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Impact of Climate Change on the Peace River Thermal Ice Regime

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In this investigation, a one-dimensional hydrodynamic model that includes river ice formation and melting processes is developed and used to conduct a preliminary assessment of climate change impact on the ice regime of the Peace River in Alberta. The model employs an Eulerian frame of reference for both the flow hydrodynamics and the ice processes (ice cover formation and deterioration) and uses the *characteristic-dissipative-Galerkin* finite element method to solve the primary equations.

This paper details the model formulation and its application to the Peace River. Model calibration and validation results with historical data are presented; these indicate that the present model adequately simulates water temperature and ice front profiles. However, its further development to include certain dynamic freeze-up processes is required to refine the ice front results.

Higher air temperatures predicted by the CGCM2 climate model were used to generate future ice front profiles that correspond to the historical runs. This preliminary climate change impact analysis suggests that there is a significant potential for a shorter ice-covered season on the Peace River by the mid-twenty-first century. At the Town of Peace River, the average total reduction in ice cover duration is 28 days (31%) under the scenario applied.

1. Introduction

The winter ice cover that forms on most northern rivers plays an important role in ecosystems and water quality (Prowse and Culp, 2003) and in many cases is a significant factor in Canada's northern transportation network (e.g. Gerard et al., 1992; Kuryk and Domaratzki, 1999). Climate change, in particular climate warming, has the potential to affect not only the duration and extent of ice cover on northern rivers but also the frequency and/or severity of ice jam events (Beltaos and Prowse, 2001). Clearly, it is important to be able to assess the potential impact of climate change and climate variability on the ice regime of rivers and to develop adaptive strategies to minimize the negative impacts of these changes.

It has been determined that climate warming has already occurred in northern Canada; in fact, to a greater extent there than the global average (Figure 1). As participants in the Global Energy and Water Cycle Experiment (GEWEX), Canadian researchers are investigating the potential effects of climate change on the hydrology of the Mackenzie River Basin in collaboration with Environment Canada scientists. Their collective work is known as the Mackenzie GEWEX Study (MAGS). This project, which focuses on assessing the impact of climate change on the thermal ice regime of rivers, is one component of the MAGS study, and was also conducted in collaboration with Alberta Environment's Climate Change Research Group. The particular river of interest for this investigation is the Peace River, located in the upper Mackenzie River basin.

In this preliminary investigation, we explore the potential impacts of climate warming on the thermal regime of the Peace River for the reach extending from Hudson Hope, BC, to Fort Vermillion, AB, as shown in Figure 2. This river is regulated by hydropower dams at its upstream end, and as a result thermal ice processes are a dominant feature of its winter regime. Building on the validated dynamic hydraulic model of the Peace River developed by Hicks (1996) and also applied by Peters and Prowse (2001), we employ a fully Eulerian framework to incorporate thermal ice formation and deterioration processes. The model is validated with historical data and then applied to provide a preliminary evaluation of the potential magnitude and significance of climate change impacts on thermal ice processes.

This paper outlines the development, calibration, and application of the thermal river ice model; the preliminary calibration and validation results for the Peace River study reach; and finally application of the model to a climate warming scenario for the Peace River.

2. Model Development

The model developed for this study is built upon the University of Alberta's public domain, dynamic river routing model, *River1D* (Hicks and Steffler, 1992). *River1D* is a one-dimensional finite element-based numerical model that solves conservation of water mass and longitudinal momentum using the *characteristic-dissipative-Galerkin* (CDG) scheme. For this investigation, the rectangular channel version of the *River1D* model has been enhanced to incorporate thermal ice related processes including consideration of water temperature, suspended frazil ice, surface ice concentration, surface frazil ice, and solid surface ice. Ice front location is a supplementary solution variable that determines where the free-drift assumption is applied to surface ice and where surface ice velocity is zero.

Existing river ice models (e.g. Shen et al., 1995; Lal and Shen, 1989) use an Eulerian-Lagrangian approach to model the governing equations. In contrast, the thermal process equations modeled in *River1D* have been developed from control volume principles in a completely Eulerian frame of reference. Each equation can be written in the form:

$$\frac{\partial}{\partial t}(\Phi)+\frac{\partial}{\partial x}(U\Phi)=\Sigma F \qquad [1]$$

where Φ represents the solution variable, U the mean or surface ice flow velocity, and ΣF the sum of the mass or energy fluxes applying to the control volume. The equations in this general form were subsequently developed into weak statement formulations based on the *characteristic-dissipative-Galerkin* finite element scheme, and then incorporated into *River1D*. For each time step in the transient solution, the modeling procedure involves a decoupled solution of the total (ice + water) mass and longitudinal momentum conservation equations, followed by solution of the water temperature and ice mass conservation equations. This approach assumes that the drifting ice moves at the surface water velocity, with ice resistance effects only considered once the ice itself is arrested. This preliminary version of the model does not include consideration of dynamic ice jam formation or release processes.

Conservation of thermal energy is used to derive the model for river water temperature:

$$\frac{\partial}{\partial t}\left(AC_pT_w\right)+\frac{\partial}{\partial x}\left(UAC_pT_w\right)=-\frac{(B-B_i)\phi_{wa}}{\rho}-\underbrace{\frac{B_i\phi_{ia}}{\rho}}_{\phi_{ia}>0}-\underbrace{\frac{B_i\phi_{iw}}{\rho}}_{\phi_{iw}>0} \qquad [2]$$

The first flux term on the right hand side of the equation represents the energy transfer between the water and the air above any open water area. The second flux term accounts for the loss of heat over the ice-covered area. This term only applies if heat is being lost, as any heat gain over an ice-covered area is directed towards ice melt. Similarly with the final term, representing heat transfer associated with solid ice melt, there must be a positive heat transfer from the water to the ice cover for this term to take effect. Linearized water-air and ice-air heat exchanges are calculated using the method described by Lal and Shen (1989). The ice-water heat exchange is computed based on the work of Ashton (1973).

Once a zero degree isotherm has developed within the simulated reach, the ice mass conservation component of the model is activated. The initial ice mass process being modeled is the generation of suspended frazil according to:

$$\frac{\partial A_f}{\partial t}+\frac{\partial UA_f}{\partial x}=\frac{1}{\rho_i}\left[\underbrace{\frac{\rho}{\rho_i}\frac{(B-B_i)\phi_{wa}}{L_i}}_{\substack{\text{frazil formation if}\\ T_w=0}}-\underbrace{\rho_i\eta C_f B}_{\substack{\text{frazil rise if}\\ C_f\geq 0}}\right] \qquad [3]$$

Note that the flux term associated with frazil formation requires the water temperature be zero degrees at that location. The other flux term quantifies the ice mass lost from suspension to the surface, due to frazil buoyancy. The rise parameter, η, is a calibration parameter that controls the rate of surface ice formation.

As frazil ice rises, the surface ice coverage increases at a rate also influenced by an initial frazil floe thickness, t'_f, specified by the modeler. The change in surface ice coverage, B_i, is given by:

$$\frac{\partial B_i}{\partial t} + \frac{\partial U_i B_i}{\partial x} = \frac{1}{\rho' t'_f}\left[\underbrace{\left(\rho_i + \rho\frac{e_f}{\left(1-e_f\right)}\right)\eta C_f B}_{\substack{\text{frazil and pore water deposition if} \\ C_f \geq 0}}\right] \qquad [4]$$

At the surface, the frazil deposits in proportion to the porosity of frazil floes, e_f. The capture of pore water mass within the floe area is also included in the above equation.

The thickness of frazil slush on the underside of pans and solid ice at the surface is derived from the following two equations when frazil slush exists:

$$\frac{\partial A'_i}{\partial t} + \frac{\partial U_i A'_i}{\partial x} = \frac{1}{\rho'}\left[\underbrace{\left(\rho_i + \rho\frac{e_f}{\left(1-e_f\right)}\right)\eta C_f B_i}_{\substack{\text{frazil and pore water deposition if} \\ C_f \geq 0}} - \underbrace{\frac{\rho'}{\rho_i}\frac{B_i\phi_{ia}}{L_i}}_{\substack{\text{pore water freezing if} \\ \phi_{ia} > 0}} - \underbrace{\frac{\rho'}{\rho_i}\frac{B_i\phi_{iw}}{L_i}}_{\substack{\text{slush melt if} \\ \phi_{iw} > 0}}\right] \qquad [5]$$

$$\frac{\partial A_i}{\partial t} + \frac{\partial U_i A_i}{\partial x} = \frac{1}{\rho_i}\left[\underbrace{\frac{\rho'}{\rho_i}\frac{B_i\phi_{ia}}{L_i}}_{\substack{\text{pore water freezing if} \\ \phi_{ia} > 0}} + \underbrace{\frac{\rho}{\rho_i}\frac{B_i\phi_{ia}}{L_i}}_{\substack{\text{solid ice melt if} \\ \phi_{ia} < 0}}\right] \qquad [6]$$

When the solution for frazil slush thickness goes to zero, the flux associated with pore water freezing no longer applies to the solid ice equation, while new terms for growth of columnar ice and solid ice melt due to warm water enter the equation.

In this case, the solid ice equation becomes:

$$\frac{\partial A_i}{\partial t}+\frac{\partial U_i A_i}{\partial x}=\frac{1}{\rho_i}\left[\underbrace{\frac{\rho}{\rho_i}\frac{B_i\phi_{ia}}{L_i}}_{\substack{\text{growth of columnar ice if}\\ \phi_{ia}>0\\ T_w=0}}+\underbrace{\frac{\rho}{\rho_i}\frac{B_i\phi_{ia}}{L_i}}_{\substack{\text{solid ice melt if}\\ \phi_{ia}<0}}-\underbrace{\frac{\rho}{\rho_i}\frac{B_i\phi_{iw}}{L_i}}_{\substack{\text{solid ice melt to warm water if}\\ \phi_{iw}>0}}\right] \qquad [7]$$

In the present version of the model, the user must specify the time at which bridging occurs at the downstream boundary. When this time in the simulation is reached, the initial condition for the ice front location is set at the downstream boundary and the approach of ice from upstream leads to the upstream progression of the ice front. A straightforward conservation of surface ice method, inspired by that employed in the *RICEN* model (Shen et al., 1995), is used to follow the ice front location:

$$X_i(t+\Delta t)=X_i(t)-\frac{C_i\,U_i}{P_{jux}}\Delta t \qquad [8]$$

The juxtaposition parameter, P_{jux}, is a calibration parameter that affects the simulated rate of ice cover advance. Its value is intended to account for the reduction of ice velocity as pans arrive at the leading edge of the ice cover as well as any associated crushing, under-turning, or consolidation of floes.

Recession of the ice cover due to melt is handled more naturally by the model. The ice front location moves node by node upstream as the ice thickness at the ice front decreases towards zero. Intermediate ice front locations are not calculated during the melt process, as they are during upstream progression.

3. Model Calibration and Application to the Peace River, Canada

3.1 Data Requirements

The data required to run the *River1D* thermal river ice model consists of initial conditions and inflow time series for the hydraulic, water temperature, and ice conditions. A downstream rating curve or water level time series is also required for the hydraulic modeling component. Finally, one or more air temperature time series must be specified to drive the thermal modeling components. Heat input from solar radiation can also be considered, but this feature was not employed in this preliminary application, as insufficient data were available. Downstream boundary conditions for water temperature and ice conditions are not required as the finite element method employed in *River1D* uses the applicable 'natural' boundary conditions.

Discharge records and water temperature for the Bennett/Peace Canyon Dam were made available by Alberta Environment and used to develop the upstream boundary conditions for the model. Ice inflow at the upstream boundary was set at zero for all simulations, which is consistent with the physical situation in this case. Extensive air temperature records at Fort St. John, BC, the Town of Peace River, AB, and at High Level, AB, were used to construct the air temperature time series for the simulations (station locations noted in Figure 2). For this study, the average mean daily air temperature at the first two stations was used to define the air temperature upstream of the Town of Peace River and the mean daily air temperature at High Level was applied to the lower reach. The remaining input parameter is the time of ice front initiation at the downstream boundary. This value was either estimated or (when known) taken directly from historical ice front observations provided by Alberta Environment.

3.2 Model Calibration and Validation

Calibration and validation of the thermal river ice model involved two phases: the first required calibration/validation of the air-water heat exchange coefficient to observed water temperature data; the second phase involved calibrating and validating the remaining set of parameters that dictate the simulated ice front profile.

Calibration / Validation Using Observed Water Temperature Data

Water temperature observations on the Peace River in Alberta are currently limited to two locations: the Water Survey of Canada (WSC) gauges at Alces River (164 km downstream of the Bennett Dam) and the Town of Peace River (396 km downstream of the Bennett Dam). As only two years of record were available, for the 2002/03 and 2003/04 ice seasons, the former season was used for calibration and the latter for validation.

For the calibration using the 2002/03 data, heat exchange coefficients of 15 and 20 W/m^2 were tested (chosen based on the results of previous studies on the Peace River (e.g. Andres, 1993)). The resulting simulated water temperature profiles at the Alces and Peace River gauge sites are shown in Figures 3 and 4, respectively. As the figures illustrate, both values of the heat exchange coefficient tested appear to produce modeled water temperatures at Alces that are consistently higher than the observed values. For the Peace River gauge site, the model appears to produce results comparable to the measured data. However, the simulated water temperatures show higher peaks and there is no clear indication that one or the other of the heat exchange coefficients tested provides a superior match to the observed data. In the end, for this preliminary investigation, it was decided to proceed using a value of 15 W/m^2 for the heat exchange coefficient, as it provided the better representation of the date the zero degree isotherm reached the Town of Peace River.

Figures 5 and 6 compare the simulated water temperature profile (using 15 W/m^2 for the heat exchange coefficient) with the observed data at the two gauge sites for the 2003/04 (validation) season. As the figures illustrate, model results are generally consistent with the measured data, but again in the case of the Alces site, the model indicates higher water temperatures than those measured. Similar to the calibration runs for the Peace River gauge, the model results for the validation season tend to show higher peak values than those seen in the data.

Overall, the results of this preliminary calibration and validation to the water temperature data suggest that the model is producing reasonable results, though not perfectly capturing the water temperature behavior. A choice of 15 W/m^2 seems a reasonable compromise given the limited available data for calibration and validation. Clearly more data and additional modeling is required to refine the simulation results for the Alces gauge site in particular. The current over-prediction at Alces may simply reflect a question of the suitability of the air temperature data for that location or the quality of the water temperature data at that site or at the upstream boundary. In any case, the water temperatures were considered to be adequately modeled for the purposes of this preliminary investigation.

Calibration / Validation of the Ice Process Parameter Set

More than 20 years of historical records, including documentation of the ice front progression in each year, were supplied by Alberta Environment for calibration and validation of the ice process model components. Unfortunately, much of the record is sparse, most notably in terms of the water temperature information required for the inflow boundary condition. In the end, it was decided that, for this preliminary investigation, most of the empirical ice process parameters would be set to 'typical' values and only the juxtaposition parameter, P_{jux}, would be adjusted.

A value of P_{jux}= 2.5 was found to produce the best overall ice front results for the 20 years of historical record simulated. The remaining parameters and their adopted values were:

- frazil floe porosity = 0.5;
- frazil rise parameter = 0.0001 *m/s*;
- Manning's n for ice cover = 0.02; and
- ice-water heat exchange coefficient = 1187 $W\,s^{0.8}/m^{2.6}/°C$ (Ashton, 1973).

Other variables can also be used to calibrate the model parameters and to assess the quality of its performance: measured water levels, documented surface ice concentrations, and observed ice thicknesses. However, given the objective of this study, which was to investigate climate warming influences on the extent and duration of ice cover, ice front location was considered the most relevant. Thus, validation consisted of comparing the modeled ice front locations to the observed data.

In comparing model results to measured ice front progression, it was found that the performance of the model varied from year to year. For example, the simulated profile for the years 2002/03 and 2003/04 extended considerably farther upstream than the observed profile in the reach upstream of the Town of Peace River (TPR) and Dunvegan (DUN) as shown in Figures 7 and 8. However, in other years, such as 1995/96 and 1996/97, the model performed extremely well, as shown in Figures 9 and 10. In addition to the necessary approximations regarding the inflow boundary water temperatures for those years where the data was suspect or missing, a key factor contributing to this apparently inconsistent model performance is the fact that, at present, the *River1D* thermal ice model does not consider ice cover consolidation or hydraulic thickening. These processes are known to occur on occasion along the Peace River, particularly during the freeze-up period, and therefore it is not unexpected that the current version of the model would over-estimate the upstream progression of the ice cover in such cases.

Despite these limitations in the model’s capabilities, it still produces sufficiently reasonable results to be useful in conducting a preliminary assessment of the potential influences of climate change on the thermal ice regime of the of Peace River. For example, based on the 20 years of historical record simulated, *River1D* predicted the average duration of ice cover and dates of freeze-up and break-up at the Town of Peace River to within two days of the observed. The maximum extent of ice simulated was, on average, 50 km farther upstream than the observed value.

4. Climate Change Analysis

The Canadian CGCM2 climate model was selected to assess the impact of climate change on the historical winter seasons modeled. Two standardized future climate scenarios were available from the Mackenzie GEWEX Study (MAGS) research network database; these are commonly referred to as A2 and B2. The A2 scenario, which is based on larger population growth and higher cumulative CO_2 emissions over the period 1990 to 2100 than the B2 scenario, was chosen for this study, in order to examine the more severe climate prediction. The CGCM2 model provides mean monthly temperature change projections relative to the period 1961 to 1990 for various locations in Canada. For this preliminary analysis, the mid-range projection for the year 2050 was selected over the two extremes of 2010 and 2080.

To assess the potential effects of climate change on the winter regime of the Peace River, it was necessary to assume that the mean monthly air temperature change projections from the climate change scenario could be applied directly to the mean daily historical values used as model input. Other compounding potential effects of climate warming, such warmer water temperatures in the hydropower dam reservoir and/or a delay in the timing of initial ice cover bridging at Fort Vermilion, could not be considered here but do warrant future investigation. Intuitive judgment suggests that neglecting these factors would mean that the results of this analysis would likely underestimate the potential impact of warming on the duration and extent of the river’s ice cover.

Examples of climate change ice front profiles compared with the historical simulations are presented in Figures 11 through 14, for the same example years presented in the previous section. The predicted November, December, January, February, March, and April temperature increases for the southern region (including the Town of Peace River) of 0.37, 4.02, 5.11, 3.85, 4.10, and 1.85 °C, and 0.30, 3.82, 5.67, 3.90, 4.05, and 1.70 °C for the northern region, clearly have a significant impact on the overall ice front progression. In particular, the duration and maximum extent of ice cover are reduced. As Figure 15 illustrates, the maximum upstream extent of the ice cover would be expected to be consistently further downstream of the dam, by an average of 60 km.

Figure 16 presents more site specific results, at the Town of Peace River, where re-analysis of 20 years of historical ice simulations reduced the duration of ice cover there by an average of 28 days or 31% compared to the historical observations from the same time period.

5. Conclusions

The purpose of this investigation was to apply the *River1D* thermal ice model to the Peace River and to assess the potential impacts of climate change on the river’s thermal ice regime. In general, it was found that the model produced reasonable predictions of ice cover progression for the validation period, when taking into account the limited availability of some input data (particularly inflow water temperature data). However, because the model is currently capable of modeling thermal ice processes only, it cannot precisely capture ice cover progression in years where dynamic processes, such as secondary ice cover consolidation, significantly influence the location of the ice front. Nevertheless, the model's capability is considered adequate for the purposes of this preliminary study.

To explore the potential impacts of climate change on the Peace River thermal ice regime, the validated model was then applied for the same historical period, using the air temperature changes indicated for Fort St. John, the Town of Peace River, and High Level under the A2 climate change projection for the year 2050, generated by the CGCM2 model. An important consideration affecting the interpretation of these results is that increased air temperatures would also potentially have an impact on the upstream water temperature boundary condition (i.e. by increasing the reservoir water temperatures) and would likely delay the time of first ice formation at the downstream boundary. Both these effects would tend to delay the development of the ice cover, and lead to earlier thermal melt. Thus, in this context, the results indicated here are likely conservative in terms of the degree of climate change impact on the river's ice regime that might occur under the CGCM2/A2 scenario.

Results of this preliminary climate change impact assessment suggest that there is a significant potential for a shorter ice-covered season under the climate change scenario investigated. In terms of the delay in the date of freeze-up at the Town of Peace River, an average of 13 days is indicated and for break-up, the average date is 15 days earlier. These results amount to a 28-day reduction in duration of ice cover at the Town of Peace River. The simulated minimum ice front distance downstream of the Bennett Dam was an average of 60 kilometres greater after climate change was applied, as compared to the historical model results.

Given the limited input and validation data, the fact that the model only considers thermal ice processes at this time, the lack of consideration of the effects of climate change on reservoir outflow temperatures and ice cover initiation date, and uncertainties associated with the meteorological climate change analysis itself (as well as its applicability for this particular period of record), these quantitative averages cannot be considered firm predictions. However, their magnitudes do definitely suggest that there will be a measurable, and possibly even significant, impact attributable to climate change on the future ice regime of the Peace River. Therefore, it is important to start developing adaptive strategies as well as improved models and data archives, in order to gain a more reliable quantitative assessment of these impacts.

6. Recommendations for Future Research

Numerous opportunities exist to improve the current *River1D* thermal model. The most immediate need is to incorporate the physics of ice cover stability and mechanical thickening into the current version. This should greatly improve the model's consistency when simulating the ice front profile from year-to-year. Secondarily, computation of ice floe velocity can be advanced to include the effect of channel constriction on the passage of large concentrations of surface ice. Finally, consideration of natural channel geometry would facilitate validation of water levels, not just ice front progression.

The bridging phenomenon is still not completely understood and remains largely site specific. It would be extremely beneficial, particularly with respect to modeling climate change effects on river ice, to have a reliable bridging criterion built-into the model. Future research, modeling, and field observation could reveal a great deal about this aspect of the river's ice regime. Other issues not currently included in the model such as lateral thermal inflow and snow cover could also be the focus of future work.

Continued and improved data collection is also critical to the quality and success of this and other river ice studies. For the Peace River, one or more additional water temperature monitoring sites downstream of the Town of Peace River would provide extremely useful calibration and validation data. The hydropower dam's discharge temperature should continue to be measured and reservoir models should be developed to assess the impact of climate change on the seasonal water temperature boundary condition.

Finally, additional climate change scenarios can be investigated with the current model and the importance of the inflow water temperature and date of bridging on the overall ice front simulation can be determined.

List of Symbols

A	liquid water flow area (m^2)
A_f	suspended frazil ice flow area (m^2)
A_i	solid ice flow area (m^2)
A_i'	flow area of frazil slush at the surface (m^2)
B	top width of channel *(m)*
B_i	surface ice width or coverage *(m)*
C_f	suspended frazil ice concentration *(dimensionless)*
C_i	surface ice concentration *(dimensionless)*
C_p	specific heat of water *(J/kg/°C)*
e_f	porosity of frazil slush *(dimensionless)*
L_i	latent heat of ice *(J/kg)*
P_{jux}	juxtaposition parameter *(dimensionless)*
t	time *(s)*
t_f'	initial frazil ice thickness *(m)*
T_w	water temperature *(°C)*
U	mean water velocity *(m/s)*
U_i	surface ice velocity *(m/s)*
x	longitudinal distance along channel centreline *(m)*
X_i	location of ice front / distance from upstream boundary *(m)*
Δt	solution time step *(s)*

η	frazil rise parameter *(m/s)*
ρ	density of water (kg/m^3)
ρ'	combined density of frazil slush and pore water (kg/m^3)
ρ_i	density of ice (kg/m^3)
ϕ_{ia}	net rate of heat exchange per unit area between ice and air (W/m^2)
ϕ_{iw}	net rate of heat loss per unit area between ice and water (W/m^2)
ϕ_{wa}	net rate of heat loss per unit area between water and air (W/m^2)

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References

Andres, D.D. (1993). "Effects of Climate Change on the Freeze-up Regime of the Peace River: Phase I Ice Production Algorithm Development and Calibration". Report No. SWE 93/01, Environmental Research & Engineering Department, Alberta Research Council, Edmonton, Alberta, 52 pp.

Ashton, G. D. (1973). "Heat Transfer to River Ice covers". Proc. 30th Eastern Snow Conference, Amherst, Massachusetts, 125-135.

Ashton, G.D. (1986). "River and Lake Ice Engineering". Water Resources Publications, Littleton, Colorado, 485 pp.

Bletaos, S. and Prowse, T.D. (2001). "Climate Impacts on Extreme Ice-jam Events in Canadian Rivers". Journal of Hydrologic Sciences, Vol. 46, No. 1, 157-181.

Gerard, R., Hicks, F.E., MacAlpine, T., and Chen X. (1992). "Severe Winter Ferry Operation: The Mackenzie River at Ft. Providence, NWT". Proc. of the 11th International Assoc. for Hydraulic Research Ice Symposium, Banff, Alberta, June 1992, 503- 514.

Hicks, F.E. and Steffler, P.M. (1992). "A Characteristic-Dissipative-Galerkin Scheme for Open Channel Flow". ASCE Journal of Hydraulic Eng., Vol. 118, No. 2, 337-352.

Hicks, F.E. (1996). "Hydraulic Flood Routing with Minimal Channel Data: Peace River, Canada.". Canadian Journal of Civil Eng., Vol. 23, No. 2, 524-535.

Kuryk, D. and Domaratzki, M. (1999). "Construction and Maintenance of Winter Roads in Manitoba". Proc. of the 10th Workshop on the Hydraulics of Ice-covered Rivers, Winnipeg, 265-275.

Lal, A.M.W., and Shen, H.T. (1989). "A Mathematical Model for River Ice Processes (RICE)". Report No. 89-4, Department of Civil and Environmental Engineering, Clarkson University, Potsdam, New York, 164 pp.

Peters, D.L. and Prowse, T.D. (2001). "Regulation Effects on the Lower Peace River, Canada". Journal of Hydrologic Processes, Vol. 15, 3181-3194.

Prowse, T.D. and Culp, J.M. (2003). "Ice Breakup: A Neglected Factor in River Ecology", Canadian Journal of Civil Eng., Vol. 30, 1-17.

Shen, H.T., Wang, S., and Lal, A.M.W. (1995). "Numerical Simulation of River Ice Processes". Journal Cold Regions Eng., Vol. 9, No. 3, 107-118.

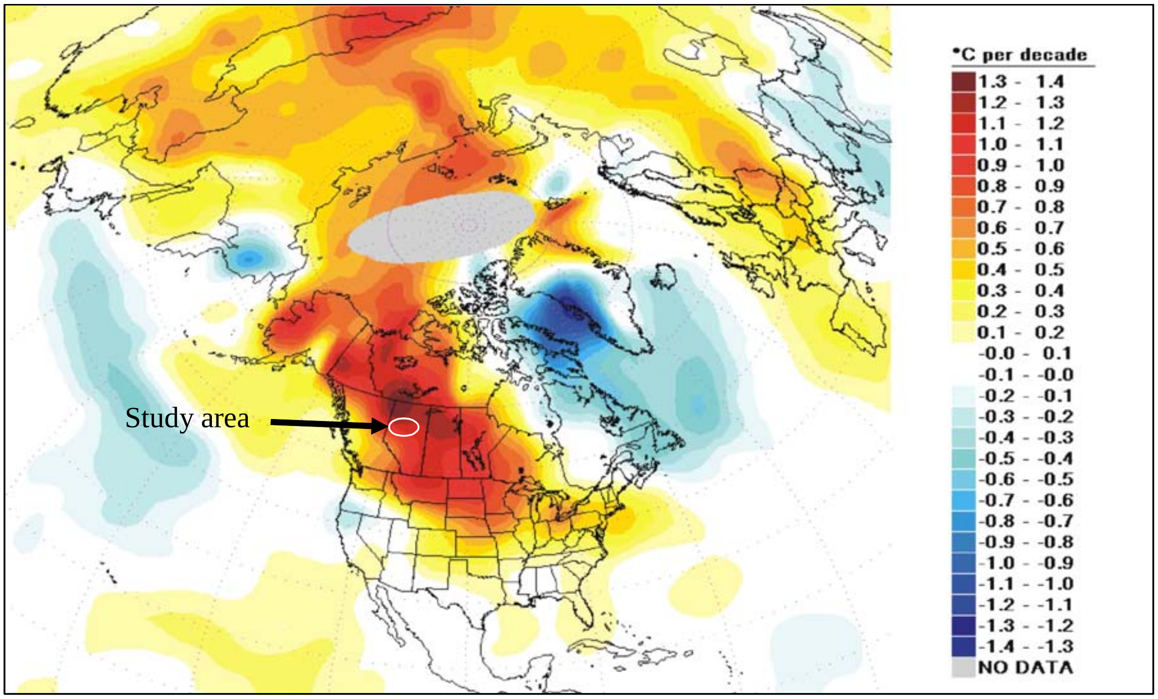

Figure 1. Winter temperature trends, 1961-1990. (Adapted from: Climate Research Unit, University of East Anglia, U.K., http://www.cru.uea.ac.uk/)

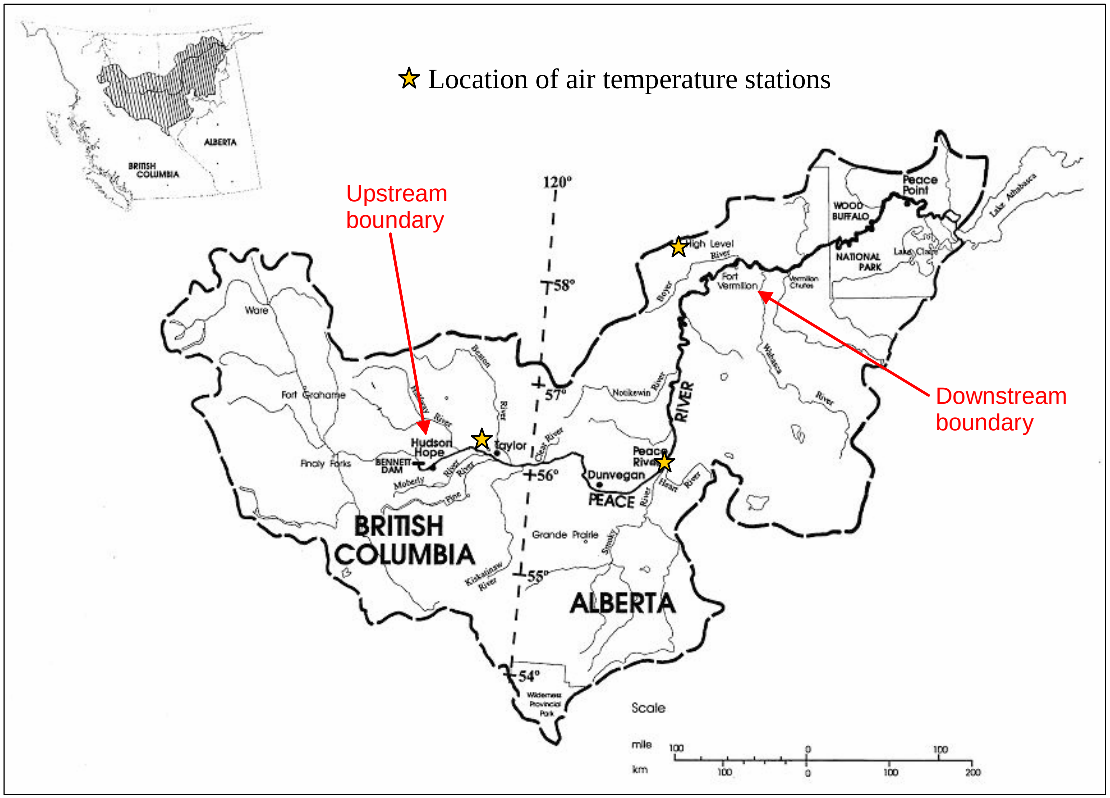

Figure 2. Peace River basin, showing study reach from Hudson Hope to Fort Vermillion. (Adapted from: Hicks, 1996)

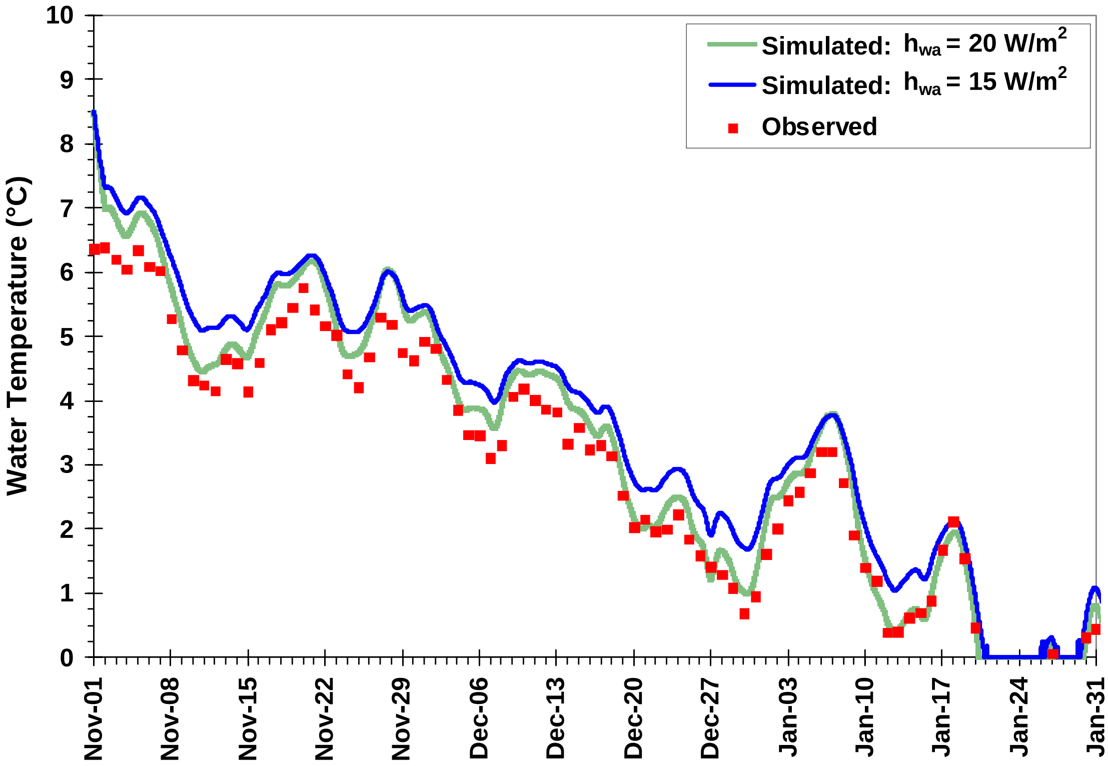

Figure 3. Peace River water temperature calibration to the Alces gauge (2002/03).

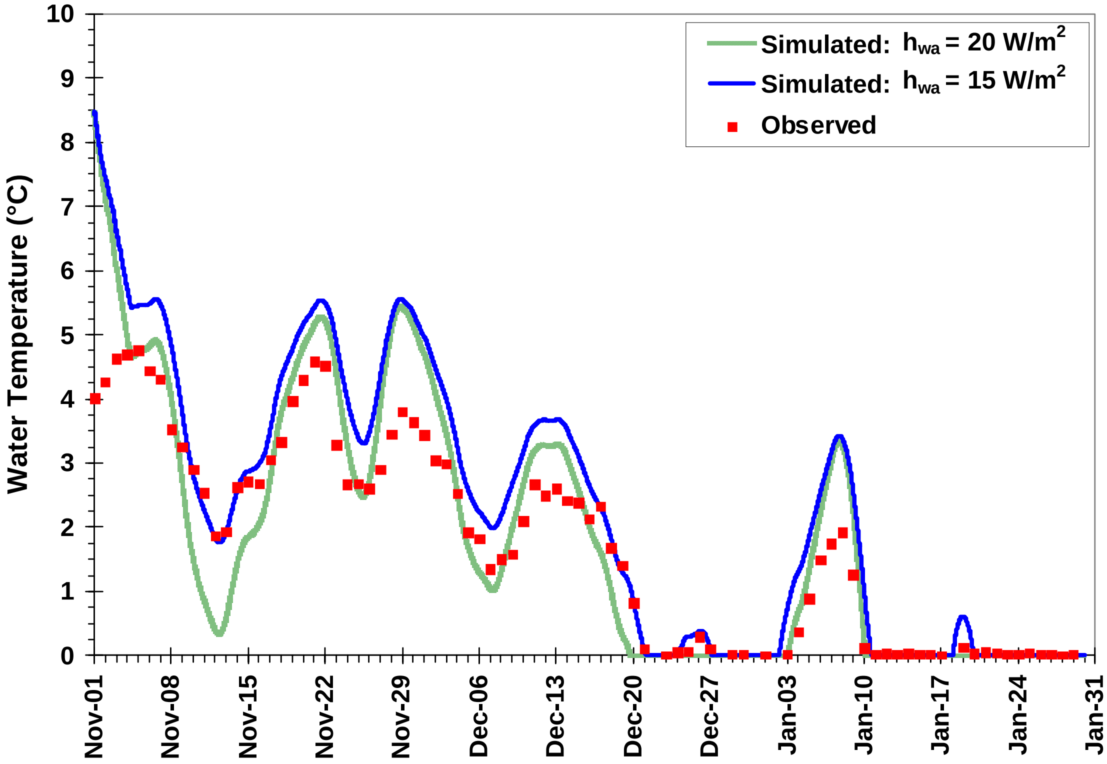

Figure 4. Peace River water temperature calibration to the Town of Peace River gauge (2002/03).

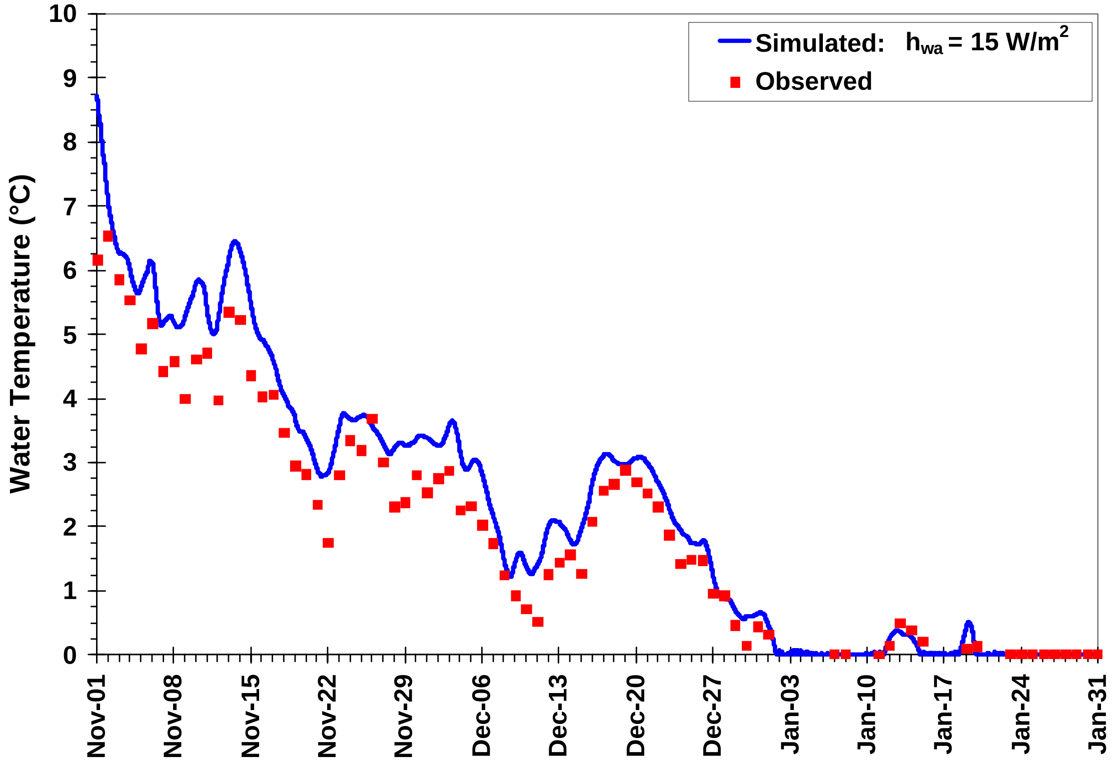

Figure 5. Water temperature model validation at the Alces gauge (2003/04).

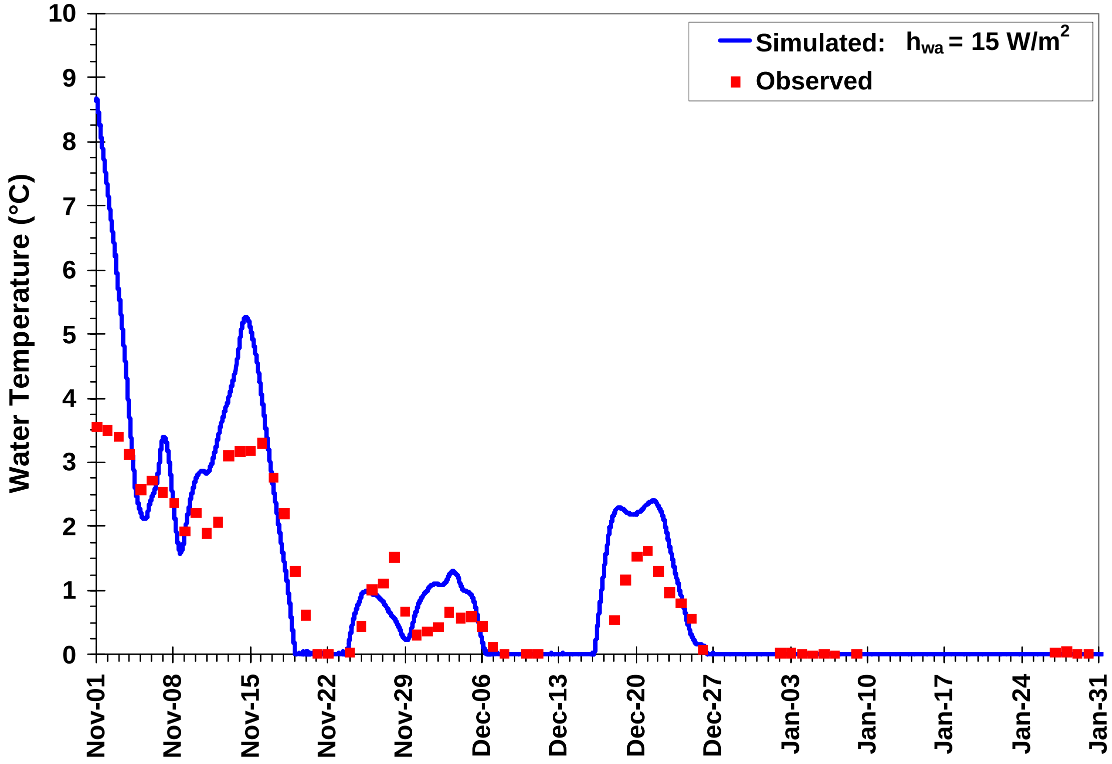

Figure 6. Water temperature model validation at the Town of Peace River gauge (2003/04).

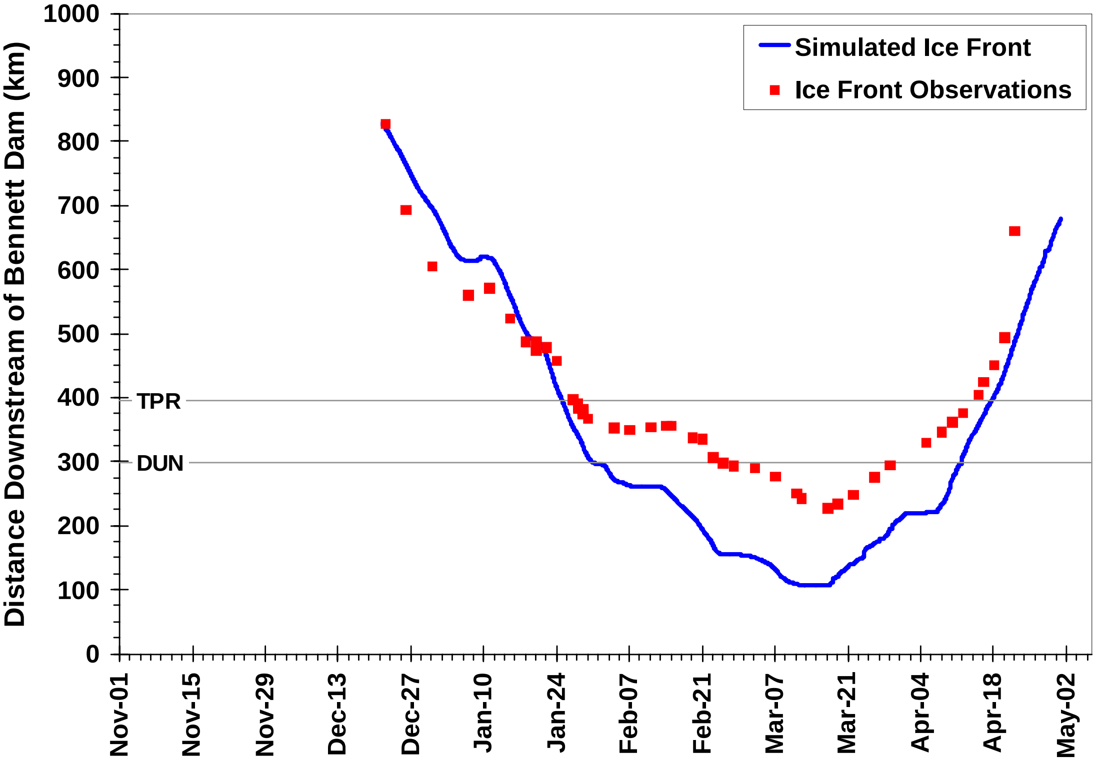

Figure 7. Modeled and observed ice front profile (2002/03).

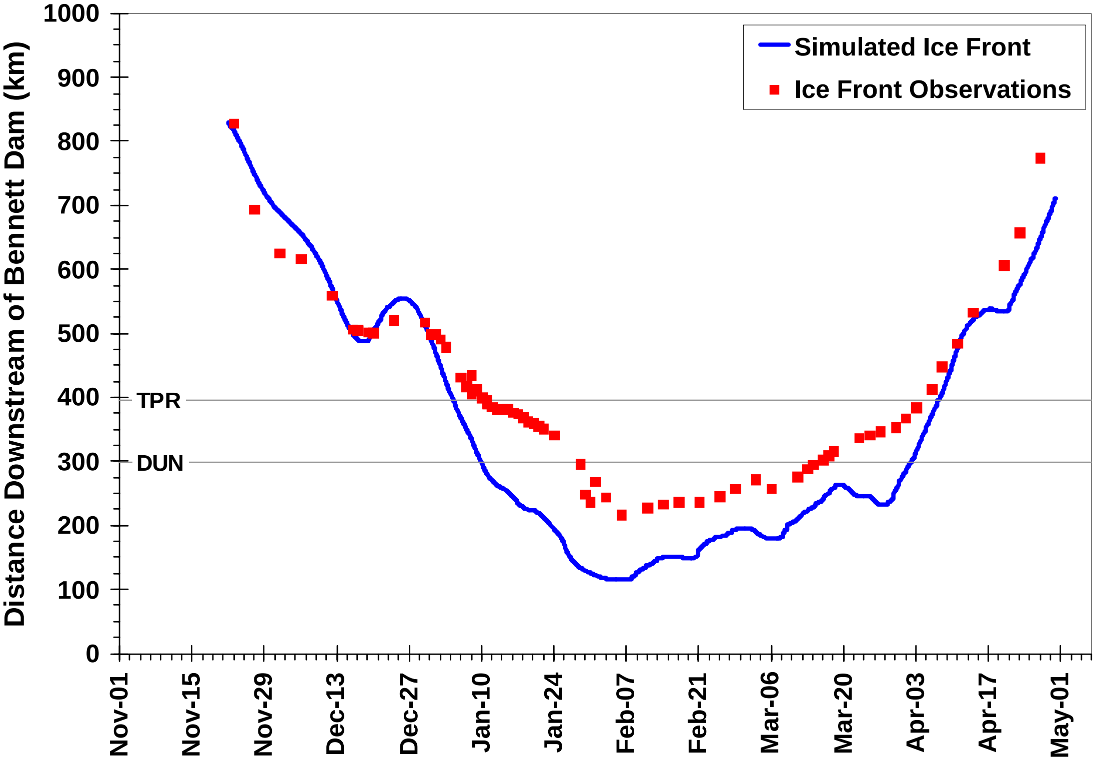

Figure 8. Modeled and observed ice front profile (2003/04).

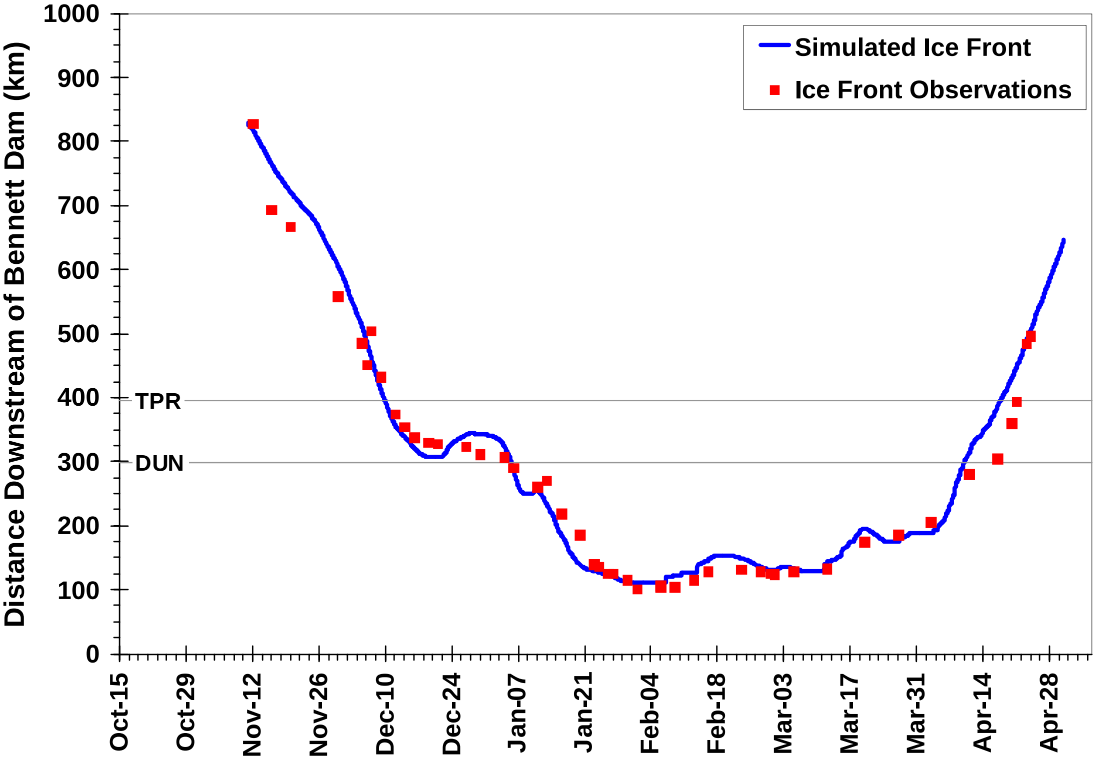

Figure 9. Modeled and observed ice front profile (1995/96).

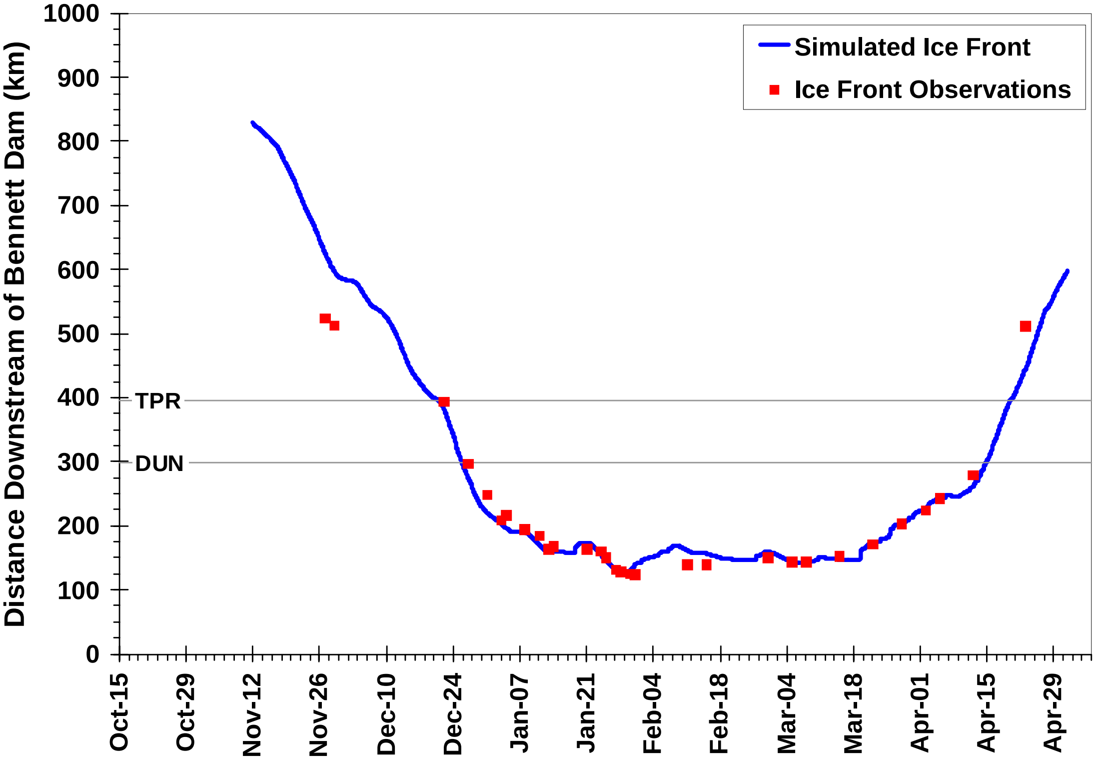

Figure 10. Modeled and observed ice front profile (1996/97).

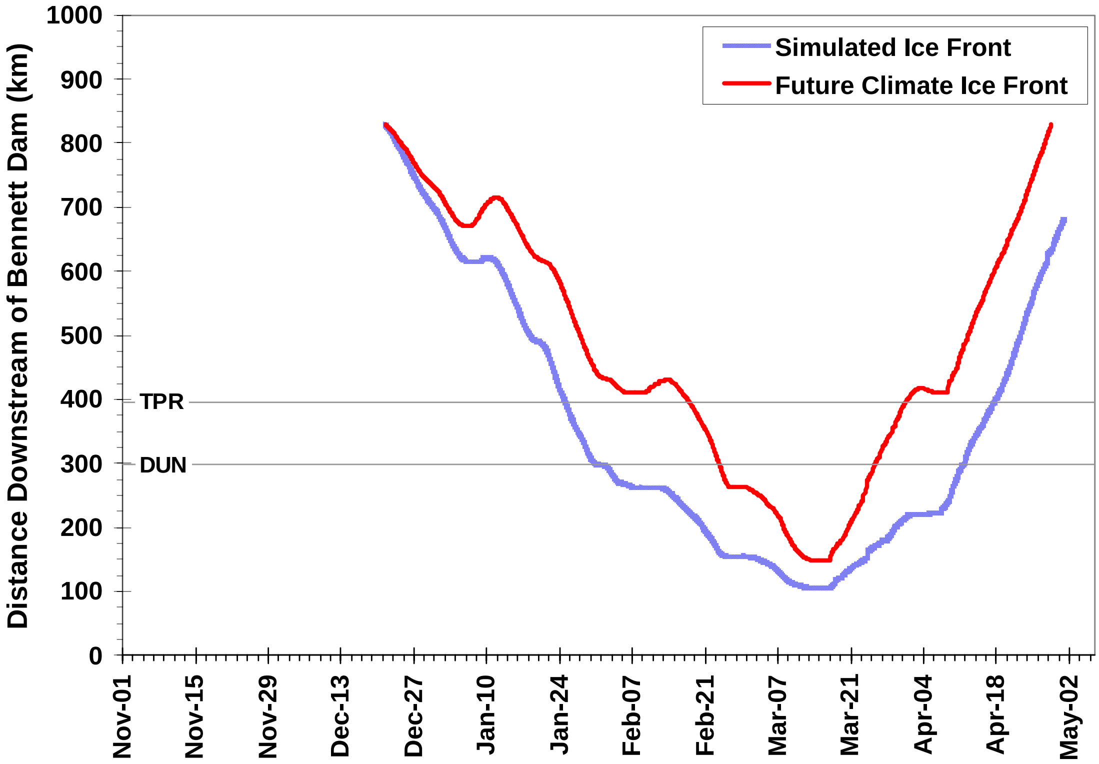

Figure 11. Simulated historical and future climate ice front profiles (2002/03).

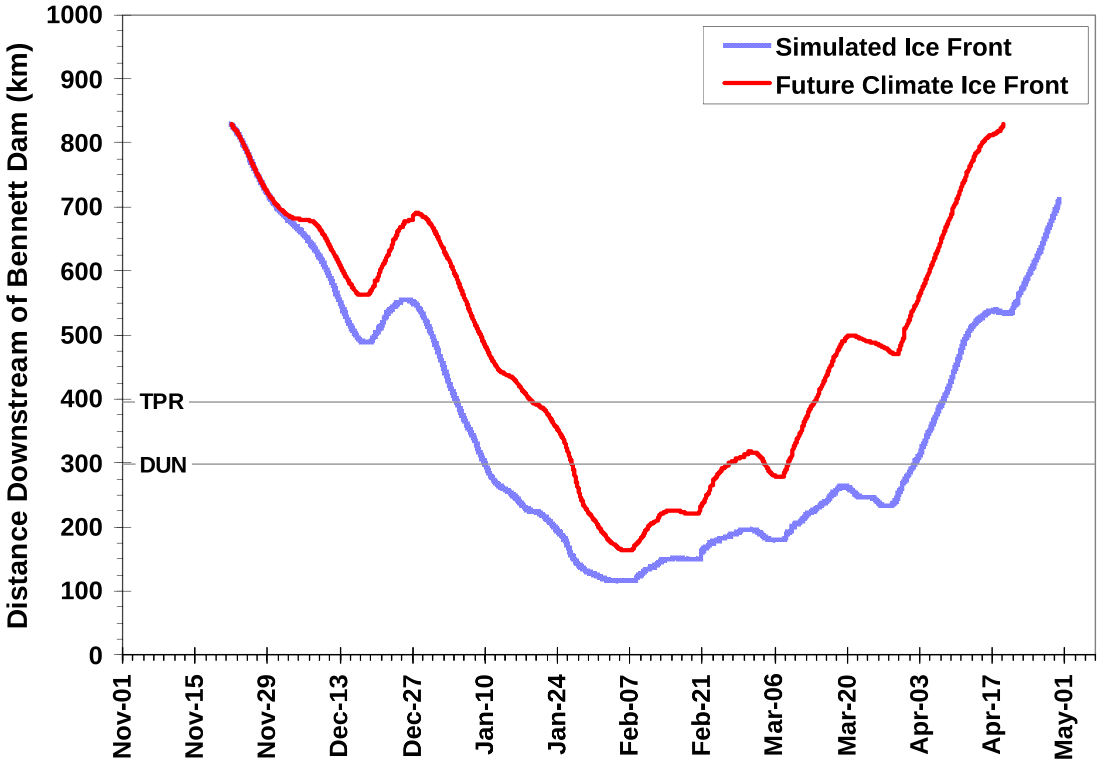

Figure 12. Simulated historical and future climate ice front profiles (2003/04).

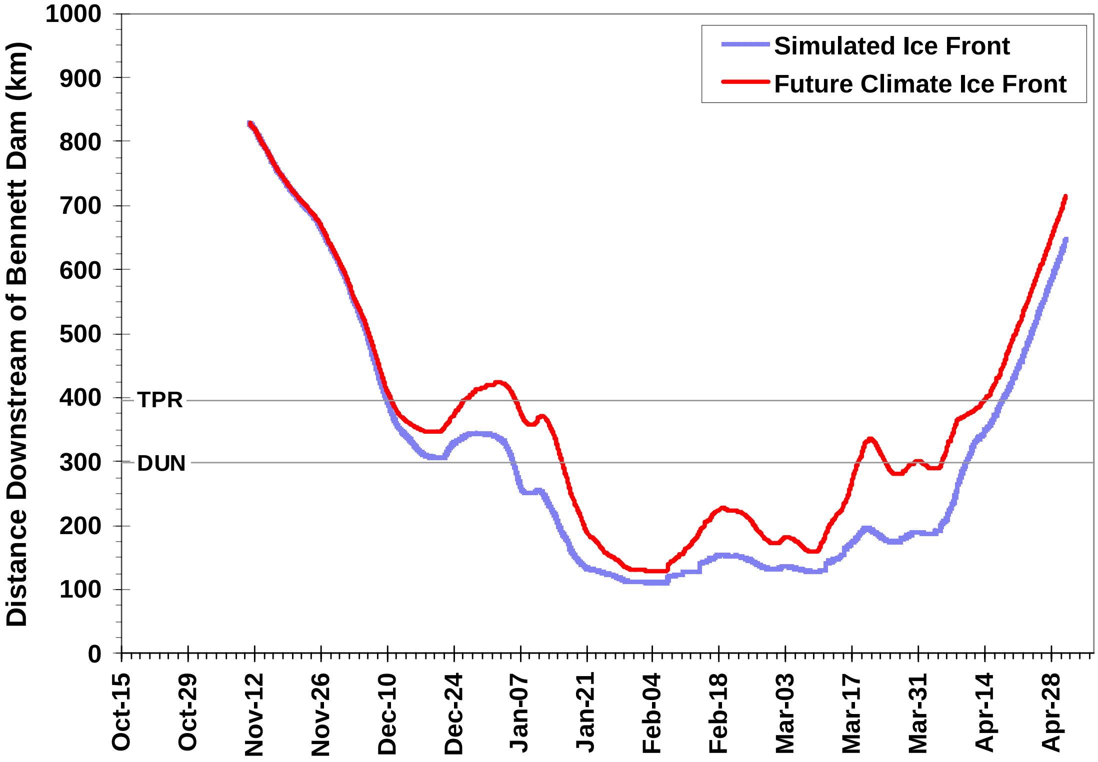

Figure 13. Simulated historical and future climate ice front profiles (1995/96).

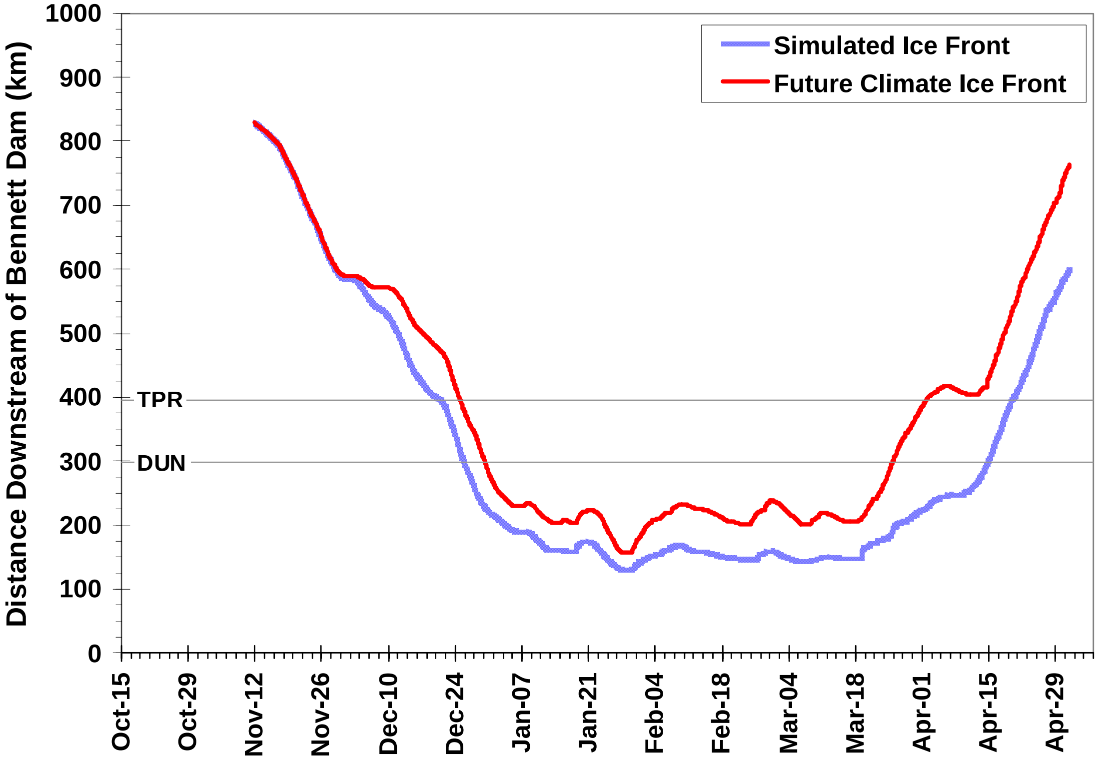

Figure 14. Simulated historical and future climate ice front profiles (1996/97).

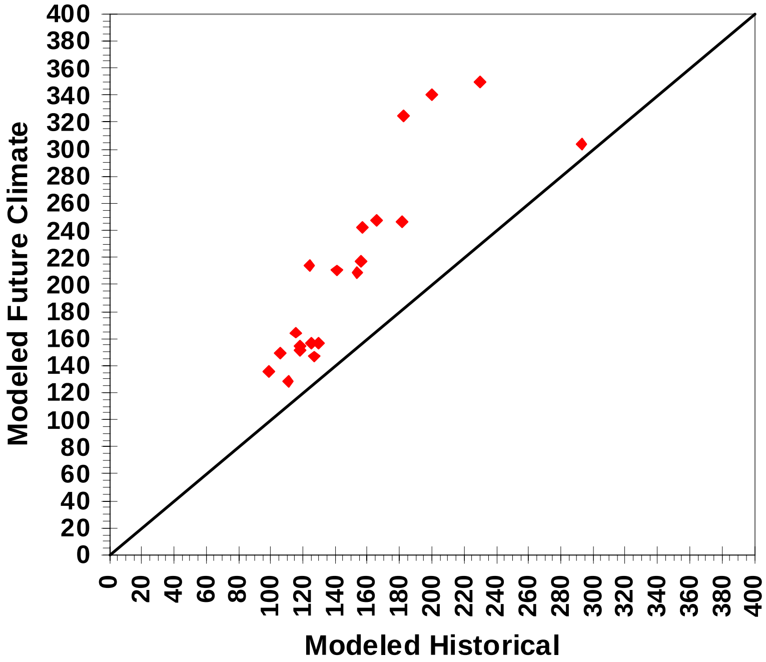

Figure 15. Modeled historical versus future climate change minimum ice front distance (in kilometres) from the Bennett Dam in British Columbia.

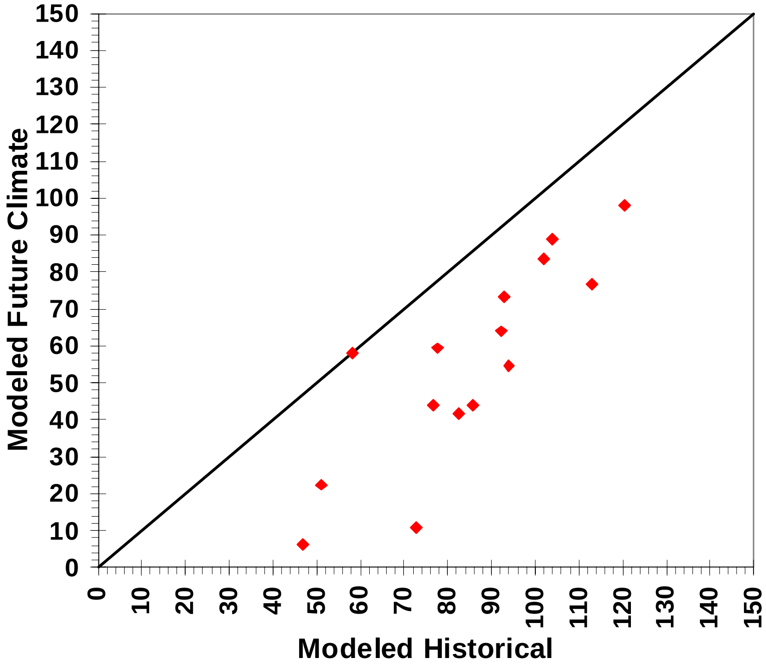

Figure 16. Modeled historical versus future climate change duration of ice cover (in days) at the Town of Peace River in Alberta.