

# Climate change impacts on streamflow availability for the Athabasca Oil Sands

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Received: 25 August 2014 / Accepted: 28 July 2015 / Published online: 8 August 2015  
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**Abstract** Future bitumen production in the Athabasca Oil Sands, one of the largest remaining reserves of petroleum on the planet, is a key factor in global climate policy and politics. Climate warming in the Athabasca River Basin (ARB) has the potential to limit future streamflow availability for aquatic ecosystem needs, as well as for water withdrawals in oil sands mining operations. This study applies the land surface model IBIS and the hydrological routing algorithm THMB, with forced output from CMIP5 global climate models, to examine the response of streamflow in the ARB to climate change this century. In comparison to the small impact of water withdrawals on streamflow, climate change impacts are projected to be the primary driver of future low flow occurrences. Although winter flows are most sensitive to water withdrawals under the historical hydroclimatological regime, future climate change is projected to increase winter flows and decrease summer flows instead, with the frequency of summer low flows projected to rise by up to 85 % in the highest future emissions scenario by the end of the century. A decline in water availability due to more frequent low flows could interrupt oil sands water withdrawals and subsequent daily bitumen production for an additional 2–3 months each year by mid-century. Adaptation to climate warming in the ARB will need to recognize these changing seasonal patterns of flow in order to maintain available flows for ecological needs and water withdrawals.

## 1 Introduction

The Athabasca Oil Sands is one of the largest remaining reserves of petroleum on the planet and a central point of friction in Canadian, American and global climate politics and policy. The estimated reserves of bitumen in Canadian oil sands is equivalent to 238 Pg of carbon,

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**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-015-1479-y) contains supplementary material, which is available to authorized users.

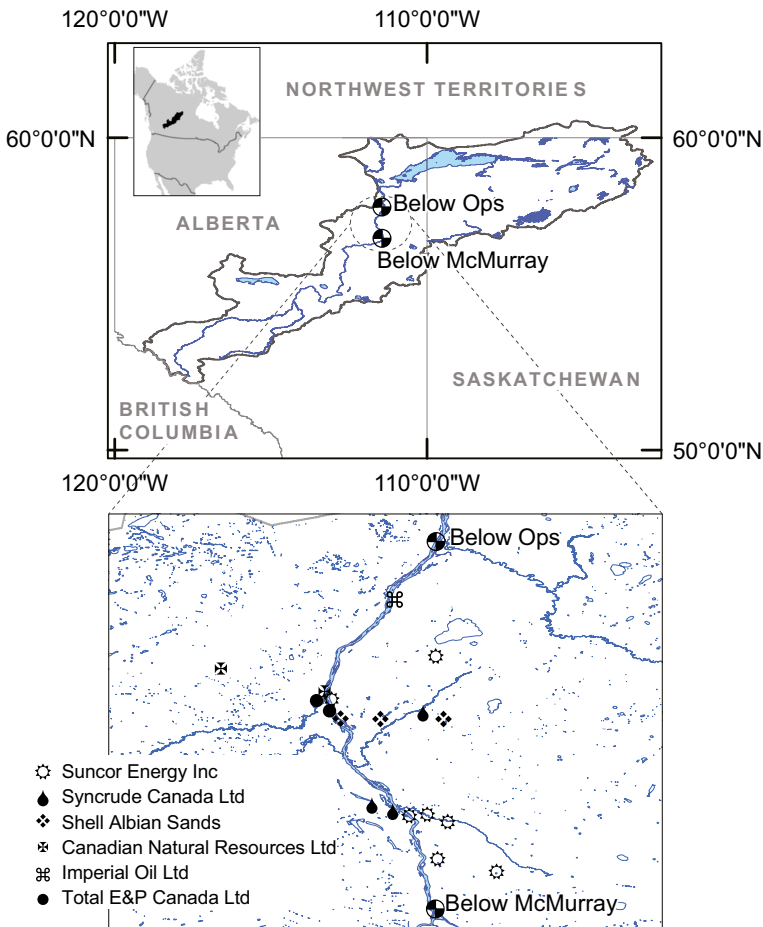
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sufficient to alone raise global temperatures by 0.24–0.50 °C if fully exploited (Swart and Weaver 2012). The impact of climate change on streamflow of the Athabasca River Basin (ARB; Fig. 1), and how that may create or exacerbate trade-offs between ecological and industrial water needs, is largely absent from the discourse on future bitumen production. Oil sands surface mining operations require constant water withdrawals from the Athabasca River in order to extract, process, and upgrade crude bitumen. Surface water use by mining operations accounts for the largest sectoral water allocations (62 %) and actual water use (57 %) in the ARB (AMEC Earth and Environmental 2007). As mining activity expands, surface water use demand is projected to rapidly increase, adding pressure to water availability in the ARB (Natural Resources Canada 2009).

Streamflow in the snowmelt-dominated ARB is sensitive to climate warming. The average annual temperature of the ARB is 2 °C (Burn et al. 2004) and annual precipitation averages 800 mm in the mountains, 500–600 mm in the central part of



**Fig. 1** Map of the Athabasca River Basin (ARB) including the Athabasca River (1538 km) and Lake Athabasca (7935 km<sup>2</sup>), and showing the location of the hydrometric station Below McMurray and the location of analysis for streamflow simulations downstream of oil sands mining operations, Below Ops. The basin drains an area of 269,000 km<sup>2</sup>, northward into the Arctic Ocean. Inset shows water withdrawal source locations used in the study

the basin, and 400–500 mm in the northeast (Kerkhoven and Gan 2006; Hamilton et al. 1985). The majority of precipitation, up to 75 %, falls in the summer months between June and October as major rainstorms (Longley and Janz 1978; Burn et al. 2004). The most recent IPCC projections for Northwest Canada show a mean annual temperature increase of 2.7 °C by mid-century and 3.5 °C by the end of the century, along with an annual precipitation increase of 10 % by mid-century and 14 % by the end of the century (Christensen et al. 2013). Observations of snowpack decline and periodic winter melting in recent decades in the ARB (Zhang et al. 2001; Sauchyn and Kulshreshtha 2008) are consistent with model projections of an earlier spring freshet and reduced summer flows under future warming (Pietroniro et al. 2006; Schindler and Donahue 2006). These climate-driven changes to streamflow patterns have been linked to a decrease in the frequency of floods that replenish the lakes and wetlands in the Peace-Athabasca Delta (Prowse et al. 2006; Wolfe et al. 2008), an ecologically sensitive region that provides important nesting and staging areas and habitat for a diverse wildlife population.

While climate change impacts on the ARB's hydrological regime have been well studied (e.g., Zhang et al. 2001; Prowse et al. 2006; Kerkhoven and Gan 2011), it is not known whether future industrial water demand will exacerbate and/or be threatened by the impacts of climate change. Currently, oil sands water withdrawals are licensed to ensure that in-stream flow needs, defined as the quantity, timing, and quality of water that is required to sustain a healthy aquatic ecosystem, are met (Alberta Environment 2007). Although the total annual licensed allocations are small relative to total annual streamflow (1–2 %), sustained bitumen production rates throughout the year, together with seasonality in flow, means that withdrawals can be large relative to low winter flows (Swainson 2009). In addition, industrial water use may explain the observed decline in summer streamflow, despite increased runoff from melting glaciers (Schindler and Donahue 2006; Squires et al. 2009). While past studies have shown that a long-term approach to applying water restrictions is needed (e.g., Mannix et al. 2010), there has been no assessment of how future changes in streamflow availability may affect planned water withdrawals because of the lack of a spatially-explicit modeling system that dynamically simulates the response of hydrology to climate variability, climate change, and site-specific water withdrawals.

This study examines the impacts of both climate change and oil sands water withdrawals on streamflow availability for industrial and ecological needs. Physically-based models of the land surface and hydrologic network are linked to simulate the response of streamflow in the ARB to multiple future climate change and water use scenarios. The results suggest that climate change has the greater impact on the frequency of low flows, and could limit the future availability of water for oil sands mining operations by mid-century

## 2 Methods

### 2.1 Model description

The Integrated Biosphere Simulator (IBIS), a land surface model that simulates the coupled soil-vegetation-atmosphere water and energy budgets (Foley et al. 1996; Kucharik et al. 2000),

and the Terrestrial Hydrology Model with Biogeochemistry (THMB), a hydrological model that uses prescribed river paths to simulate the storage and transport of water (Coe et al. 2002), are employed together to simulate land surface processes and streamflow across the ARB. IBIS and THMB have been used together in dozens of global, large-scale studies, including simulations of continental-scale runoff in North America (Lenters et al. 2000; Coe and Foley 2001) and Africa (Li et al. 2005), water cycling in Canadian boreal forests (El Maayar et al. 2001; Liu et al. 2005), Amazonian flooding (Coe et al. 2002), and Mississippi nutrient flux (Donner 2002). Although this study focusses on the lower reaches of the Athabasca River, the whole basin was modelled in order to capture the sensitivity of upstream processes to climate change, which can influence downstream flow.

IBIS was driven with seven required daily climate inputs (near surface specific humidity, near surface air temperature, eastward and northward near surface wind speed, total cloud fraction in the atmosphere column, precipitation, and surface air pressure) at a  $3/8^\circ \times 3/8^\circ$  lat-long resolution that matches the available climate re-analysis used to validate the model. Its modules operate at different time steps ranging from minutes to years, to yield the monthly-averaged surface and subsurface runoff outputs used in this study. IBIS and THMB were linked by driving THMB with the runoff outputs from IBIS to simulate the hourly flow of water through rivers, lakes and floodplains at a  $1/12^\circ \times 1/12^\circ$  lat-long resolution, and subsequently output a spatially explicit representation of monthly river discharge.

Validation of both models for the ARB (Online Resource 1) demonstrated that IBIS-THMB simulations adequately captured the average hydrograph shape of the Athabasca River at the Below McMurray station (closest to oil sands mining operations), including low flows in the winter, followed by rising discharge, leading to a broad, late-spring peak in flow. The interannual variability in simulated flow was also well correlated ( $r=0.73$ ) with observations. An overestimate of peak annual streamflow by the model during the last decade, which influences the seasonal hydrograph and the correlation between simulations and observations, is largely derived from a positive bias in the NARR precipitation rather than a systematic model bias (Online Resource 1). The influence of this precipitation bias on the 30-year mean baseline flows used in this study is small (maximum 10 % error, based on 60 % over-prediction for 50 % of the last decade). In addition, the overestimate of peak annual streamflow may also reflect other factors such as groundwater withdrawals or losses not accounted for in the model.

## 2.2 Future climate projections

Projected climate output for a 120 year period from 1981–2100 was obtained from the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012), which provides global climate model (GCM) output using the four IPCC Representative Concentration Pathway (RCP) climate scenarios (Moss et al. 2010). The climate scenarios range from RCP2.6, an extreme mitigation scenario (with a mid-century peak in radiative forcing), to RCP8.5, the highest radiative forcing scenario, which matches the trajectory of greenhouse gas emissions for the past decade. Only the three CMIP5 GCMs (GFDL-ESM2G, MIROC5, and IPSL-CM5A-LR) which provided all seven of the required IBIS climate input variables, in all four RCPs at the required temporal resolution could be used in this study. The models represent a range of climate sensitivities, from 2.4 °C for GFDL-ESM2G to 4.1 °C for IPSL-CM5A-LR (Andrews et al. 2012). Output variables from each GCM were re-projected from a native grid

onto the IBIS grid using bilinear interpolation. All variables were obtained at a daily time step, with the exception of surface pressure which was only available in 6-h intervals and averaged into daily intervals.

### 2.3 IBIS-THMB simulations

For all simulations in this study, IBIS was driven by daily climate output over a 120-year time period, 1981–2100, to yield monthly average surface and subsurface runoff. The simulated hydrograph produced with daily IBIS output did not differ significantly from that produced with monthly IBIS output, so the latter was chosen for computational speed (see Online Resource 1).

The GCM-driven monthly outputs from IBIS were adjusted to a historical baseline, before driving THMB. First, IBIS was driven by observation-based North American Regional Reanalysis (NARR) data over a 30-year historical time period between 1981 and 2010 (see Online Resource 1). A NARR-driven historical climatology for the IBIS output variables,  $NARR_{clim}(\bar{m})$ , was calculated from this IBIS output as an average for each month ( $m$ ) over all 30 years ( $y$ ). Second, IBIS was driven by GCM outputs over a 120-year time period between 1981 and 2100 to yield a monthly simulated time series,  $GCM_{sim}(m, y)$ . A GCM-driven historical climatology,  $GCM_{clim}(\bar{m})$ , was calculated from the 1981–2010 period of this IBIS output. A default anomaly correction (Eq. 1) was then applied by multiplying the IBIS simulated outputs by the ratio of NARR-driven and GCM-driven historical climatologies (Arnell and Reynard 1996), to yield the future projected IBIS outputs for each month and year,

$$GCM_{proj}(m, y) = GCM_{sim}(m, y) \cdot \frac{NARR_{clim}(\bar{m})}{GCM_{clim}(\bar{m})} \quad (1)$$

where  $\bar{m} = \frac{1}{30} \sum_{y=1981}^{2010} m_y$

In cases where the GCM-driven historical climatology was zero, the delta change method (Hay et al. 2000) was applied instead by subtracting the GCM-driven historical climatology from the GCM-driven simulation time series, and then adding the NARR-driven historical climatology. This was the secondary method for anomaly correction, since the delta-change method can produce negative values for positive-only variables like runoff.

Since Eq. 1 can lead to very large adjusted values when  $GCM_{clim}(\bar{m}) \ll NARR_{clim}(\bar{m})$ , a maximum value for each grid cell was defined to be ten times the maximum of the NARR-driven historical time series. If the anomaly-corrected values using Eq. 1 exceeded this maximum, the delta change method was employed. This factor of ten threshold was tested on the time series of multiple climate variables and was found to be appropriate in removing anomalous spikes that resulted from the default correction method.

The projected (i.e., anomaly-corrected) IBIS outputs were then used to drive THMB to simulate streamflow in the ARB over the 120 year period. In order to simulate the maximum potential effect of water withdrawals, each THMB simulation was run twice, once with no withdrawals and once with a maximum withdrawal rate of 21 m<sup>3</sup>/s, estimated based on licensed streamflow allocations. As of 2013, there were twenty licenses for oil sands mining water withdrawals from the Athabasca River, associated with six operating mine sites and four additional sites that had been granted regulatory approval (Online Resource 2). Since

allocations generally exceeded actual use, licensed water allocations were used to set the upper limit of projected withdrawals. Spatially explicit water withdrawals were simulated in THMB by extracting the licensed water allocations at each time step, for each grid cell that corresponds to a withdrawal location.

A total of 24 IBIS-THMB simulations were run using a combination of the three GCMs, four climate scenarios and two water withdrawal scenarios. The streamflow output was evaluated at the location ‘Below Ops’ (57.7083°N, -111.4583°E), which lies downstream of all surface mining oil sands operations. IBIS-THMB outputs were analyzed as running averages over 20-year time windows, with a focus on changes in mid-century (2041–2060) and end-of-century (2081–2100), relative to today (1991–2010).

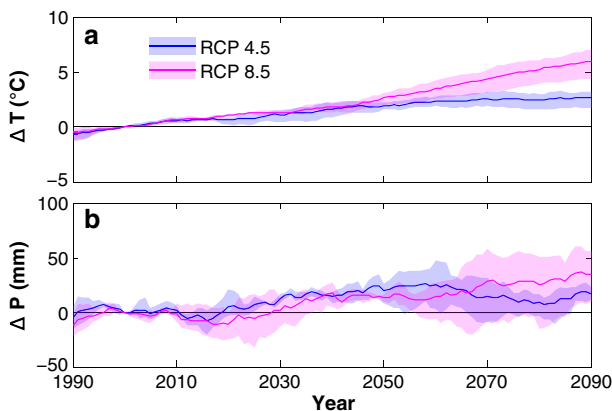
### 3 Results

#### 3.1 Climate projections

Relative to today, the mid-century annual mean air temperature is projected by the three GCMs to rise by 0.9 to 3.1 °C, while the end-of-century annual mean air temperature is projected to rise by 0.5 to 7.0 °C (Fig. 2, Table 1 in Online Resource 3). Mean annual precipitation is also projected to increase, although the magnitude of the change varies across the three GCMs. IPSL-CM5A-LR projects the largest precipitation increase of 56 mm (12 %) in RCP8.5 by end-of-century and GFDL-ESM2G and MIROC5 project the largest decrease of 28 mm (6 %) in RCP6.0 by mid-century. By mid-century and end-of-century, all three GCMs project an increase in precipitation in RCP8.5. The ratio of rain to snow increases linearly in response to warming ( $r^2=0.6$ ,  $p<0.01$ ), with less variability than the precipitation response.

#### 3.2 Streamflow projections

The GFDL-ESM2G-driven simulations project an increase in streamflow for all climate scenarios by the end-of century, while the IPSL-CM5A-LR-driven simulations project a

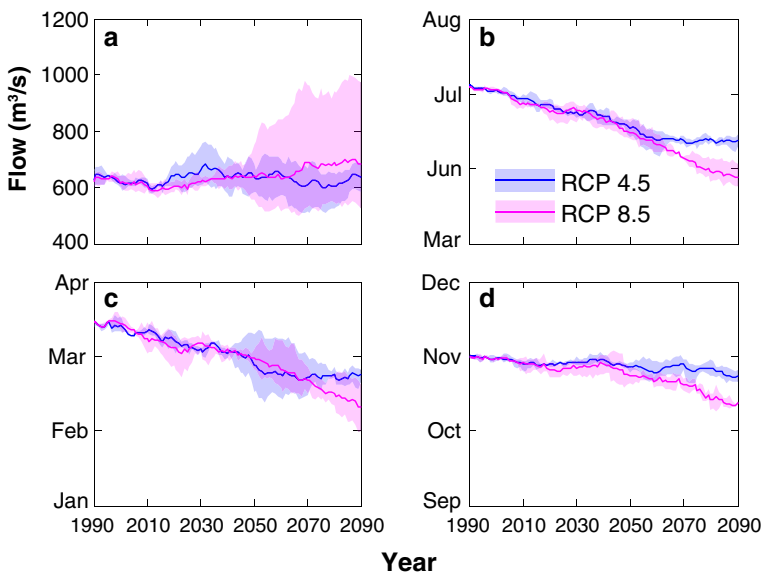


**Fig. 2** Simulated **a** change in annual temperature ( $\Delta T$ ), and **b** change in annual precipitation ( $\Delta P$ ) projected by the three GCMs. Results for RCP2.6 and RCP6.0 are available in Online Resource 3

decrease in streamflow for three of the four climate scenarios (Fig. 3a, Table 2 in Online Resource 3). By end-of-century in RCP8.5, the IBIS-THMB simulated mean annual streamflow increases by 53 % in the GFDL-ESM2G-driven simulations and decreases by 10 and 12 % for the MIROC5- and IPSL-CM5A-LR- driven simulations respectively, relative to today.

Streamflow did not show a linear dependence on changes in temperature, but did increase linearly with changes in precipitation ( $r^2=0.2$ ,  $p<0.01$ ). This is in contrast to previous MISBA projections where runoff was more strongly correlated with changes in temperature than precipitation (Kerkhoven and Gan 2011). Kerkhoven and Gan (2011) projected mean annual flow to change by  $-8$  to  $-54$  % from the 1957–2007 period to the 2040–2069 period, compared to the IBIS-THMB projections of change in mean annual flow of  $-6.5$  to  $19.0$  % by 2041–2060. The results are not directly comparable, however, because of different baseline periods.

Three metrics were used to evaluate shifts in the seasonal patterns of streamflow (Fig. 3b–d, Table 2 in Online Resource 3), following Burn (2008). First, the timing of spring runoff was estimated as the date by which 10 % of the annual streamflow volume had occurred. Second, the centroid of flow distribution was calculated as the flow-weighted average time of discharge. Third, the persistence of runoff was estimated as the date by which 95 % of annual flow volume had occurred. The annual centroid and spring runoff occur earlier in all IBIS-THMB simulations by mid-century and end-of-century (Fig. 3b–c, Table 2 in Online Resource 3). By end-of-century in RCP8.5, all three GCMs project the centroid of flow distribution to occur a month or more earlier, shifting from early July to late-May (Fig. 3b, Table 2 in Online Resource 3), and the timing of spring runoff to shift from mid-March to early February



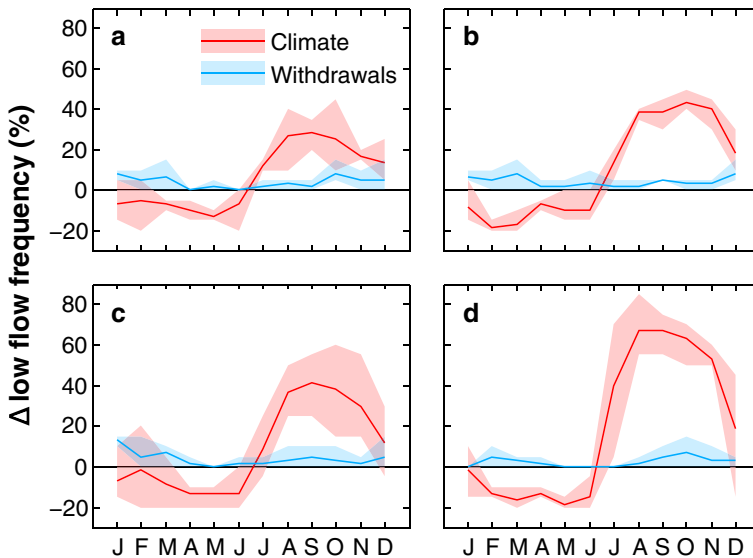
**Fig. 3** Streamflow patterns for the Athabasca River at the location Below Ops: **a** annual mean streamflow, **b** centroid of flow distribution, **c** timing of spring runoff, **d** persistence of flow. *Dashed lines* show the mean values across all GCMs and *shaded areas* show the range of values across GCMs. Years are the mid-point of running 20-year time windows over which results are averaged. Results for RCP2.6 and RCP6.0 are available in Online Resource 3

(Fig. 3c, Table 2 in Online Resource 3). Late season runoff is less persistent by over half a month by end-of-century in RCP8.5, in all three GCMs (Fig. 3d, Table 2 in Online Resource 3). The centroid of flow distribution, timing of spring runoff, and flow persistence also occur progressively earlier in linear proportion ( $p < 0.01$ ) to an increase in the ratio of rain to snow.

### 3.3 Frequency of low flows

The frequency of statistical low flows was calculated as a measure of streamflow impact on in-stream flow needs, since the seasonality of low flows has been documented as a primary water management concern in the ARB (Locke and Paul 2011). Following the Alberta Government method, minimum environmental flows were defined for each month relative to a threshold that was computed based on the magnitude of flow that is exceeded 80 % of the time in that month, over a 30-year (1981–2010) historical period (Locke and Paul 2011). This low flow threshold corresponds to a minimum flow level required to maintain the conditions of an unaltered flow regime. Flows below the threshold are considered low flows, and the frequency of low flows describes how often river flows fall below the flow threshold for historical in-stream flow needs.

Patterns of decreasing and increasing low flow frequency occur in the first (January–June) and second (July–December) halves of the year, respectively (Fig. 4, Table 3 in Online Resource 3). All three GCMs project an increase in low flow frequency across all climate scenarios (except in RCP2.6) from August–October by mid-century, and from July–November by end-of-century. By end-of-century in RCP8.5, low flows are projected to occur 85 % more frequently in August for IPSL-CM5A-LR-driven projections, and 75 % more frequently in September for GFDL-ESM2G-driven projections.

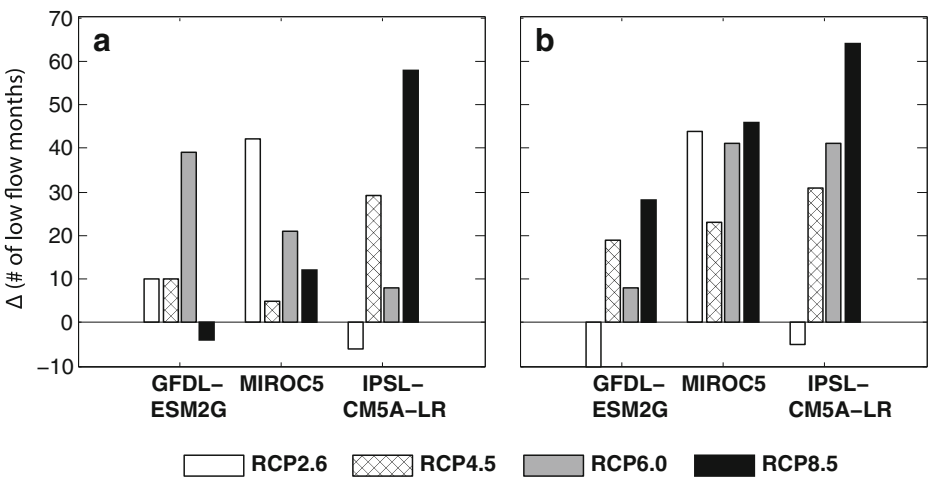


**Fig. 4** Change in low flow frequency relative to today for **a** RCP4.5 at mid-century **b** RCP4.5 at end-of-century, **c** RCP8.5 at mid-century, **d** RCP8.5 at end-of-century. *Red and blue* show the change due to climate change and water withdrawals respectively. *Dashed and dotted lines* show the mean value across all GCMs and *shaded areas* show the range of values across GCMs



A comparison of the impact of (licensed) water withdrawals relative to no water withdrawals over the historical time period showed that the low flow frequency increased in 8 months of the year, by 4–17 %, with the largest increase during March, the minimum flow month. For the 4 months of June, July, August and November, there was no increase in the frequency of low flows. In general, simulated water withdrawals decreased projected streamflow by a fixed amount that was small compared to the magnitude of projected changes in flow due to climate change (Fig. 4). For example, by mid-century, between April and June in RCP8.5, the projected low flow frequency decreases on average by 13 % due to climate change and increases on average by 1 % due to water withdrawals. From August–October in RCP8.5, the projected low flow frequency increases on average by 39 % due to climate change and only by an additional 4 % due to withdrawals by mid-century. By end-of-century, the relative contribution of water withdrawals to the low flow frequency becomes even smaller.

The frequency of low flows indicates periods of potential water shortage that may halt oil sands water withdrawals and therefore bitumen production, if the protection of in-stream services is required. Periods of water shortage for oil sands mining operations were quantified as a change in the number of months that low flows occur by mid-century and end-of-century (Fig. 5). By mid-century, all but three streamflow simulations (GFDL-ESM2G in RCP8.5, MIROC5 in RCP4.5, and IPSL-CM5A-LR in RCP2.6) project an increase in the number of months with potential water shortages. By end-of-century, all but one simulation (GFDL-ESM2G in RCP2.6) projects an increase in water shortage. Projected water shortage is also seasonal, increasing by end-of-century by up to 17 % during spring (April–June), while decreasing by up to 75 % during summer (July–October). The IPSL-CM5A-LR-driven simulation for RCP8.5 projects a maximum increase in water shortages by mid-century, which translates into a 22 % increase in interruptions to oil sands operations, and equivalent to over 2 years of oil production per decade. By end-of-century, this rises to a 28 % increase in interruptions.



**Fig. 5** Change in the number of months during the mid-century and end-of-century time periods that flow falls below the low flow threshold, relative to today, for each climate scenario

## 4 Discussion

Despite disagreement over the impact of future climate change on mean Athabasca River streamflow, the three climate models used in this study generally agreed on the projected frequency of low flows. Clear seasonal patterns in the frequency of low flows for the Athabasca River are projected to emerge over time as climate warming continues. The streamflow simulations project that by end-of-century, low flows (defined based on historical low flow levels) will no longer occur (0 % frequency) in some winter months (November–March) and will always occur (100 % frequency) in some summer months. In contrast, water withdrawals have a small aggregate effect on low flow frequency; for example, under conditions of maximum permitted water withdrawals and no climate change (an extreme, unlikely scenario), low flows will occur with a maximum 37 % frequency and only during the winter. Constant water withdrawals throughout the year reduce a greater fraction of the streamflow during low winter flow periods as expected. Climate warming, however, is projected to increase flow in the winter months and counter the small effect of water withdrawals. Instead, frequent low summer and late season flows become a key concern.

While low flows are a limited means for assessing the function of river ecosystems (Landres et al. 1999), the projected climate-driven changes in low flows may have consequences for the ability of oil sands operations to continuously withdraw water, depending on the regulations related to maintaining minimum environmental flows. Assuming that withdrawals are not permitted below the Q80 flow threshold, a production stop of up to 58 months, projected by mid-century in one case, would be equivalent to the interruption of roughly 900 million barrels of oil production at Suncor's Millenium and Steepbank mines, based on estimated future production capacity (The Oil Sands Developers Group 2013). Athabasca oil sands mining operations are forecasted to continue through much of the mid-century time period, given that the timeline for planned projects currently under regulatory review include the Teck Resources Ltd Frontier mine, with Phase 1 scheduled to begin in 2021 and Phase 4 to begin in 2030, as well as Imperial Oil's Phase 3 of the Kearl mine, to begin in 2020 (The Oil Sands Developers Group 2013). At a rate of three million barrels of oil production per day (both mined and in-situ recovery) Alberta oil sands reserves are expected to last for over 150 years (Alberta Environment 2009). The mid-century time period is therefore a realistic planning horizon for water withdrawals.

The timing of low flows is an important consideration in water resource management, where operational decisions often depend on the availability of a baseline flow at a given time (e.g., Alberta Environment 2007). The frequency of future oil sands water withdrawal restrictions and water shortages will depend in part on how an acceptable low flow threshold is quantified. A major aim of Phase Two of the Lower Athabasca Water Management Framework, currently under development, is to define an acceptable low flow threshold below which it is recommended there be no further withdrawals of water (Ohlson et al. 2010). One challenge in establishing a low flow threshold is that thresholds based on long-term historical flow are only valid under stationary climate conditions (Dettinger et al. 2004; Stewart et al. 2004). Another is that the threshold must negotiate the competing needs of industry and aquatic ecosystems for water, which will require a balance between maintaining in-stream flow needs with achievable restrictions on oil sands water demand. Regardless, implementing a low flow threshold in the next phase of the water management framework will require that industrial water demand adapt to projected changes in streamflow due to climate change.

The projected patterns of flow, particularly the timing of future low flow occurrences, are broadly consistent with the results of previous modelling studies and a general understanding of the response of snow-dominated river basins to climate warming (e.g., Sauchyn and Kulshreshtha 2008; Kerkhoven and Gan 2011). Future streamflow is expected to be a product of changes in precipitation amount and type, evapotranspiration, and snowpack accumulation and melt in large western Canadian river basins like the ARB (Schnorbus et al. 2011). Although there is disagreement between the simulated precipitation in some time periods and scenarios between the three GCMs available for this study, the projected precipitation changes are consistent with expectations of increasing precipitation and a higher rain to snow ratio in a warmer future (Schindler and Donahue 2006). In addition, projections that both the spring runoff and the centroid of flow distribution will occur earlier in the year are consistent with recent observed trends that show increasing temperatures driving a progressively earlier snowmelt, a decline in maximum snowpack depth and persistence, and more frequent periodic winter melting (Zhang et al. 2001; Schindler and Donahue 2006). Overall, the projected changes in key flow variables agree with other studies (e.g., Kerkhoven and Gan 2011) for a warming boreal basin, despite differences in the range of projected change in annual mean, minimum, and maximum runoff, which are at least in part due to differences in baseline years and the time step of model runs.

Projected flow patterns are also sensitive to the temporal and spatial variability in temperature and precipitation patterns across different climate scenarios and GCMs (Prowse et al. 2006; Toth et al. 2006). For example, a warmer and drier scenario could increase evaporation relative to precipitation and result in reduced runoff. Conversely, less warming in a wetter scenario could result in increased snowpack accumulation and runoff (Hinzman et al. 2005). The selected GCMs in this study project an annual precipitation increase of 2–5 % for the ARB in RCP4.5 by end-of-century, which represents the middle of the range in precipitation change (–4 to 14 %) projected by all CMIP5 models for West North America (28.6°N to 60°N, 130°W to 105°W) (Christensen et al. 2013), which includes the ARB. Employing a wider selection of GCMs in this study may broaden the range of future projected streamflow, however, such analysis was not possible because current available output from the other CMIP5 models lack the complete set of daily climate variables needed to force IBIS for all climate scenarios.

## 5 Conclusions

This study suggests that bitumen production in the Athabasca oil sands may not only influence future carbon emission and Canada's contribution to climate change, but may itself be influenced by the impacts of climate change depending on the regulatory environment. Changes in future low flow frequency during the respective historical summer and winter periods are projected to affect the seasonal availability of water for oil sands water withdrawals. The frequency of low flows can be used to quantify the frequency of future interruptions to water availability for oil sands production, assuming that restrictions will exist on water withdrawals during low flow periods. As a result, a trade-off arises between meeting industrial and ecological water demands. Future water use in the Athabasca oil sands may require operational decisions that adapt the timing of water withdrawals to the timing of available flows. Projected changes in streamflow due to climate warming can inform such decisions by providing a tool to estimate the magnitude and uncertainty of change in future water availability.

**Acknowledgments** The authors thank P. Snyder and D. Price for assistance with IBIS, M.T. Coe for assistance with THMB, C. Milly for insight into interpreting the GCM outputs, and two anonymous reviewers for helpful comments. This work was supported by a NSERC Graduate Fellowship and a NSERC Discovery Grant (S.D. Donner).

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