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Assessing the impacts of climate change on ice jams along the Athabasca River at Fort McMurray, Alberta, Canada

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In northern rivers, ice jams can be one of the most dangerous hydrological events during spring ice cover breakup because they can produce extremely high water stages compared to open water flood levels potentially resulting in property and infrastructure damages, loss of human life and detrimental effects on riverine ecosystems. Ice jam related floods have caused millions of dollars of damages during the breakup period along the Athabasca River at the Town of Fort McMurray. Although a considerable number of studies have already been carried out researching the formation of extreme ice jam events, recent climate variability makes it very challenging to predict the behaviour of such events in the future. This study uses the meteorological forcing data from the North American Regional Climate Change Assessment Program (NARCCAP) to model future climatic scenarios using the physically based hydrological model MESH. The resulting hydrograph, along with projected climate data, are incorporated in a one-dimensional hydrodynamic numerical river ice model, RIVICE, to simulate the development of ice jams along the river in future climatic conditions. The main objectives of this study are to determine the possible water stages of ice jam flooding in this changing environment, and assess future ice jam flood hazard for the Town of Fort McMurray.

1. Introduction

Ice jam formation and release during the spring breakup are major concerns for government agencies, planners, development companies and communities along northern rivers. Ice jams can produce significant high water levels and flood damages compared to open water floods. Historically, the Athabasca River at Fort McMurray, Alberta is an ice-jam flood prone area in Canada. To date, there have been many documented ice-jam events at this location, particularly the events of 1962 (Alberta Environmental Protection & Division, 1993), 1978 (Andres & Eng, 1980), 1972, 1977 (She et al., 2007), and 1997 (Hutchison & Hicks, 2007). Most of these jams caused severe flooding and millions of dollars in damages to infrastructures in the town. A significant portion of the Town of Fort McMurray is still located within the 1:100 year flood hazard area (IBI and Golder Associates Ltd Report, 2015). Efforts have already been undertaken to mitigate and plan for the ice-jam flood effects in this area such as estimating the direct and indirect flood damage potential, assessment of stage frequencies, installation of dykes and land use regulation based on the historical data (IBI and Golder Associates Ltd Report, 2015). However, ice jam formation and flooding mechanisms at this location are still not well understood and the changes in climate and the flow regime in this region introduce uncertainty in river ice-jam studies and ice-jam flood mitigation strategies.

Flow characteristics, winter ice phenology and stream morphology (related to the sediment regime) are the three main factors that control river ice processes (Beltaos & Burrell, 2003). Recent studies suggest that these three factors are significantly impacted by climate change. As a result, patterns in the ice season are changing leading to the severity of ice-jam flooding either decreasing or increasing depending on local climatic conditions (Beltaos & Prowse, 2009). A considerable number of studies have been carried out to determine the long-term hydrologic and climatic variations along the Athabasca River (Bawden et al., 2014; Burn et al., 2004; Peters et al., 2013; Schindler & Donahue, 2006; Zhang et al., 2001). All of these studies report an overall decreasing trend in the annual mean river flows. In the last century, a warming trend in the mean annual air temperature has also been observed over western Canada, including the Athabasca River basin (Zhang et al., 2000). Bawden et al. (2014) and Peters et al. (2013) show that there has not been a consistent trend in warm season air temperatures along the Athabasca River since 1977; a decreasing trend in warm-season air temperatures has been observed in the upper portion of the basin while a significant increasing trend has been observed in the lower part of the basin. The combined effects of this changing flow regime and climate are affecting the ice regimes of the river and changing the frequency of ice-jam flooding. Therefore, climate change impacts on river ice is a growing concern for riverside communities to determine the future risks of ice-jam flooding.

The main purpose of this study is to examine the impact of climate change on the ice regime of the Athabasca River at Fort McMurray. The specific objective of this research is to determine the ice regimes and ice-jam stage-frequency distributions under the projected climate scenarios along the Athabasca River.

2. Methods

2.1 Study Site

The Athabasca River (Figure 1) is one of Canada's longest rivers which originates in the Rocky Mountains of Southern Alberta and flows into the Peace-Athabasca Delta (PAD) in northern Alberta. The 1,538 km long river flows past numerous urban communities such as Jasper, Brule, Entrance, Hinton, Whitecourt, Fort Assiniboine, Smith, Athabasca, Fort McMurray, and Fort MacKay before emptying into Lake Athabasca and the PAD. The study area is a 51 km stretch extending from approximately 26 km upstream from the Town of Fort McMurray at the Cascade Rapids to approximately 25 km downstream from the town at Inglis Island. This part of the river is characterized by the series of rapids and numerous sand bars and islands. The river's widths range from 450 to 750 m and the slope varies from 0.001 in the upper reach to 0.00023 in the lower reach. The downtown area is situated at the confluence of the Athabasca and Clearwater rivers. The Clearwater River is an additional source of water and ice to the Athabasca River and can be an influential flooding factor during an ice jam event.

The climate at Fort McMurray is continental with mean annual daily air temperatures varying between– 6.8 and 5.3 °C and annual precipitation varying from 400 to 500 mm. The hydrograph of the river is characterized by low flows in the winter months and high flows during the spring and summer seasons.

2.2 Hydrologic and Meteorological Data

Modélisation Environmentale – Surface et Hydrologie (MESH), a semi-distributed physically based land surface-hydrological modeling system developed by Environment Canada (Pietroniro et al., 2007) was used for the hydrological modelling in this study. The model was forced with data from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2012; Mearns et al., 2009) to assess the future implications of a changing climate on streamflow and river ice processes. NARCCAP consists of six Regional Climate Models simulated over consistent time periods (1971-2000 and 2041-2070) and spatial domains of equal resolution (∼50 km) (Weller et al., 2013). It uses the A2 emission scenario, since it was one of the 'marker' scenarios developed by the IPCC (Nakicenovic et al., 2000). It is at the higher end of the SRES emission scenarios (but not the highest) and most relevant based on the impact and adaptation view (NARCCAP, 2016). From the available global circulation models (GCMs), the Community Climate System Model (CCSM) and the Third Generation Coupled Climate Model (CGCM3) were chosen, as each of them have the data for both historical (for calibration and validation purposes) and future periods. They were both used to drive the Canadian Regional Climate Model (CRCM) (Caya & Laprise, 1999) to produce regional projections. Data from NARCCAP was preferred due to their high temporal resolutions and availability of all seven forcing files (air temperature, precipitation, long wave radiation, short wave radiation, humidity, wind, atmospheric pressure) necessary for MESH simulations.

Figure 2 compares the daily mean air temperature for a historical 30-year period (1971-2000) between the observed and CRCM+CCSM and CRCM+CGCM3 simulations. The graphs show that CRCM+CGCM3 is quite comparable with the observed data with a bias of less than 5%. However, CRCM+CCSM was found to have a slightly higher bias (up to 15%). Similarly, flood frequency distributions were calculated from the observed and simulated flows (see Rokaya et al.

(submitted) for details on hydrological model set up, calibration and validation). The resulting flood frequency distribution of the CRCM+CGCM3 flow scenario and observed discharge show good agreement. The results from CRCM+CCSM, however, like the air temperature analysis, is underestimated (Figure 3).

The cumulative degree days of freezing (CDDF) and cumulative degree days of melting (CDDM) were calculated using both observed and climate change air temperature data to analyze the ice growth and ice duration at the study site. The CDDF was calculated by summing all the daily mean air temperatures below zero starting from October 01 and ending in May 31 and the CDDM was calculated by adding all of the daily mean air temperatures above -5 degree from February 01 to May 01.

2.3 RIVICE Model Setup

A one-dimensional, hydrodynamic river ice model, RIVICE, was used in this study to assess the ice-jam formation along the Athabasca River at Fort McMurray under future climate and hydrological conditions. This study used the same RIVICE model setup that is presented by Lindenschmidt (2017). The model domain extends from the Cascade Rapids to Inglis Island along the Town of Fort McMurray. More detailed information about the model parameter setup, calibration and validation can be obtained from Lindenschmidt (2017).

The model was embedded in PEST (Parameter Estimation Program) for the Monte-Carlo Analysis (MOCA) framework to run sets of thirty simulations repeatedly using a different set of parameters and boundary conditions. This study extracted the same parameter setup that is used in Lindenschmidt (2017), however the boundary conditions are extended in this study based on future climatic and hydrological conditions. The boundary conditions used in the MOCA framework are discussed below:

Inflowing ice volume: the extreme value frequency distribution of inflowing ice volume at Fort McMurray during ice jam events was determined to have a location parameter of 6.5 million m^3 and a scale parameter of approximately 3 million m^3 (Lindenschmidt, 2017). These values were then adjusted to estimate the future ice volume distribution using the estimated future ice thicknesses along the river. Observed ice thickness data were made available from the study reach by Environment Canada (Figure 4). The Stefan equation was applied to estimate the future average ice thicknesses on 01 March using CDDF values calculated from the two climate change model combinations CRCM+CCSM and CRCM+CGCM3. The changes ice thicknesses were then used to estimate the percentage change of inflowing ice volumes in the future.

$$h = \alpha\sqrt{CDDF} + b \qquad (1)$$

where, h is ice thickness in meters, CDDF in °C-days and α is the slope. The b intercept determines a typical initial ice thickness at freeze-up.

Upstream discharge: upstream flow distribution for the future was estimated from the hydrological model MESH using the extreme value Gumbel distribution. Thirty random values were drawn from the distribution and used as input to the MOCA simulations.

Downstream water level: future flows were applied to a rating curve to determine the changes in water level at freeze-up. These values served as plotting positions to fit the extreme value Gumbel distribution to determine the future water level distribution at the downstream boundary of the model domain.

Toe of the ice jam: a uniform distribution of the river chainage downstream of the gauge was applied for the random selection of the toe locations of ice jams along the river.

3. Result and Discussion

3.1 Ice Duration under Future Climate Scenarios

The duration of the ice season is defined for this study as the total number of days from the starting date of ice formation to the end date of ice cover breakup along the river. The 'B' values in the hydrometric flow records indicate the presence of ice in the river. Thus, the historical ice duration for the study site was obtained from the hydrometric station.

To predict the future ice duration, the historical ice duration must be related to the climatic conditions of the corresponding time period. The historical CDDF and CDDM at the start and end date of the ice cover was used as a proxy for predicting the future ice-on and ice-off dates in the river. Figure 6 shows the CDDF curves and the ranges of first day of freezing for the two climate model combinations, for the historical and future time periods. Both models predict that the river is going to freeze up earlier in the future. The historical CDDF curve indicates that the river usually starts to freeze at the beginning of November while the future curves indicate that the river may start to freeze at the end of October, overall 4 or 5 days earlier than the historical time period. This result is also consistent with the future mean air temperature trend of the river area (Fig. 5). It shows that the mean air temperature is going to be below zero starting the second week of October in the future. Therefore, earlier cold air temperatures will trigger an earlier freeze-up along the river.

Similarly, the CDDM curves show the ranges of the last days of breakup for the two climate model combinations in the historical and future time periods (Figure 7). The results show that the historical range of the last day of breakup has comparatively wider ranges from the third week of April to the first week of May. In the future, the CRCM+CCSM model combination predicts that the last day of breakup is likely to occur at the end of April and the CRCM+CGCM3 model combination predicts that it will occur during the first week of May. Therefore, the breakup in the future is likely to occur at least one week later. Although, the air temperature curves show warmer trends during the winter in the future, it will be relatively colder in the months of April and May. This cooler trend in the future may extend the probable breakup period during the breakup season.

3.2 Ice-jam flood assessment under future climate

The spring flow hydrograph is one of the most influential factors for river ice breakup and ice-jam formation along the river. Figure 8 shows the future mean daily discharges at Fort McMurray generated from the MESH modeling system with two climate model combinations (CRCM+CCSM and CRCM+CGCM3) over the period from 2041 to 2070. The results show that the spring flow in the future will be lower compared to the historical period (Figure 8) which is more conducive to thermal breakup in the future. Although the thermal decay processes of the ice cover can reduce the probability of ice-jam formation, intact ice cover formation downstream of the town can still be competent enough to create ice-jams and raise the water levels enough to lead to flooding in the town. RIVICE was run a total of thirty times in the MOCA framework, each simulation having boundary conditions randomly selected from future distributions derived from the two future climate model combinations to assess the future ice-jam stage frequencies at Fort McMurray.

The stage-frequency curves (SFC) for the future period was developed from the ensemble of simulated water level profiles at the Fort McMurray gauging station and compared with the observed SFC (Figure 9). The results show that the SFC in the future from the CRCM+CCSM model combination will be reduced on less extreme staging regime ($p>0.3$) and increased in the more extreme staging regime ($p < 0.2$). The SFC from the CRCM+CGCM3 model combination will be more or less the same as the historical SFC. Although there will be lots of variability on the flow and ice regimes in the future, ice jams formation along the river can still lead to flooding in the town.

4. Conclusion

In summary, it is expected that the ice season in the future will be lengthened by one to two weeks, because of earlier river freeze-up and later ice cover breakup. An extended breakup period will reduce the chances of mechanical breakup while increasing the probability of thermal breakup. Overall, it may also reduce the severity of ice jams along the river. However, other factors such as incoming ice volume or intact ice cover downstream of an ice jam can still influence the formation of ice jams and subsequent flooding at Fort McMurray.

Although, the study uses quantitative methods, there is lot of uncertainty in the GCM data which can propagate into the setup of the river ice model. Further research and detailed analysis of the air temperatures and flows are still required to understand the impacts of climate change on ice jam regime along the river in the future. We plan to set up a Water Quality Analysis Program (WASP) model to simulate the thermal ice cover for the future and extend the RIVICE model domain up to the Town of Athabasca to assess the ice jam flooding in different locations along the river.

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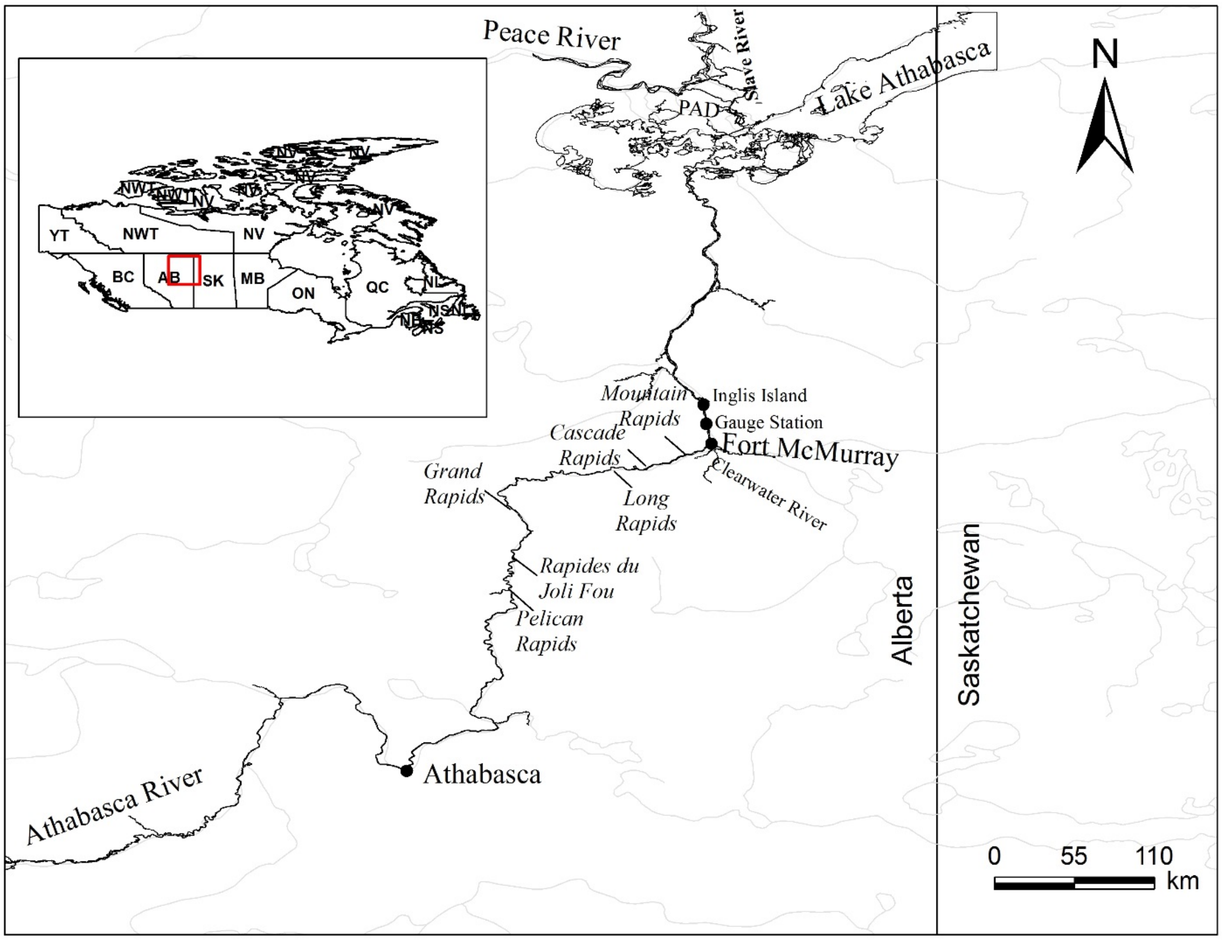

Fig. 1 The map of the lower reach of the Athabasca River.

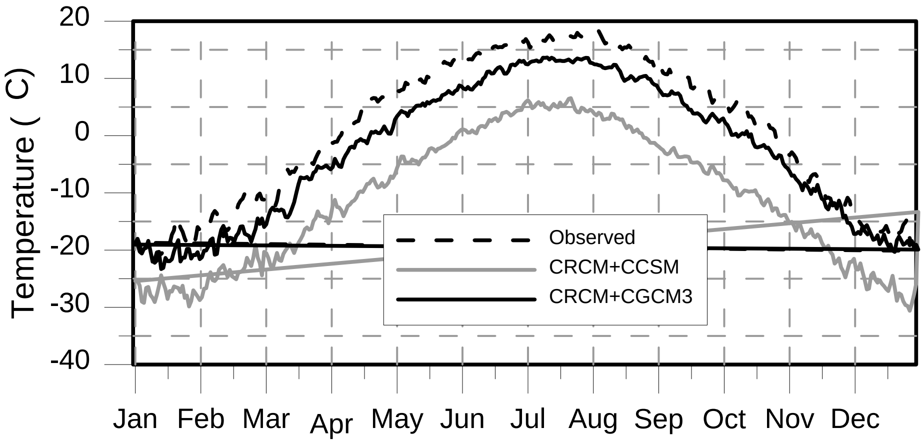

Fig. 2 The daily mean air temperature of observed and model data for the 30 year period (1971-2000) at Fort McMurray.

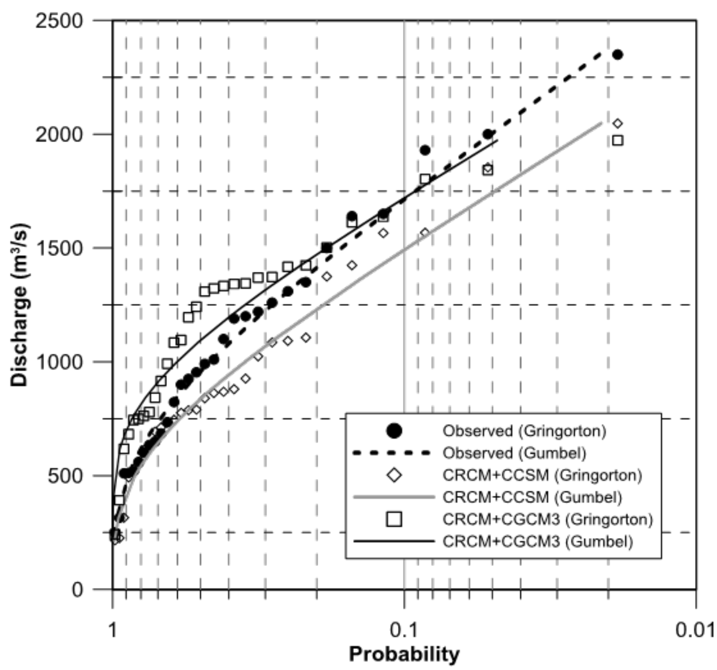

Fig. 3 The flood frequency distributions of the observed and model data for the historical period (1971-2000).

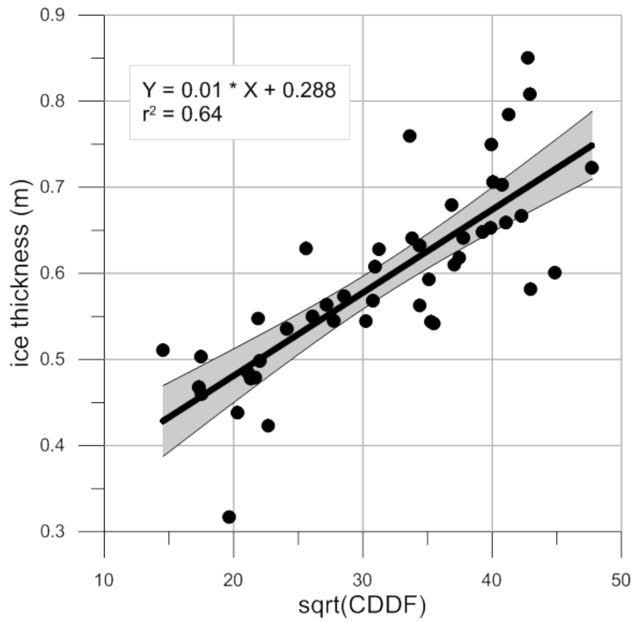

Fig. 4 Ice thicknesses versus square-root of CDDF at the hydrometric gauge station "Athabasca River below Fort McMurray".

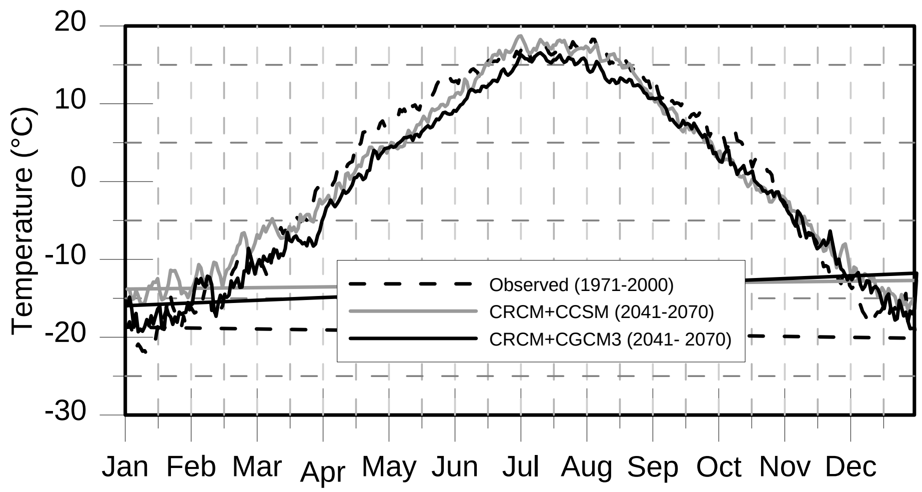

Fig 5. The daily mean air temperature of the observed (1971-2000) and future (2041-2070) periods.

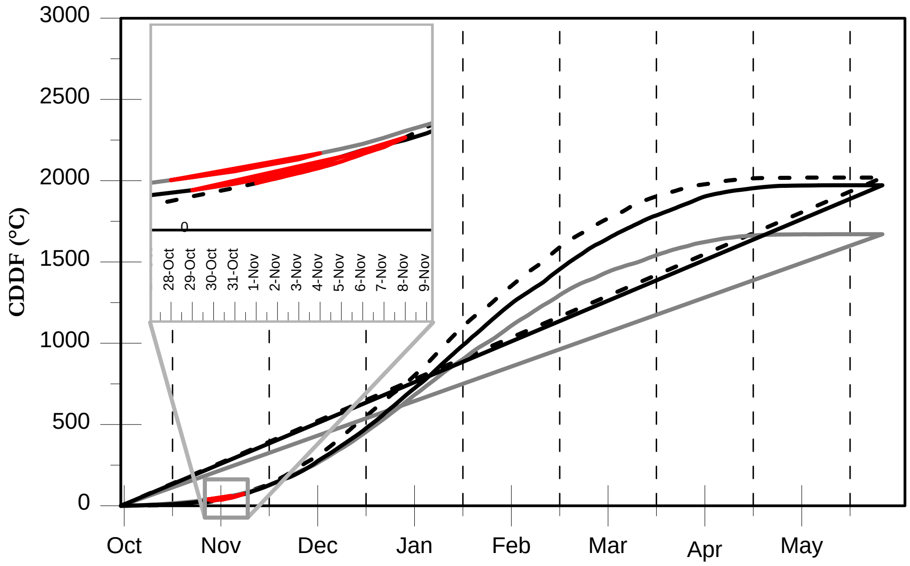

Fig. 6 The daily average CDDF curves of the observed (1971-2000) and future (2041-2070) periods. The red bands show the ranges of the dates of the river freeze-up at Fort McMurray.

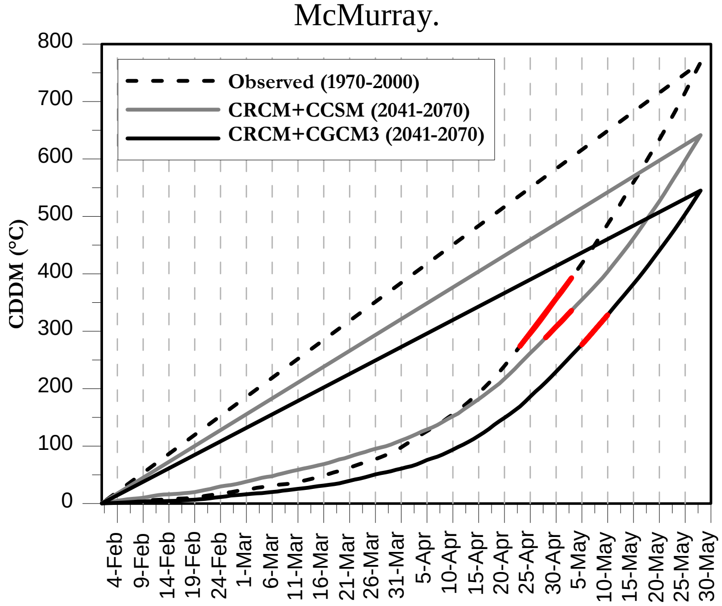

Fig. 7 The daily average CDDM curves of the observed (1971-2000) and future (2041-2070) periods. The red bands show the ranges of last day of the river breakup at Fort McMurray.

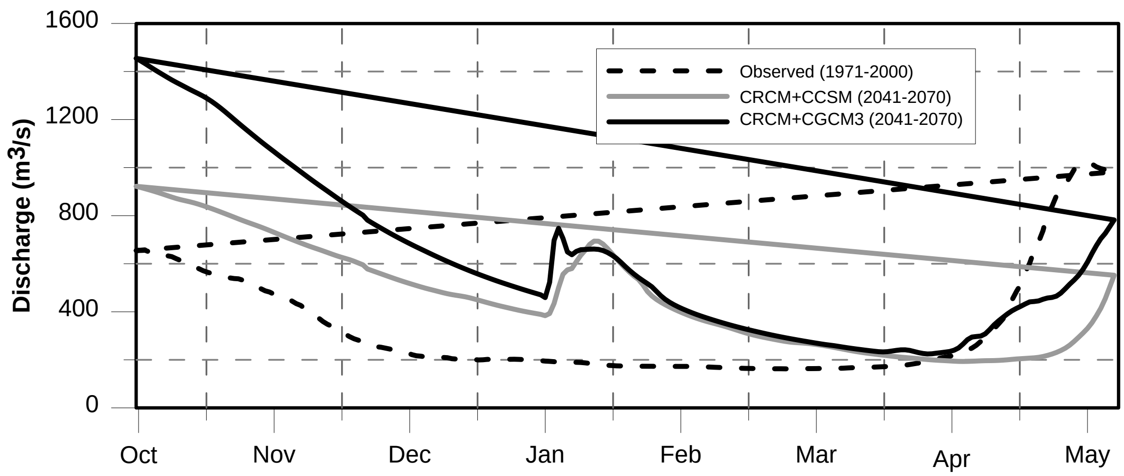

Fig. 8 The daily mean hydrographs of the observed (1971-2000) and future (2041-2070) periods during the winter and breakup along the Athabasca River at Fort McMurray.

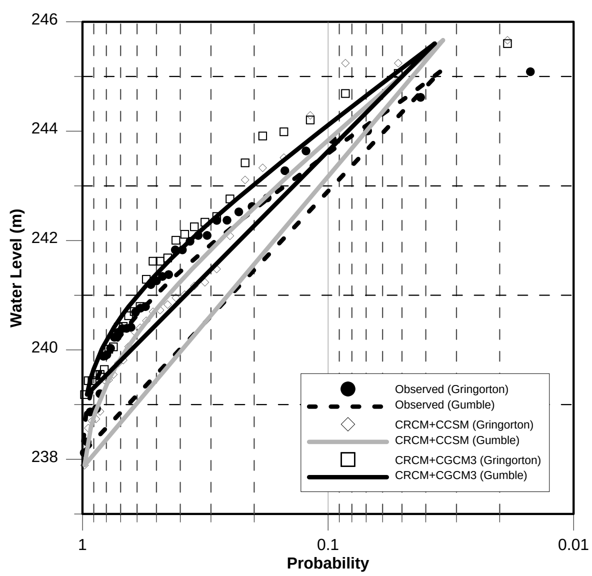

Fig. 9 Stage-frequency curves for the observed period (1971-2000) and simulated ice-jam water levels for the future period (2041-2070) of the two climate model combinations.