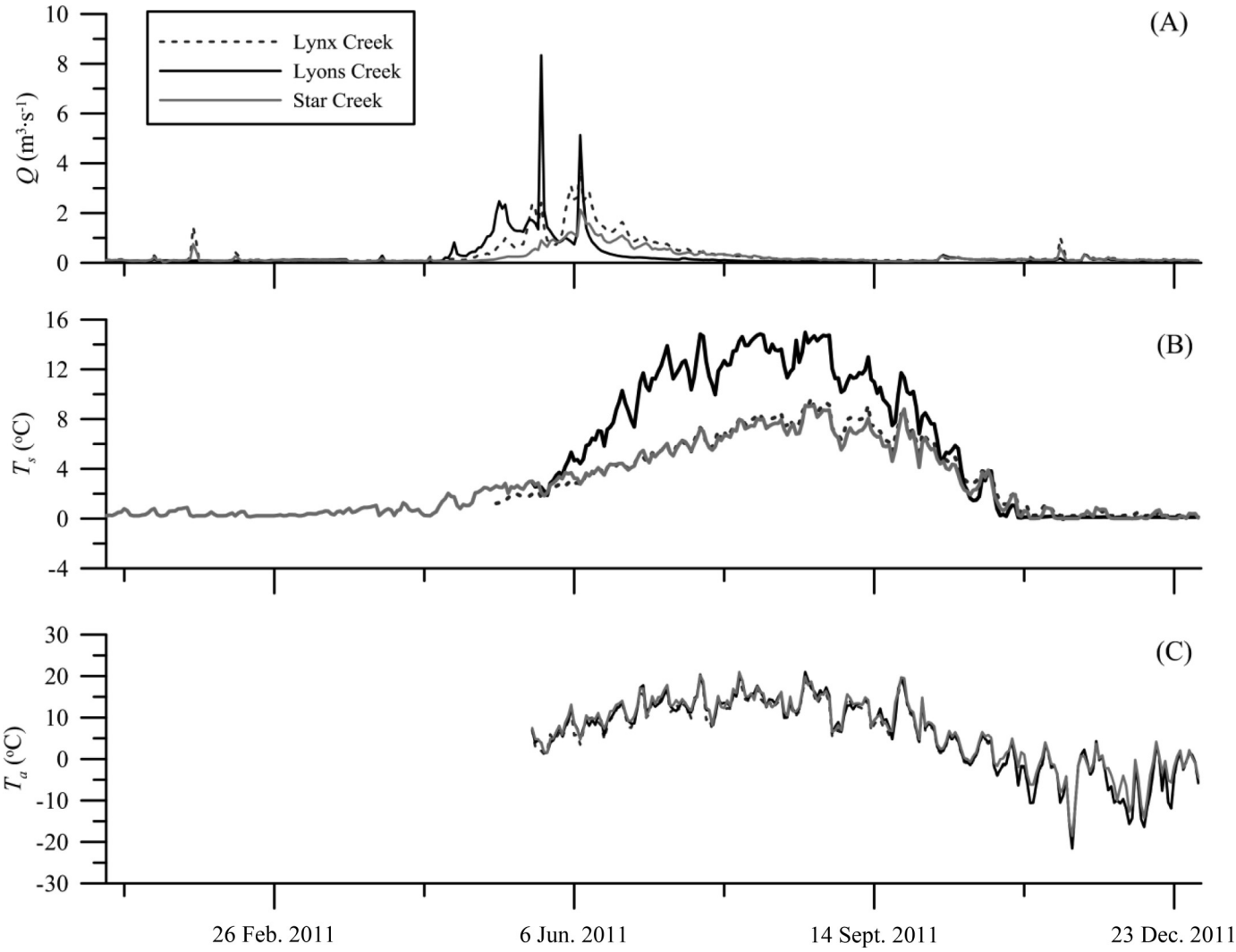
Fig. 10. Comparison of mean daily Q, T_s, and T_a from Star Main, Lynx, and Lyons East creek catchments for the period from 1 January 2011 to 31 December 2011.



and representation because modelling studies have strong potential for guiding management-related decisions.

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