Predicting stream temperatures under a climate change scenario: impacts on critical temperatures for Atlantic salmon (*Salmo salar*)

N. N. Brodeur, C. Hébert, D. Caissie, and C. Breau

Fisheries and Oceans Canada
Science Branch
Diadromous Fish Section
343 Université Avenue
Moncton, NB
E1C 9B6

2015

Canadian Technical Report of Fisheries and Aquatic Sciences 3118

Fisheries and Oceans Canada Pêches et Océans Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développe-ment, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3118

2015

Predicting stream temperatures under a climate change scenario: impacts on critical temperatures for Atlantic salmon (*Salmo salar*)

by

Nathalie N. Brodeur, Cindie Hébert, Daniel Caissie and Cindy Breau

Fisheries and Oceans Canada
Science Branch
Diadromous Fish Section
343 Université Avenue
Moncton, NB
E1C 9B6

Cat. No. Fs97-6/3118E-PDF ISBN 978-1-100-25493-7 ISSN 1488-5379

Correct citation for this publication:

Brodeur, N. N., C. Hébert, D. Caissie, C. Breau. 2015. Predicting stream temperatures under a climate change scenario: impacts on critical temperatures for Atlantic salmon (*Salmo salar*). Can. Tech. Rep. Fish. Aquat. Sci. 3118: ix + 44p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Brodeur, N. N., C. Hébert, D. Caissie, and C. Breau. 2015. Predicting stream temperatures under a climate change scenario: impacts on critical temperatures for Atlantic salmon (*Salmo salar*). Can. Tech. Rep. Fish. Aquat. Sci. 3118: ix + 44p.

Salmon have adopted coping strategies to deal with high water temperature events during the summer. However, when water temperatures exceed a critical daytime maximum (23°C) and minimum temperatures remain above 20°C at night, any additional stress, such as that due to angling, may be detrimental. To explore how thermal regimes have changed in the past and how they might be impacted in the next century under climate change, a stochastic multiple linear regression model was developed. This model was calibrated using 20 years of data, together with data from a Global Climate Model (A2 scenario), to estimate future water temperatures in the Little Southwest Miramichi River (New Brunswick). Over the next century, the mean annual air and water temperatures of the Little Southwest Miramichi River are projected to increase by 4.4°C and 3.2°C, respectively. The predicted increase in water temperature will ultimately impact the number of days exceeding critical water temperature thresholds for Atlantic salmon. Under these changes, days surpassing the critical thresholds (T_w-*min* > 20°C and T_w-*max* > 23°C) could increase by 21 to 41 days per year. Results from this study support many others that have predicted increasing stream temperature trends over the next century. As such, the management of cold water habitats and angling activities will become increasingly more important in the future for the protection Atlantic salmon populations.

RÉSUMÉ

Brodeur, N. N., C. Hébert, D. Caissie, C. Breau. 2015. Predicting stream temperatures under a climate change scenario: impacts on critical temperatures for Atlantic salmon (*Salmo salar*). Can. Tech. Rep. Fish. Aquat. Sci. 3118: ix + 44p.

Le saumon a adopté des stratégies d'adaptation pour faire face aux évènements de températures élevées pendant l'été. Toutefois, lorsque les températures de l'eau excèdent les limites journalières maximales (23 °C) et minimales (20 °C), tous facteurs de stress supplémentaires, comme la pêche, peuvent devenir nuisibles. Pour comprendre comment les régimes thermiques ont changé dans le passé et comment ils pourraient être affectés dans le siècle à venir dans un contexte de changements climatiques, un modèle stochastique à régression linéaire multiple a été développé. Ce modèle a été calibré avec 20 ans de données, et a utilisé un modèle couplé climatique global (scénario A2) pour estimer les températures de l'eau future de la rivière Little Southwest Miramichi (Nouveau-Brunswick). Au cours du prochain siècle, les températures moyennes annuelles de l'air et de l'eau de la rivière Little Southwest Miramichi augmenteraient de 4.4°C et de 3.2°C, respectivement. Les hausses de température de l'eau vont ultimement affecter les limites critiques des températures de l'eau pour le saumon Atlantique. En vertu de ces changements, les températures critiques (T_w-*min* > 20 °C et T_w-*max* > 23 °C) pourraient augmenter de 21 à 41 jours par année, respectivement. Les résultats de la présente étude supportent plusieurs autres études prédisant une augmentation des températures de l'eau au cours du prochain siècle. Par conséquent, la gestion des habitats d'eau froide et les activités de pêche prendront de plus en plus d'importances à l'avenir afin de protéger les populations de saumon de l'Atlantique.

1.0 INTRODUCTION

Stream water temperature has many chemical, biological and ecological impacts, and is considered to be one of the most important parameters when studying aquatic ecosystems (Caissie *et al*. 1998; Caissie 2006), and when assessing water quality (Ward 1963; Kothandaraman 1971). Factors that influence river water temperature can be natural, such as solar radiation, groundwater input and river discharge. They can also be human-induced, such as the removal of stream bank vegetation or deforestation, water withdrawal, return flow from agricultural irrigation, water releases from dams and reservoirs, cooling of nuclear power plants, etc. (Brown and Krygier 1970; Bjornn and Reiser 1991; Prats *et al*. 2012). Furthermore, as a consequence of climate change, many studies have predicted that stream water temperatures will significantly increase in decades to come (Webb 1996; Mohseni *et al.* 2003). Therefore, it is imperative that we strive to understand how river thermal regimes have changed in the past and how they may change in the future (Webb 1996). Such understanding will assist in the development of management strategies to mitigate negative effects of warming river temperatures.

Water temperature has a major influence on the metabolic rates of aquatic ectothermic organisms (Gordon *et al*. 1992; Breau 2013) and is one of the factors that contribute to habitat quality and suitability for fish (Bjornn and Reiser 1991; Stenhouse *et al*. 2012). For anadromous salmonids, stream water temperature affects, among other things, the behaviour, the timing of upstream migration of adults, the spawning time, the incubation time of developing eggs, the growth of individuals and the timing of downstream migration to the sea (Bjornn and Reiser 1991). Predation and competition among individuals is also affected by temperature (Materna 2001). In addition, microhabitat preferences and use (during the course of the life cycle of certain species) is dependent on temperature (Bovee 1982). Studying biological effects of climate change is a challenge, but is crucial to the understanding of changes in thermal tolerance and disease resistance and how these will affect the survival of salmonid populations in the future (Crozier *et al*. 2008). Individuals within a population, having already experienced several high temperature events, may be weakened from energy depletion and have a heightened susceptibility to parasitic and bacterial disease (McCullough 1999; Materna 2001). Moreover, environmental changes due to climate change may act on multiple life stages of specific species (McCullough 1999; Crozier *et al*. 2008), and may also act differently on multiple interacting species (Harrington *et al*. 1999), thereby creating a differential shift in phenology of community interactions (Visser and Both 2005). Changing species interactions may be crucial to the growth and survival of the focal species that is being managed or protected.

Studies have looked at the impact of climate change on river water temperatures (Meisner 1990). In Eastern Canada, mean annual air temperature is expected to increase by 2°C to 6°C in the next 100 years (Parks Canada 1999). Such an increase in air temperature will greatly affect stream water temperatures (Kothyari *et al.* 1997). Most studies are predicting an increase in stream temperatures (up to 5°C), especially in the summer months (Pilgrim *et al*. 1998; Morrison *et al*. 2002; Morril *et al*. 2005; Tung *et al*. 2006; El-Jabi *et al.* 2013).

Increases in summer water temperatures due to climate change could cause the dissolved oxygen in the water to decrease and aggravate the effects of stream acidity, threatening the growth and life of some aquatic species (Hill and Magnuson 1990; Schindler 2001; Gooseff *et al*. 2005). Major reductions in suitable habitat conditions could result from climate warming in regions inhabited by cold and cool water fish species (Eater and Scheller 1996). Changes in growth rate of fish may be possible, especially during the spring to autumn, due to increased water temperatures (Hill and Magnuson 1990). Climate change may also increase groundwater temperatures, affecting the incubation of eggs within the stream substrate (Meisner *et al.* 1988).

Hrachowitz *et al*. (2010) have shown that under a climate change scenario with an increase of 2.5°C to 4°C in air temperatures, the thermal habitat of Atlantic salmon and brown trout will likely be altered.

Extreme temperatures are expected to be more common under climate change (Kjellström *et al*. 2007), pointing the need to study the impact of climate change on critical temperature of fish species. For Atlantic salmon, mature adults migrate to their native stream to spawn after spending (usually) one to three years at sea (Chaput *et al*. 2010). The homing enables individuals within each population to become locally adapted to chemical and physical variables found in the native stream environment, such as thermal regimes (Crozier *et al*. 2008). Many studies have shown that the thermal tolerance of salmonids can evolve in the wild (e.g., Beacham and Murray 1989; Beacham and Withler 1991). In the Little Southwest Miramichi River, high water temperature events can occur during the summer months and generally peak in July and August (Caissie *et al*. 2013). Maximum water temperatures in the Miramichi River are approaching the upper lethal limit (25°C to 28°C) for Atlantic salmon (Breau and Caissie 2013). Early migrants, which enter the Miramichi water system in early to mid-July and then wait to spawn in autumn (Chaput *et al*. 2010), have adapted strategies to cope with these high temperature events, such as physiological and behavioural responses (Pörtner and Farrell 2008; Breau 2013). However, all salmonids have an upper critical thermal tolerance limit, above which the energy required to survive is limited and death will occur (Huntsman 1942; Wilkie *et al*. 1997; McCullough 1999; Pörtner and Farrell 2008; Breau 2013).

For Atlantic salmon, two critical temperatures have been proposed (Breau 2013): (1) a maximum critical water temperature (T_w-*max*) of 23°C; and (2) a minimum critical water temperature (T_w-*min*) of 20°C. In the present study, a water temperature above T_w-*max* during the day is considered to be a high temperature event. At these high temperatures, adult salmon usually rest in deep pools, where cooler waters are present (Breau *et al*. 2007). Atlantic salmon adults need to recuperate after being exposed to daytime high temperature events and water temperatures below T_w*-min (*i.e., below 20°C) was proposed for such recovery (Breau 2013). T_w*-min* generally occurs in early morning before sunrise. These environmental thresholds have been proposed to regulate angling of Atlantic salmon during the summer months when high temperature events occur in Gulf Region rivers (DFO 2012). These critical thresholds will be further analyzed using a modeling approach in the present study.

Water temperature models can be classified into two groups: deterministic and stochastic (Caissie 2006). Deterministic models consider causal mechanisms of thermal transfer between meteorological conditions and the river environment (Raphael 1962; Morin and Couillard 1990; Morin *et al.* 1994). The disadvantage of this approach is that it requires a large number of input parameters, which may be difficult to collect. Alternatively, statistical or stochastic models can be used to predict water temperatures based on the internal structure of a time series and an established relationship between air and water temperatures (Cunjak *et al*. 1993; Caissie *et al.* 1998). Notably, stochastic models consider the autocorrelation within the time series whereas statistical models do not. Since air temperature is the dominant factor explaining long-term trends and variability in river temperature (Isaak *et al.* 2012), stochastic models can be used (with relatively few variables, *i.e.*, air temperature) to predict water temperatures. Among these stochastic models, the multiple linear regression model is the simplest, but just as effective as the second-order Markov process, and the Box-Jenkins time-series models (Caissie *et al.* 1998). This study used a multiple linear regression model and this model is particularly well suited for climate change studies, requiring only air temperature as the input variable. In fact, air temperature is often the only parameter available with a good level of certainty from climate change models.

The goal of the present study was to model stream water temperatures under a future climate change scenario. The specific objectives of the study are 1) to develop a stochastic model to predict daily stream water temperature for the Little Southwest Miramichi River under current climate conditions (1970-1999), 2) to simulate future water temperatures under a climate change scenario (CGCM A2; known as the "worst case scenario"), 3) to examine the impact of climate change on critical water temperature thresholds for the Atlantic salmon (daily minimum and maximum water temperature). Specifically, we will address the following questions: (1) How do predicted water temperatures compare with observed water temperatures? (2) How much are the mean, maximum and minimum air and water temperatures predicted to increase in the future? (3) How many days per year will water temperatures exceed critical thresholds (T_w-*min* and T_w-*max*) in the future compared to the historical period?

2.0 MATERIALS AND METHODS

2.1 Study area

The study site is located on the Little Southwest Miramichi River (LSWM), part of the Miramichi River system (New Brunswick, Canada), which is world renowned for its population of Atlantic salmon (Figure 1). This system has an annual precipitation ranging from 860 mm to 1365 mm, with a long-term average of 1142 mm (Caissie and El-Jabi 1995). The mean monthly air temperature varies between -11.8°C (January) and 18.8°C (July). The mean annual runoff was estimated by Caissie and El-Jabi (1995) to be 714 mm, ranging from 631 mm to 763 mm. The vegetation consists mainly of second-growth forest of mature species estimated at 65% coniferous and 35% deciduous (Cunjak *et al*. 1990).

The Little Southwest Miramichi River is a fifth-order stream with a drainage basin area of 1190 km^2, a mean width of 75 m, an average water depth of 0.55 m, and has less than 20% canopy cover (Breau *et al.* 2007; El-Jabi *et al.* 2012). In the summer, high water temperature events are common in the Miramichi River system (El-Jabi *et al.* 2012; Caissie *et al.* 2013), including the LSWM.

Air temperature data were collected from 1992 to 2011 at the meteorological station positioned at mid-basin in Catamaran Brook, a tributary of the Little Southwest Miramichi River (Figure 1). The air temperature was monitored hourly using a Vaisala Relative Humidity and Temperature sensor. The accuracy is typically within 0.2°C. The sensor was installed at approximately 1.8 m from the ground. Gaps in the historical air temperature data were filled using data from two nearby stations. The first, the Doaktown meteorological station, is located at about 38 km from the Little Southwest Miramichi temperature site. The second, the McGraw Brook meteorological station, is located on the Renous River, adjacent to the study site (Figure 1). This station has an extensive long-term meteorological data set since 1969 (Cunjak *et al.* 1993). A water temperature sensor was installed in the Little Southwest Miramichi River at approximately 20 m upstream from the confluence of Catamaran Brook (at approximately 2 m from the true right bank, near the bottom; data available from 1992). The sensor was a model 107B (Campbell Scientific Corp.). The error associated with this sensor is typically less than 0.2°C. Water temperature was measured every 5 seconds and data (average) were logged hourly. Daily mean temperatures were calculated from these hourly water temperature measurements.

Since the air-water temperature relationship departs from linearity at below freezing air temperatures (Crisp and Howson 1982), this study only used data within the open-water period (*i.e.*, water temperatures above 0°C). For the Miramichi River system, this period runs from mid-April to late November (El-Jabi *et al.* 2012). Therefore, the annual period was from March 31st to November 6th (day 90 to 310) and the summer period was from July 1st to August 31st (day 182 to 243).

2.2 Water temperature model

2.2.1 Stochastic model

The stochastic daily temperature model consists of two water temperature components: the annual cycle (long-term seasonal) and the short-term component (non-seasonal). The short-term component is the departure from the annual cycle during each day, due to daily above or below normal air temperatures. Daily water temperature $T_w(t)$ can be expressed as a function of its annual $TA_w(t)$ and short-term $R_w(T)$ components with the following equation:

(1) $$T_w(t) = TA_w(t) + R_w(t)$$

where t represents the day of year (1 to 365; Caissie *et al.* 1998). The annual cycle in water and air temperatures can be represented using a sinusoidal function (Ward 1963; Cluis 1972; Caissie *et al.* 1998). It has been demonstrated that air and water temperatures measured at the same time each day are cyclical and are distributed about an annual sinusoidal curve with good inter-annual stability (Ward 1963). The annual cycle of both air and water temperatures can be expressed as follows:

(2) $$TA_w(t) = a + b\sin\left(\frac{2\pi(t - t_0)}{365}\right)$$

where a and b are the annual cycle coefficients (a = mean temperature and b = amplitude of the seasonal cycle), t is the day of year, t_0 correspond to the phase parameter and is a function of the peak value (i.e., maximum of the cycle). Value of t_0 was fixed at day 114 for air temperatures and day 119 for water temperatures based on literature data (Ward 1963; Caissie *et al.* 1998).

The short-term component in daily water temperature is estimated based on the air temperature short-term component of the day and of the preceding two days (Kothandaraman 1971) and was obtained using multiple linear regression using the following equation (Caissie *et al.* 1998; El-Jabi *et al.* 2012):

(3) $$R_w(t) = a_1 R_a(t) + a_2 R_a(t-1) + a_3 R_a(t-2)$$

where $Rw(t)$ is the short-term components of water temperatures, a_1, a_2, and a_3 are regression coefficients, $R_a(t)$, $R_a(t\text{-}1)$, $R_a(t\text{-}2)$ are the short-term components of the present day, the previous day and the two days before (Kothandaraman 1971). The short-term component of air temperature R_a was calculated as the difference between the annual component of air temperature and the observed air temperature.

This stochastic model was developed to predict water temperatures. The air and water temperatures collected from 1992 to 2011 (day 90 to 310) were used to calibrate the stochastic model. First, the annual cycle of air and water temperatures were calculated. Each coefficient (*a* and *b*) of the annual cycle of air and water temperatures was estimated by minimizing the error between the observed long-term temperatures and the sinusoidal function. The short-term component of water temperature was then estimated using the regression model. The regression model parameters (a_1, a_2, and a_3) were solved by minimizing the error between observed and predicted water temperatures. The regression parameters were first calibrated over the summer months of July and August (day of year 182 to 243) and then applied to the annual period (day of year 90 to 310). This provided a better fit of the model for the summer months, which are the months of interest for the future predictions of water temperatures. Water temperatures were then calculated by adding the corresponding annual and short-term component. This process was repeated for minimum, mean and maximum water temperatures. Once calibrated, the stochastic model was used to predict river water temperatures for four 30-year time periods: historic (1970-1999), and three future periods (2010-2039; 2040-2069; 2070-2099).

2.2.2 Global Climate Model (GCM)

Models of future climate change, also known as Global Climate Models (GCMs), are based on mathematical relationships in processes operating in the atmosphere, the ocean, the ice caps and land surface (El-Jabi *et al.* 2010; Turkkan *et al.* 2011). They are used for predicting future variables, such as stream water temperature, in the face of increasing greenhouse gases and climate change. However, these models do not necessarily represent local scale processes due to their limited spatial resolution (El-Jabi *et al.* 2010). For this reason, the GCM data for the province of New Brunswick (Canadian coupled global climate model CGCM3.1/T63) were downscaled with regional data from the Miramichi River system using the delta method (Turkkan *et al.* 2011). The delta method is an approach which calculates the differences between observed data and GCM simulations during a given historical period. Then the future projected GCM simulation data are corrected to reflect these differences. The climate change model CGCM3.1/T63, in this study, was used with the Special Report on Emissions Scenarios (SRES) A2, also known as the "worst case scenario". It describes a heterogeneous world with high population growth, slow economic development and slow technological change (IPCC 2007). The underlying theme is self-reliance and preservation of local identities (Turkkan *et al.* 2011), therefore no resources are committed to either maintain present levels or reduce future levels of greenhouse gas emissions in the atmosphere.

Once the data from the CGCM (A2 scenario) were downscaled, the model provided daily minimum, mean and maximum air temperatures from an historical period (1970-1999), and 3 future periods (2010-2039; 2040-2069; 2070-2099). Using the calibrated stochastic model and air temperatures from the CGCM(A2) scenario, daily minimum, mean and maximum water temperatures were predicted for the same periods.

2.3 Modeling Performance Criteria

The relative performance of the minimum, mean and maximum temperature models overall and among different years were compared using the root mean square error (*RMSE*), which was calculated with the following equation:

(4) $$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}}$$

where P_i and O_i are predicted and observed water temperatures, and N the number of daily observations (Caissie *et al.* 1998). The *RMSE* values are presented to ±0.01°C for comparative purposes only and are not reflective of the accuracy of the sensors.

3.0 RESULTS

3.1 Calibration of the river temperature model (1992 to 2011)

Data from 1992 to 2011 (day 90 to 310) were used to calibrate the stochastic river temperature model. This water temperature model uses a sinusoidal function to represent the annual cycle for both air and water temperatures. The coefficients *a* and *b* for minimum, mean and maximum air and water temperatures and their associated *RMSEs* are presented in Table 1. The coefficients *a* and *b* were calibrated by minimizing the sum of squared error (*RMSE*) between the observed data and the sinusoidal function. For the annual air temperature component, the *RMSE* was lower for the daily mean temperature (0.81°C) than minimum and maximum temperatures (both 1.13°C). The coefficients for *a* were -0.44 (minimum), 4.9 (mean) and 10.7 (maximum). Values for the coefficient *b* (air temperatures) were 2.2 (minimum), 13.9

(mean) and 14.7 (maximum), reflecting the amplitude of the annual cycle. Lower *RMSE* values were observed for the sinusoidal function describing water temperature, with values close to 0.7°C. The *a* coefficient ranged from 4.0 to 6.0, and between 14.0 and 17.0 for *b*. The stochastic regression model parameters (a_1, a_2, and a_3) were calibrated for the summer period (Table 1). The calibrated model showed *RMSE* ranging between 1.38°C and 1.93°C.

The stochastic model was then applied for both annual and summer periods using the calculated model. Minimum, mean and maximum predicted water temperatures were obtained for two periods (summer and annual). The best performance was observed for daily mean water temperatures (*RMSE* = 1.38°C for annual and 1.31°C for summer; Table 2). Nonetheless, good results were also observed for minimum (*RMSE* = 1.65°C and 1.61°C) and maximum (*RMSE* = 1.93°C and 1.65°C) water temperatures. When considering both annual and summer periods, *RMSEs* were slightly better for the summer period, which is the period of interest in the present study.

The stochastic model performed well for most years (Table 2). For minimum water temperatures, the model performed well with the exception of years 1992, 1996 and 2010, with *RMSE* values of 2.03°C, 2.11°C, and 2.32°C (annual), respectively. For the daily mean water temperatures, the stochastic model performed well for most years with *RMSEs* between 1.06°C and 1.70°C (annual). A few summers (2000, 2001, 2007) achieved *RMSEs* less than 1°C. The *RMSE* values were the highest for the maximum water temperatures compared to mean and minimum water temperatures (annual and summer). The prediction of maximum water temperatures showed *RMSE* values between 1.55°C and 1.94°C; however, some years showed *RMSEs* over 2°C (annual; Table 2). Summer *RMSEs* were slightly lower.

The observed and predicted overall mean water temperatures for the annual period (1992-2011) were similar for the minimum (11.4°C and 11.5°C), mean (both 13.2°C) and maximum (15.1°C and 15.2°C) temperatures (Table 3). This shows that the model was effective in predicting river water temperatures with a low bias of 0.1°C. The average observed and predicted water temperatures varied from 9.9°C to 12.5°C (observed) and 10.3°C to 13.3°C (predicted) for the minimum, 11.4°C to 15.6°C and 12.1°C to 14.7°C for the mean, and 13.2°C to 17.6°C and 14.1°C to 16.7°C for maximum water temperatures (Table 3). There was a clear overestimation of water temperatures, in years 1992 and 1996, whereas, an underestimation was observed in 2010 (Table 3).

Predicted vs. observed minimum, mean, and maximum water temperatures for the summer as well as for July and August are presented in Figure 2. Note that water temperatures in this figure are average over the summer period (July and August) and for each month. The model performed best for the summer mean water temperatures (*RMSE* = 1.31°C) followed by the summer minimum (1.61°C) and maximum (1.65°C). The month of August showed generally lower *RMSEs* than the month of July. Figure 3 show the regression results between observed and predicted number of days where temperatures exceeded $T_w\text{-}min$ > 20°C and $T_w\text{-}max$ > 23°C. Results showed poor predictability for the number of days where $T_w\text{-}min$ > 20°C with an R^2 of only 0.297; however, better predictions were obtained for $T_w\text{-}max$ with an R^2 of 0.627.

The number of days where predicted and observed daily minimum (Table 4) and maximum (Table 5) water temperature exceeded critical temperatures of 20°C and 23°C, respectively, were calculated from the annual period data. In general, predicted minimum water temperatures were underestimated (Figures 3a and 4a). The model had a better fit between predicted and observed daily maximum water temperatures (Figures 3b and 4b). The number of days where the minimum observed water temperature exceeded critical temperature (20°C) was an average of 8.6 days per year (Table 4). The model under-predicted this variable by a factor close to 3: predicting an average of 3.0 days per year. For maximum water temperatures, the predicted average number of days where the critical temperature exceeded 23°C was 24.4 days per year, somewhat similar to the observed value of 28.1 days per year.

3.2 Historical and future periods CGCM(A2)

Air temperature data estimated from the downscaled CGCM(A2) model data were used in the stochastic model to predict water temperatures. One historical period (1970-1999) and three future 30-year time periods (2010-2039; 2040-2069; 2070-2099) were analyzed. Figure 5 and 6 shows the average daily minimum, mean and maximum air and water temperatures for the period related to the CGCM(A2) model. The time series variability and similarities among time slices in Figures 5 and 6 comes from the fact that the downscaled CGM data comes from the historical data within the Miramichi area. Table 6 and 7 show the annual and summer average of air and water temperature for the calibration period (1992-2011), the historical period (1970-1999) and the future periods (2010-2039; 2040-2069; 2070-2099). It should be noted that the calibration period was only used to determine the parameters of the water temperature model. Only air and water temperatures calculated based on CGM model inputs (i.e., historical period; 1970-1999) can be compared to future climate change scenario. For the average mean annual air temperature, an increase from 12.1°C to 16.5°C (ΔT_a = 4.4°C) is expected over the next 100 years (Table 6). The corresponding average mean annual water temperatures are expected to increase from 12.7°C to 15.9°C (ΔT_w = 3.2°C). In summer, the average mean water temperature will most likely increase from 20.0°C to 23.3°C (ΔT_w = 3.3°C) with corresponding air temperatures from 18.6°C to 23.1°C (ΔT_a = 4.5°C) (Table 7). Figure 7 shows the average summer minimum, mean and maximum air and water temperatures for the different CGCM(A2) periods.

From the data, future cumulative changes (i.e., change from historical period) in air and water temperatures can be estimated for each future period (Table 8). For both the annual and summer periods, the cumulative change in air temperatures was greater than that for the water temperatures. By 2070-2099, on average, the annual air temperature is predicted to increase by 4.6°C, 4.4°C, and 4.3°C for the daily minimum, mean, and maximum. Corresponding daily minimum, mean and maximum water temperatures are predicted to increase by 2.0°C, 3.2°C and 3.2°C. Similar cumulative changes are expected in summer, for the month of July and the month of August. The greatest change is estimated to be an increase of 4.6°C for the minimum air temperature and 3.2°C in the maximum and mean water temperature for the annual period. For the summer period, the highest increases are 4.5°C for the mean air temperatures and 3.3°C for the minimum and maximum water temperatures. Greater changes in air and water temperatures are predicted for the month of August compared to the month of July (Table 8).

From the predicted future water temperatures, the predicted number of days where daily minimum and maximum water temperatures exceeded critical temperatures (T_w-*min* > 20°C and T_w-*max* > 23°C, respectively) for the historical and future periods were calculated (Table 9 and Figure 8). Over the next century, not only are the number of high temperature events predicted to increase for T_w-*max* >23°C, they are also predicted to increase for T_w-*min* > 20°C. For future period 1 (2010 to 2039), the number of days where minimum and maximum water temperatures exceeded critical temperatures of 20°C and 23°C, was, on average, 7.0 and 40.6 days per year, respectively. For future period 2 (2040 to 2069) the number of days per year was 12.3 and 52.3, respectively, and for future period 3, the model estimated 25.0 and 68.6 days per year, respectively.

An increase of the average number of days where the water temperature exceeds minimum and maximum critical temperatures was predicted to occur over the next century (Table 10). Minimum water temperatures are predicted to increase at a slower rate than maximum water temperatures. The number of days where minimum water temperatures are over 20°C (T_w-*min*) is predicted to increase by 3.2, 8.5 and 21.1 days per year, for the future period 1 (2010-2039), future period 2 (2040-2069) and future period 3 (2070-2099), respectively. For maximum water temperatures (T_w-*max*), the number of days exceeding this threshold is expected to increase by 13.3, 25 and 41.3 days per year for each future period.

4.0 DISCUSSION AND CONCLUSIONS

In this study, a stochastic multiple linear regression model was used to estimate future water temperatures in the Little Southwest Miramichi River from 2010 to 2099. This was accomplished by calibrating the model to observed air and water temperature data (1992 to 2011). Once calibrated, the model used both historical and future air temperature data from the Global Climate Model (CGCM3.1/T63, Special Report on Emissions Scenarios A2) to predict water temperatures. The A2 scenario represents a "worst case scenario" as pointed out by IPCC (2007). Results of the calibration showed that the model performed well in estimating the daily minimum, mean and maximum water temperatures for the annual period (*RMSE* = 1.65°C to 1.93°C) and for the summer period (*RMSE* = 1.31°C to 1.65°C). However, the model generally underestimated the T_w-*min* threshold values whereas the model's predictions were slightly better for T_w-*max*.

The results of this study were similar to those observed by Quinn and Adams (1996), who found that warmer and longer periods of maximum water temperatures were occurring in the Columbia River, U.S.A. The GCM scenario A2 was used in the present study to estimate future air temperatures. The future outcome in river temperature could be better than the A2 scenario, especially if CO_2 emissions are controlled in the future. It should be pointed out that water temperature models in general are less accurate at predicting the very high water temperatures (Mohseni and Stefan 1999), due to evaporative cooling. At high air temperatures, although water temperature increases, studies have shown that the rate of increase is weakened past a certain temperature threshold (*e.g.*, 25°C; Mohseni and Stefan 1999). At high air temperatures, the moisture holding capacity of the atmosphere increases, and river evaporation increases as well, thus contributing to the evaporative cooling. As the water body loses a significant amount of heat through evaporation, then the river temperature increases at a slower rate (Mohseni *et al.* 1998; Mohseni and Stefan 1999). These observations are consistent with results observed in the present study, which shows future increases in water temperatures to be less than air temperature. Furthermore, other variables such as a decreased river discharge, increased groundwater temperature, or changes in riparian vegetation could also impact on future river thermal regimes (*e.g.*, Webb and Nobilis 1994; Webb 1996; Cunjak *et al*. 2013). Other aspects of the thermal regime of rivers, such as cold water tributaries, are also important in the overall survival and protection of thermal habitats. For instance, Cunjak *et al.* (1993) showed that small tributaries can be a source of thermal refugia during high temperature events.

Many studies monitoring both air and water temperature trends have reported a significant increase in temperatures over the last century (Webb 1996; Thistle and Caissie 2013). However, very few of these studies are based on long-term water temperature data. Two such studies were from Webb and Nobilis (1994; 2007) who analyzed data sets spanning 90 and 100 years from several Austrian rivers. These studies of mean monthly air and water temperatures showed that water temperatures have increased by between approximately 0.8°C and 1.5°C over the last century. They also noted a rapid increase in temperatures after 1970, especially between 1990 and 2000. Webb and Nobilis (2007) speculated that this could be evidence to support the hypothesis of global warming.

Generally, studies that have reported future water temperature trends based on different GCMs have predicted increases ranging from 1°C to more than 7°C over the next century (Webb 1996). Our predictions of 3.2°C (mean annual water temperature increase) and 3.3°C (mean summer water temperature increase) by 2099 fall well within this range. Cristea and Burges (2010) used a regional GCM model with SRES B1 to predict future water temperatures in Wenatchee River Basin in Washington State (U.S.A.). Similar results were found with a mean water temperature increases of 0.83°C, 1.37°C and 2.06°C for years 2020, 2040 and 2080, respectively. These results are comparable to those of the present study, i.e., 1.0°C, 1.9°C and 3.2°C (using SRES A2). Cristea and Burges (2010) also used the scenario SRES A1B and their results showed increases of 1.06°C, 1.76°C and 2.99°C for the same time periods described above. Their model also considered river hydrology and stream discharge. However, such models may be associated with greater uncertainties, as future precipitation regimes are very difficult to predict and generally have a significantly higher level of uncertainty. Webb and Nobilis (1994) reported that monthly mean water temperatures will most likely increase between 1°C and 2°C by year 2030. These results are similar to future period 1 (2010 to 2039) and future period 2 (2040 to 2069) predictions from our study with a predicted increase in daily mean water temperatures of 1.0°C to 1.9°C (annual period), respectively. These results are similar to those by Webb (1996) for summer mean monthly river temperature (increases of 1.8°C to 2.7°C by 2050). Studies have shown that the rate of temperature increases over the next 50 years is predicted to be equal to, or greater than, that recorded increase over the last 100 years (Webb 1996). Unfortunately, many years of water temperature data are required to test this hypothesis and only a few studies will be able to make this comparison.

During the calibration period (1992-2011), our data showed that even though there were many high temperature events which exceeded the T_w-*max* threshold, fewer events exceeding the T_w-*min* threshold were recorded. This means that salmon have a better chance to recuperate during some high temperature days. However, it was also observed that the water temperature model overestimated slightly the T_w-*max* and significantly underestimated the T_w-*min*. This has implications on the predicted future high temperature and recovery events. Over the next 30 years (2010-39), the T_w-*max* threshold is expected to increase from 27 (1970-99) to 41 days per year (2010-39; increase by 50% or 14 days). As observed and predicted T_w-*max* temperatures were very similar (1992-2011), then the 41 days per year remains a good future estimate. Within the same timeframe, we expect the T_w-*min* threshold to be exceeded from 3.8 (1970-99) to 7.0 days per year (2010-39) based on the modeling. However, since the model significantly underestimated the minimum water temperatures by a factor of approximately 2.9, then the T_w-*min* threshold should be adjusted accordingly. Over the calibration period (1992-2011) the T_w-*min* threshold was exceeded by 8.6 days per year on average and over the next 30 years this value will most likely increase to approximately 20 days per years (corrected value); however, this value has a high level of uncertainty (Figure 3a; Table 4). Similar to the calibration period, the number of high water temperature events (T_w-*max*) exceeds the number of events at night (T_w-*min*), therefore, allowing salmon to recover during most days, *e.g.* 41 days (T_w-*max*) vs. 21 days (T_w-*min*); approximately 50%.

The maximum water temperatures are not only projected to increase by the end of the century, high temperature events are also predicted to start earlier in the year and continue to later in the year (Mantua *et al*. 2010). This study showed that the critical threshold of 20°C (as a thermal migration barriers and elevated risk of fish kills) will persist 5 to 11 weeks longer by the end of the 21st century. Our results indicate that the maximum critical threshold period (days with T_w-*max* > 23 °C) will increase in duration. For the historical period, daily T_w-*max* generally occurred from June 21 to August 27 (68 days). By the 2070-2099 period, T_w-*max* are predicted to occurred from June 7 to September 9 (95 days). The minimum critical threshold (T_w-*min* > 20°C) was also predicted to occur over a longer time period in summer. During the historical periods, daily T_w-*min* occurred over a shorter time period compared to T_w-*max*, *i.e.*, from July 25 to August 6 (13 days). By the 2070-2099 period, daily T_w-*min* is predicted to occur over a longer period (53 days), from July 5 to August 26.

Cool water habitat management for salmonid populations has been identified as an important factor for salmon population persistence and recovery (Stenhouse *et al.* 2012). Identifying and protecting pools where cool water input from groundwater, springs or cooler tributary plumes may become more important in the future, as more and more high water temperature events will occur in the summer months. For example, water releases from cool water reservoirs could be timed to decrease temperatures in large rivers during critical biological periods (Isaak *et al.* 2012). In addition, afforestation of river banks in sections adjacent to resting pools may also help moderate water temperature maxima during the summer period, thereby reducing the number of days where water temperatures exceed critical temperature (*e.g.*, Webb and Crisp 2006). It is clear from the results of the present and other studies that the summer period may become a bottleneck for many salmonid species in North America over the next century (Isaak *et al.* 2012). Establishing management strategies to cope with the inevitable warming trend may be crucial for the survival of Atlantic salmon populations in New Brunswick where high water temperature trends have already been documented, as in the Miramichi River system.

In conclusion, by the 2070-2099 period, mean annual air and water temperatures of the Little Southwest Miramichi River are predicted to increase by 4.4 °C and 3.2 °C under a CGCM(A2) scenario. These water temperatures will not only increase significantly, but will also last for longer time period (up to 3 weeks or more). The predicted increase in water temperature will ultimately impact the number of days exceeding the critical water temperature thresholds for Atlantic salmon. Under these changes, the critical thresholds (T_w-*min* > 20°C and T_w-*max* > 23°C) could increase by 21 to 41 days on average per year, respectively.

5.0 ACKNOWLEDGEMENTS

This study was funded through the Department of Fisheries and Oceans Aquatic Climate Change Adaptation Services Program (ACCASP). Authors also thank Drs. David Cairns and Joël Chassé for reviewing the document.

6.0 REFERENCES

Beacham, T, CB Murray. 1989. Variation in developmental biology of sockeye salmon (*Oncorhynchus nerka*) and Chinook salmon (*O. tshawytscha*) in British Columbia. Canadian Journal of Zoology. **67**: 2081-2089.

Beacham, TD, RE Withler. 1991. Genetic variation in mortality of Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), challenged with high water temperatures. Aquaculture and Fisheries Management (now: Aquaculture Research). **22**: 125-133.

Bjornn, JR, DW Reiser. 1991. Habitat requirements of salmonids in streams. In Influences of forest and rangeland management on salmonid fishes and their habitats. Edited by W. R. Meehan. American Fisheries Society, Special Publication 19, pp. 83-138.

Bovee, KD. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Instream Flow Information Paper: No 12. U.S. Fish and Wildlife Service FWS/OBS-82/26.

Breau, C. 2013. Knowledge of fish physiology used to set water temperature thresholds for inseason closures of Atlantic salmon (*Salmo salar*) recreational fisheries. DFO Canadian Science Advisory Secretariat Research Document 2012/163. iii + 24 p.

Breau, C., and Caissie, D. 2013. Adaptive management strategies to protect salmon (Salmo salar) under environmentally stressful conditions. DFO Can. Sci. Adv. Secr. Res. Doc. 2012/164. ii+14 p.

Breau, C, RA Cunjak, G Bremset. 2007. Age-specific aggregation of wild juvenile Atlantic salmon *Salmo salar* at cool water sources during high temperature events. Journal of Fish Biology. **71**: 1179-1191.

Brown, GW, JT Krygier. 1970. Effects of clear-cutting on stream temperature. Water Resources Research. **6**: 1133-1139.

Caissie, D. 2006. The thermal regime of rivers: A review. Freshwater Biology. **51**: 1389-1406.

Caissie, D, N El-Jabi. 1995. Hydrology of the Miramichi River drainage basin. In Water, Science, and the Public: the Miramichi ecosystem, Chadwick EMP (ed.).

Canadian Special Publication of Fisheries and Aquatic Sciences No. 123. NRC Research Press: Ottawa; 83-93.

Caissie, D, N El-Jabi, A St-Hilaire. 1998. Stochastic modelling of water temperatures in a small stream using air to water relations. Canadian Journal of Civil Engineering. **25**: 250-260.

Caissie, D, C Breau, J Hayward, P Cameron. 2013. Water temperature characteristics within the Miramichi and Restigouche rivers. DFO Canadian Science Advisory Secretariat Research Document 2012/165. vi + 31p.

Chaput, D, D Moore, P Hardie, P Mallet. 2010. Information on Atlantic salmon (*Salmo salar*) from Salmon Fishing Area 16 (Gulf New Brunswick) of relevance to the development of a COSEWIC status report. DFO Canadian Science Advisory Secretariat Research Document 2010/064. iv + 50p.

Cluis, D. 1972. Relationship between stream water temperature and ambient air temperature: a simple autoregressive model for mean daily stream water temperature fluctuations. Nordic Hydrology. **3(2)**: 65-71.

Crisp, DT, G Howson. 1982. Effect of air temperature upon mean water temperature in streams in the north Pennines and English Lake District. Freshwater Biology. **12**: 359-367.

Cristea, NC, SJ Burges. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. Climatic Change. **102**: 493-520.

Crozier, LG, AP Hendry, PW Lawson, TP Quinn, NJ Mantua, J Battin, RG Shaw, RB Huey. 2008. Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon. Evolutionary Applications **1**: 252-270.

Cunjak, RA, D Caissie, N El-Jabi. 1990. The Catamaran Brook Habitat Research Project: description and general design of study. Canadian Technical Report of Fisheries and Aquatic Sciences 1751: 14.

Cunjak, RA, D Caissie, N El-Jabi, P Hardie, JH Conlon, TL Pollock, DJ Giberson, S Komadina-Douthwright. 1993. The Catamaran Brook (New Brunswick) Habitat Research Project: Biological, Physical and Chemical Conditions (1990-1992). Canadian Technical Report of Fisheries and Aquatic Sciences 1914, 81p.

Cunjak, RA, T Linnansaari, D Caissie. 2013. The complex interaction of ecology and hydrology in a small catchment: a salmon's perspective. Hydrological Processes 27:741-749.

DFO. 2012. Temperature threshold to define management strategies for Atlantic salmon (*Salmo salar*) fisheries under environmentally stressful conditions. DFO Canadian Science Advisory Secretariat Science Advisory Report 2012/019.

Eater, JG, RM Scheller. 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnology and Oceanography **41(5)**: 1109-1115.

El-Jabi, N, N Turkkan, D Caissie. 2010. Final report: The impact of the climate change on floods and droughts under a climate change scenario in New Brunswick. Presented to the New Brunswick Environmental Trust Fund, Université de Moncton. 43p.

El-Jabi, N, N Turkkan, D Caissie. 2012. Stream water temperature modeling under climate change scenarios. Phase I: Modeling stream water temperature and water/air temperature relationships. Presented to the New Brunswick Environmental Trust Fund, Université de Moncton. 41p.

El-Jabi, N., N. Turkkan, D. Caissie. 2013. Stream water temperature modeling under climate change scenarios, Phase II: Study of stream water temperatures under climate change scenarios B1 & A2. Presented to the New Brunswick Environmental Trust Fund, March 2013, 37p.

Gooseff, MN, K Strzepek, SC Chapra. 2005. Modeling the potential effects of climate change on water temperature downstream of a shallow reservoir, Lower Madison River, MT. Climatic change. **68**: 331-353.

Gordon, ND, TA McMahon, BL Finlayson. 1992. Stream Hydrology. An Introduction for Ecologists. John Wiley & Sons Ltd., West Sussex, England. p. 12.

Harrington, R, I Woiwod, T Sparks. 1999. Climate change and trophic interactions. Trends in Ecology and Evolution. **14**: 146-150.

Hill, DK, JJ Magnuson. 1990. Potential effects of global climate warming on the growth and prey consumption of Great Lakes fish. Transactions of the American Fisheries Society. **119**: 265-275.

Hrachowitz, M, C Soulsby, C Imholt, IA Malcolm, D Tetzlaff. 2010. Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape controls and climate change on maximum temperatures. Hydrological Processes. **24**: 3374-3391.

Huntsman, AG. 1942. Death of salmon and trout with high temperature. Journal of the Fisheries Research Board of Canada. **5**: 485–501.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007. Synthesis report. A contribution of working groups I, II, and III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, UK: Cambridge University Press.

Isaak, DJ, S Wollrab, D Horan, G Chandler. 2012. Climate change effects and river temperatures across the northwest U.S. from 1980-2009 and implications for salmonid fishes. Climatic Change. **113**: 499-524.

Kjellström, E, L Bärring, D Jacob, R Jones, G Lenderink, C Schär. 2007. Modelling daily temperature extremes : recent climate and future changes over Europe. Climatic Change. **81**: 249-265.

Kothandaraman, V. 1971. Analysis of water temperature variations in large rivers. ASCE Journal of the Sanitary Engineering Division. **97(SA1)**: 19-31.

Kothyari, U, VP Singh, V Aravamuthan. 1997. An investigation of changes in rainfall and temperature regimes of the Ganga Basin in India. Water Resources Management. **11**: 17-34.

Mantua, N, I Tohver, A Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change. **102**: 187-223.

Materna, E. 2001. Temperature interaction, Issue Paper 4. Temperature water quality criteria guidance development project, EPA-910-D-01-004, Environmental Protection Agency Region 10. U. S. Fish and Wildlife Service, Seattle, WA.

Meisner, JD. 1990. Potential loss of thermal habitat for Brook Trout, due to climatic warming, in two Southern Ontario streams. Transactions of the American Fisheries Society. **119**: 282-291.

Meisner, JD, JS Rosenfeld, HA Regier. 1988. The role of groundwater in the impact of climate warming on stream Salmonines. Fisheries. **13**(3): 2-8.

McCullough, DA. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. U. S. Environmental Protection Agency, Region 10, Seattle, Washington.

Mohseni, O, HG Stefan. 1999. Stream temperature / air temperature relationship: a physical interpretation. Journal of Hydrology. **218**: 128-141.

Mohseni, O, HG Stefan, JG Eaton. 2003. Global warming and potential changes in fish habitat in U. S. streams. Climatic Change. **59**: 389-409.

Mohseni, O, HG Stefan, TR Erickson. 1998. A nonlinear regression model for weekly stream temperatures. Water Resources Research. **34(10)**:2685-2692.

Morin, G, D Couillard. 1990. Predicting river temperatures with a hydrological model. In Encyclopedia of Fluid Mechanic, Surface and Groundwater Flow Phenomena, Vol 10, Cheremisinoff NP (ed.). Gulf Publishing Company, Houston, Texas, pp.171-209.

Morin, C, TJ Nzakimuena, W Sochanski. 1994. Prévision des températures de l'eau en rivières a l'aide d'un modèle conceptuel: le cas de la rivière Moisie. Canadian Journal of Civil Engineering. **21**(1): 63-75.

Morrill, JC, RG Bales, MH Conklin. 2005. Estimating stream temperature from air temperature: Implication for future water quality. Journal of Environmental Engineering. **131**(1): 139-146.

Morrison, J, MC Quick, MGG Foreman. 2002. Climate change in the Fraser River watershed: flow and temperature projections. Journal of Hydrology. **263**: 230-244.

Parks Canada. 1999. Climate change scenario, summer and winter temperatures, 2090. Air Issues Bulletin No. 100, Air Quality, Climate Change and Canada's National Parks. Ottawa, Natural Resources Branch, Parks Canada.

Pilgrim, JM, X Fang, HG Stefan. 1998. Stream temperature correlations with air temperature in Minnesota: implications for climatic warming. Journal of the American Water Resources Association, 34, 1109–1121.

Pörtner, HO, AP Farrell. 2008. Physiology and climate change. Science. **322**: 690-692.

Prats, J, R Val, J Dolz, J Armengol. 2012. Water modeling in the Lower Ebro River (Spain): Heat fluxes, equilibrium temperature, and magnitude of alteration caused by reservoirs and thermal effluent. Water Resources Research. **48**: W05523, 15p.

Quinn, TP, DJ Adams. 1996. Environmental changes affecting the migratory timing of American shad and sockeye salmon. Ecology. **77(4)**:1151-1162.

Raphael, JM. 1962. Prediction of temperature in rivers and reservoirs. Journal of the Power Division **88**: 157-181.

Schindler, DW. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences. **58(1)**: 18-29.

Stenhouse, SA, CE Bean, WR Chesney, MS Pisano. 2012. Water temperature thresholds for coho salmon in a spring-fed river, Siskiyou County, California. California Fish and Game. **98(1)**: 19-37.

Thistle, ME, D Caissie. 2013. Trends in air temperature, total precipitation, and streamflow characteristics in eastern Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3018: xi + 97p.

Tung, CP, TY Lee, YC Yang. 2006. Modeling climate-change impacts on stream temperature of Formosan landlocked salmon habitat. Hydrological Processes. **20**: 1629-1649.

Turkkan, N, N El-Jabi, D Caissie. 2011. Floods and droughts under different climate change scenarios in New Brunswick. Canadian Technical Reports of Fisheries and Aquatic Sciences. **2928**: xii + 55p.

Visser, M, C Both. 2005. Review. Shifts in phenology due to global climate change: the need for a yardstick. Proceedings of the Royal Society of London B – Biological Sciences. **272**: 2561-2569.

Ward, J. 1963. Annual variation of stream water temperature. ASCE Journal of Sanitary Engineering Division. **89(SA6)**: 3710-3732.

Webb, BW. 1996. Trends in stream and river temperature. Hydrological processes. **10**: 205-226.

Webb, BW, DT Crisp. 2006. Afforestation and stream temperature in a temperate maritime environment. Hydrological Processes. **20**: 51-66.

Webb, BW, F Nobilis. 1994. Water temperature in the River Danube during the twentieth century. Hydrobiologia. **291**: 105-113.

Webb, BW, F Nobilis. 2007. Long-term changes in river temperature and the influence of climatic and hydrological factors. Hydrological Sciences-Journal-des Sciences Hydrologiques. **52(1)**: 74-85.

Wilkie, MP, MA Brobbel, K Davidson, L Forsyth, BL Tufts. 1997. Influences of temperature upon the postexercise physiology of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences. **54**: 503-511.

TABLE 1. Coefficients of the annual cycle (sinusoidal function) and stochastic regression model parameters of the minimum, mean and maximum water temperatures (calibration data: 1992-2011) for the annual period (day of year 90 to 310).

	Minimum Temperature	**Mean Temperature**	**Maximum Temperature**
	Annual cycle coefficients (Sinusoidal function)		
Air Temperature			
a	-0.44	4.9	10.7
b	12.2	13.9	14.7
t_0	114	114	114
RMSE* (°C)	1.13	0.81	1.13
Water Temperature			
a	4.0	4.9	6.0
b	14.0	15.5	17.0
t_0	119	119	119
RMSE* (°C)	0.71	0.67	0.70
	Stochastic Regression Model Parameters		
a_1	0.293	0.376	0.381
a_2	0.065	0.249	0.218
a_3	0.074	0.132	0.158
RMSE* (°C)	1.65	1.38	1.93

**RMSE = Root mean square error*

TABLE 2. Root mean squared error (*RMSE*, °C) for the stochastic multiple regression models of the minimum, mean, and maximum water temperatures during calibration (1992-2011). *RMSE*s are provided for both the annual period (day of year 90 to 310) and for the summer period (day of year 182 to 243).

Year	**Minimum Temperature Model**		**Mean Temperature Model**		**Maximum Temperature Model**	
	RMSE		**RMSE**		**RMSE**	
	Annual*	**Summer****	**Annual***	**Summer****	**Annual***	**Summer****
1992	2.03	2.59	1.14	1.85	2.02	1.76
1993	1.52	1.23	1.32	1.01	1.94	1.24
1995	1.44	1.63	1.37	1.73	1.83	2.19
1996	2.11	1.92	1.56	1.57	1.84	1.97
1997	1.89	1.34	1.70	1.11	1.88	1.25
1998	1.66	1.48	1.45	1.36	1.60	1.50
1999	1.91	1.70	1.53	1.42	2.24	2.08
2000	1.43	1.48	1.20	0.95	2.16	1.20
2001	1.60	1.16	1.24	0.92	1.76	1.76
2002	1.53	1.55	1.10	1.21	1.67	1.76
2003	1.80	1.71	1.51	1.72	2.14	1.91
2004	1.30	1.22	1.06	1.00	1.55	1.33
2005	1.47	1.46	1.23	1.17	1.83	1.52
2006	1.26	1.46	1.25	1.23	1.86	1.42
2007	1.49	1.35	1.55	0.93	2.14	1.17
2008	1.57	2.05	1.54	1.74	2.19	1.96
2009	1.29	1.41	1.20	1.69	1.59	2.15
2010	2.32	1.97	1.70	1.10	2.18	1.52
2011	1.24	1.07	1.22	1.02	1.83	1.43
Overall	1.65	1.61	1.38	1.31	1.93	1.65

** Annual: 31 March – 6 November (day 90-310)*

***Summer: 1 July – 31 August (day 182-243)*

TABLE 3. Average observed and predicted water temperatures during calibration (1992-2011). Results are based on the annual period (day of year 90 to 310).

Year	Average Minimum water temperature (°C)		Average Mean water temperature (°C)		Average Maximum water temperature (°C)	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
1992	12.1	13.0	12.9	13.2	15.1	15.2
1993	9.9	10.7	11.4	12.1	13.2	14.1
1995	10.5	10.3	12.9	12.6	14.8	14.3
1996	12.2	13.3	13.9	14.7	15.9	16.6
1997	10.4	11.6	11.9	13.0	13.9	14.8
1998	11.0	11.3	12.4	12.9	14.2	14.7
1999	12.4	11.6	14.2	13.9	16.5	16.1
2000	10.8	11.2	12.5	12.5	14.5	14.2
2001	12.2	11.5	14.1	13.6	16.4	15.7
2002	12.1	12.1	14.0	13.6	16.6	15.6
2003	12.2	12.2	13.8	14.0	15.7	16.0
2004	12.7	12.7	14.8	14.4	17.1	16.5
2005	11.3	11.4	12.9	13.0	14.7	14.8
2006	11.1	10.9	12.8	12.7	14.7	14.7
2007	10.8	10.6	12.5	12.3	14.3	14.2
2008	11.2	11.7	12.5	13.1	13.9	14.8
2009	12.2	12.4	13.9	14.5	15.6	16.4
2010	12.5	11.1	15.6	14.7	17.6	16.7
2011	10.9	11.1	12.2	12.5	13.6	14.2
Overall Average	11.4	11.5	13.2	13.2	15.1	15.2

TABLE 4: Predicted and observed number of days where daily minimum water temperature exceeded critical temperature (T_w-*min* > 20°C) during calibration (1992-2011).

Year	**Number of days analysed**	**Predicted number of days where T_w-min > 20°C**	**Observed number of days where T_w-min > 20°C**
1992	168	0	0
1993	214	3	2
1995	208	0	12
1996	132	2	2
1997	204	1	1
1998	221	0	4
1999	211	4	26
2000	199	2	1
2001	212	3	14
2002	180	5	15
2003	186	4	13
2004	182	9	8
2005	220	3	11
2006	221	4	16
2007	221	2	9
2008	194	3	3
2009	110	2	8
2010	221	5	26
2011	221	7	1
Total		**59**	**172**
Average per year		**3.0**	**8.6**

TABLE 5. Predicted and observed number of days where daily maximum water temperature exceeded critical temperature (T_w-*max* > 23°C) during calibration (1992-2011).

Year	**Number of days analysed**	**Predicted number of days where T_w-max > 23°C**	**Observed number of days where T_w-max > 23°C**
1992	125	7	5
1993	214	24	16
1995	209	33	48
1996	132	15	6
1997	204	20	14
1998	221	26	14
1999	211	41	62
2000	199	10	20
2001	212	32	52
2002	178	26	52
2003	186	39	34
2004	182	19	29
2005	218	32	46
2006	221	26	35
2007	221	18	22
2008	194	12	12
2009	110	24	11
2010	192	45	48
2011	221	15	8
Total		**464**	**534**
Average per year		**24.4**	**28.1**

TABLE 6: Average water and air temperatures by time periods: period of water temperature monitoring (1992-2011), historical period (1970-1999) and under climate change scenario (CGCM A2) (2010-2039; 2040-2069; 2070-2099). Results are for the annual period (March 31st to November 6th - day 90 to 310).

Time Period	Average Minimum Water Temperature (°C)	Average Mean Water Temperature (°C)	Average Maximum Water Temperature (°C)
1992-2011*	11.4	13.2	15.1
1970-1999	11.0	12.7	14.4
2010-2039	11.7	13.7	15.4
2040-2069	12.2	14.6	16.3
2070-2099	13.0	15.9	17.6
Time Period	**Average Minimum Air Temperature (°C)**	**Average Mean Air Temperature (°C)**	**Average Maximum Air Temperature (°C)**
1992-2011*	6.0	12.3	18.5
1970-1999	5.8	12.1	18.4
2010-2039	7.2	13.5	19.8
2040-2069	8.6	14.8	21.0
2070-2099	10.4	16.5	22.7

* Model calibration period

TABLE 7. Average water and air temperatures by time periods: period of water temperature monitoring (1992-2011), historical period (1970-1999) and under climate change scenario (CGCM A2) (2010-2039; 2040-2069; 2070-2099). Results are for the summer period (July 1st to August 31st - day 182 to 243).

Time Period	**Average Minimum Water Temperature (°C)**	**Average Mean Water Temperature (°C)**	**Average Maximum Water Temperature (°C)**
1992-2011*	17.5	19.8	22.3
1970-1999	17.5	20.0	22.3
2010-2039	18.0	20.8	23.2
2040-2069	18.6	21.8	24.2
2070-2099	19.5	23.3	25.6
Time Period	**Average Minimum Air Temperature (°C)**	**Average Mean Air Temperature (°C)**	**Average Maximum Air Temperature (°C)**
1992-2011*	11.5	17.8	24.5
1970-1999	12.0	18.6	25.3
2010-2039	13.1	19.8	26.5
2040-2069	14.3	21.1	27.8
2070-2099	16.4	23.1	29.7

* Model calibration period

TABLE 8. Future cumulative changes (increase) in average air and water temperatures under climate change (2010-2039; 2040-2069; 2070-2099) compared to the historical period (1970-1999).

	Minimum Temperature (°C) Cumulative change		**Mean Temperature (°C)** Cumulative change		**Maximum Temperature (°C)** Cumulative change	
	WATER	AIR	WATER	AIR	WATER	AIR
***Annual**						
2010-2039	+0.7	+1.4	+1.0	+1.4	+1.0	+1.4
2040-2069	+1.2	+2.8	+1.9	+2.7	+1.9	+2.6
2070-2099	+2.0	+4.6	+3.2	+4.4	+3.2	+4.3
**** Summer**						
2010-2039	+0.5	+1.1	+0.8	+1.2	+0.9	+1.2
2040-2069	+1.1	+2.3	+1.8	+2.5	+1.9	+2.5
2070-2099	+2.0	+4.4	+3.3	+4.5	+3.3	+4.4
July						
2010-2039	+0.4	+0.8	+0.6	+0.8	+0.7	+0.8
2040-2069	+0.8	+1.8	+1.5	+1.9	+1.6	+2.0
2070-2099	+1.4	+4.2	+3.2	+4.2	+3.3	+4.2
August						
2010-2039	+0.6	+1.3	+1.1	+1.5	+1.2	+1.6
2040-2069	+1.2	+2.8	+2.2	+2.9	+2.3	+3.0
2070-2099	+2.4	+4.6	+3.5	+4.6	+3.5	+4.6

*Annual: day of year 90 – 310

**Summer: day of year 182 – 243

TABLE 9. Predicted number of days where daily minimum and maximum water temperatures exceed critical temperatures (T_w-*min* > 20°C and T_w-*max* > 23°C, respectively) for the historical period (1970-1999) and future period 1 (2010-2039), period 2 (2040-2069) and period 3 (2070-2099).

	Time Period			
	1970-1999	**2010-2039**	**2040-2069**	**2070-2099**
***T_w-min* > 20°C**				
Total number of days	115	212	369	749
Average per year	3.8	7.0	12.3	25.0
***T_w-max* > 23°C**				
Total number of days	818	1218	1570	2058
Average per year	27.3	40.6	52.3	68.6

TABLE 10. Future increase in the number of days where daily minimum and maximum water temperatures exceed critical temperatures (T_w-*min* > 20°C and T_w-*max* > 23°C, respectively) for future period 1 (2010-2039), period 2 (2040-2069) and period 3 (2070-2099).

	Time period		
	2010-2039	**2040-2069**	**2070-2099**
***T_w-min* > 20°C**			
Total number of days	+97	+254	+634
Average per year	+3.2	+8.5	+21.2
***T_w-max* > 23°C**			
Total number of days	+400	+988	+1240
Average per year	+13.3	+25	+41.3

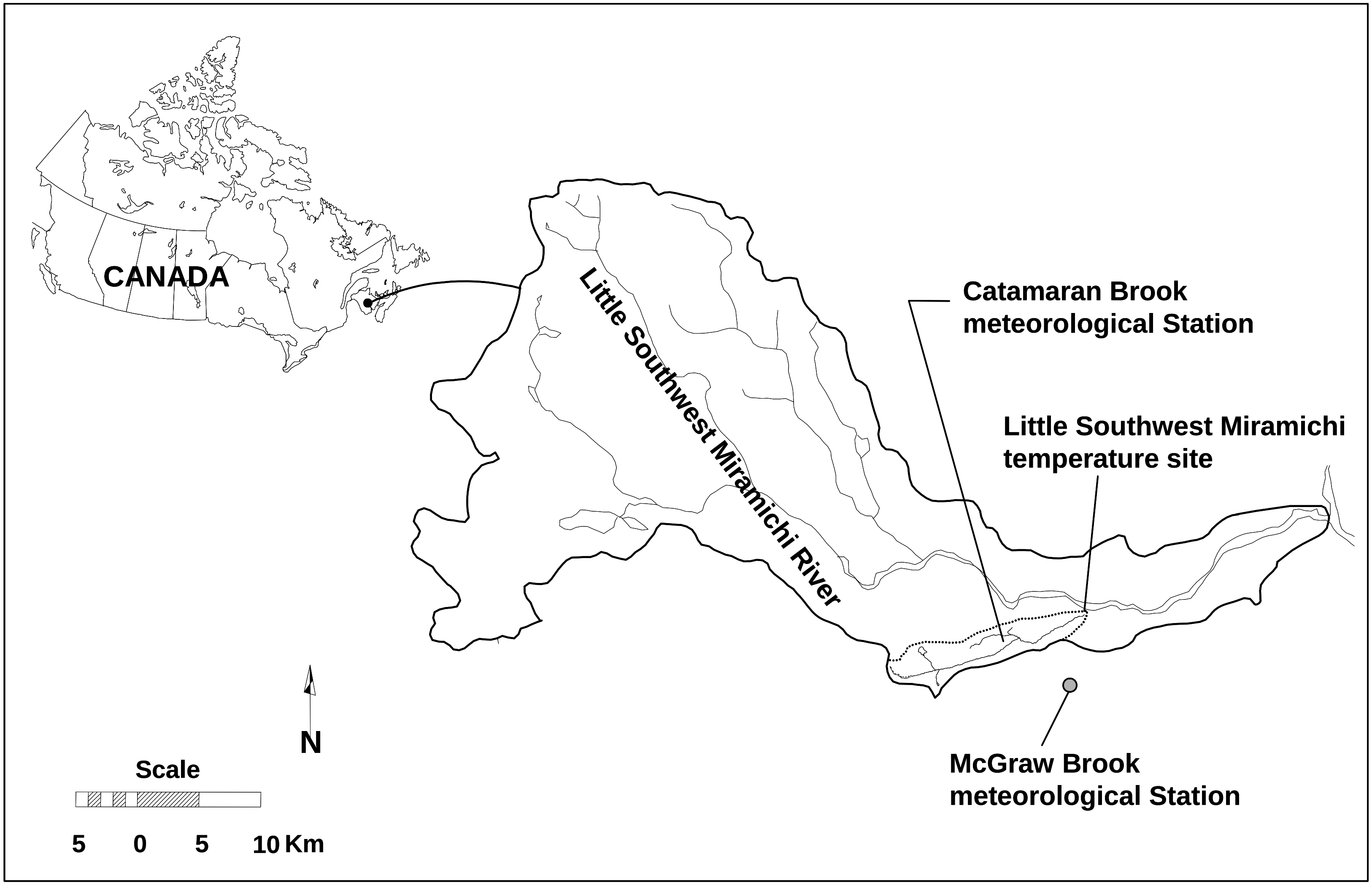


Figure 1. Map showing location of the water temperature site and the meteorological station.

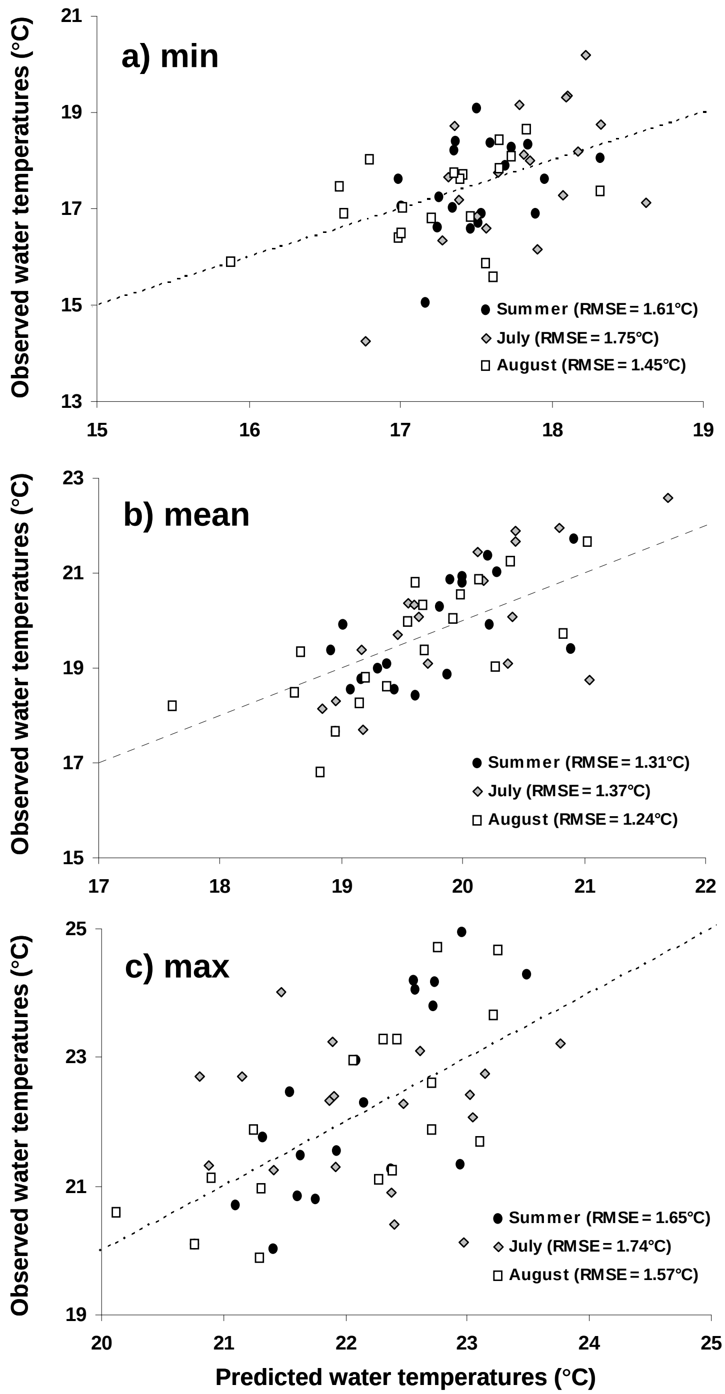


FIGURE 2. Predicted vs. observed a) minimum, b) mean and c) maximum water temperatures for the calibration period (1992-2011) for the summer (July and August, day of year 182 to 243, black circles), for July (day of year 182 to 212; gray diamonds) and August (day of year 213 to 243; white squares). The 1:1 ratio is presented (dotted line).

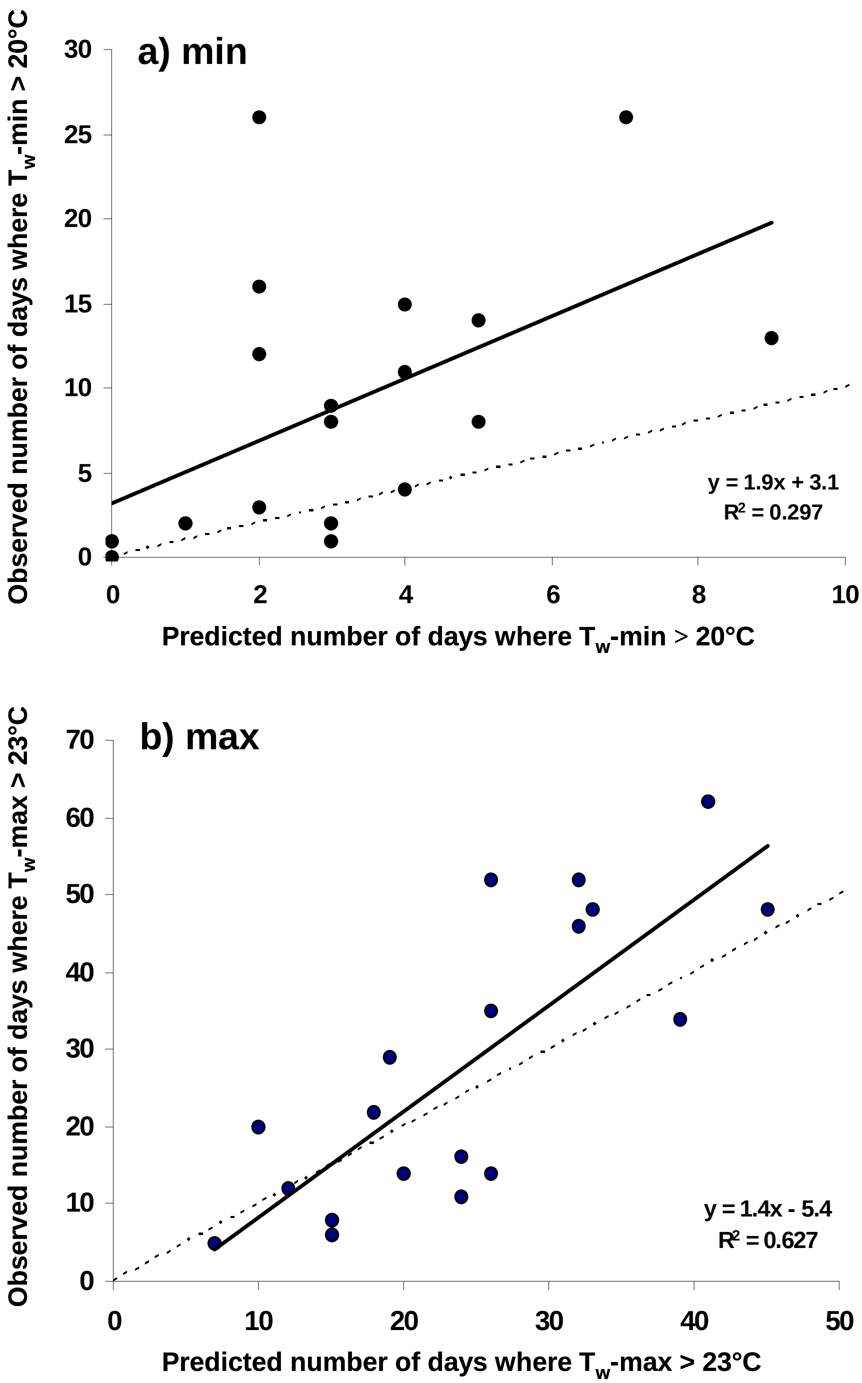


FIGURE 3. Regression of predicted vs. observed number of days where a) daily minimum water temperature exceeded critical temperature (20°C), and b) daily maximum water temperature exceed critical temperature (23°C), in the Little Southwest Miramichi River, 1992-2011. Regression (darker line) and 1:1 ratio (dashed line).

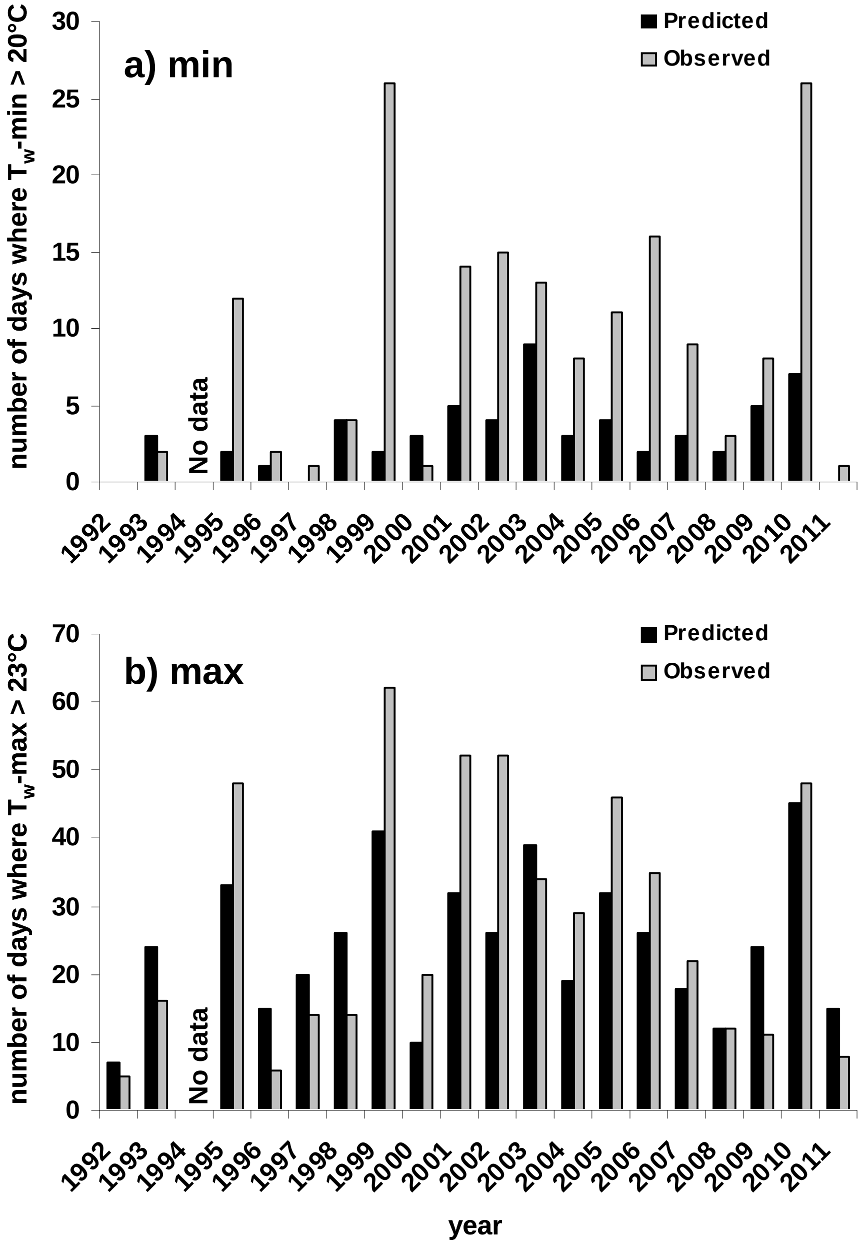


FIGURE 4. Predicted and observed number of days per year where a) daily minimum water temperature exceeded critical temperature (20°C), and b) daily maximum water temperature exceeded critical temperature (23°C), in the Little Southwest Miramichi River for the calibration period (1992-2011).

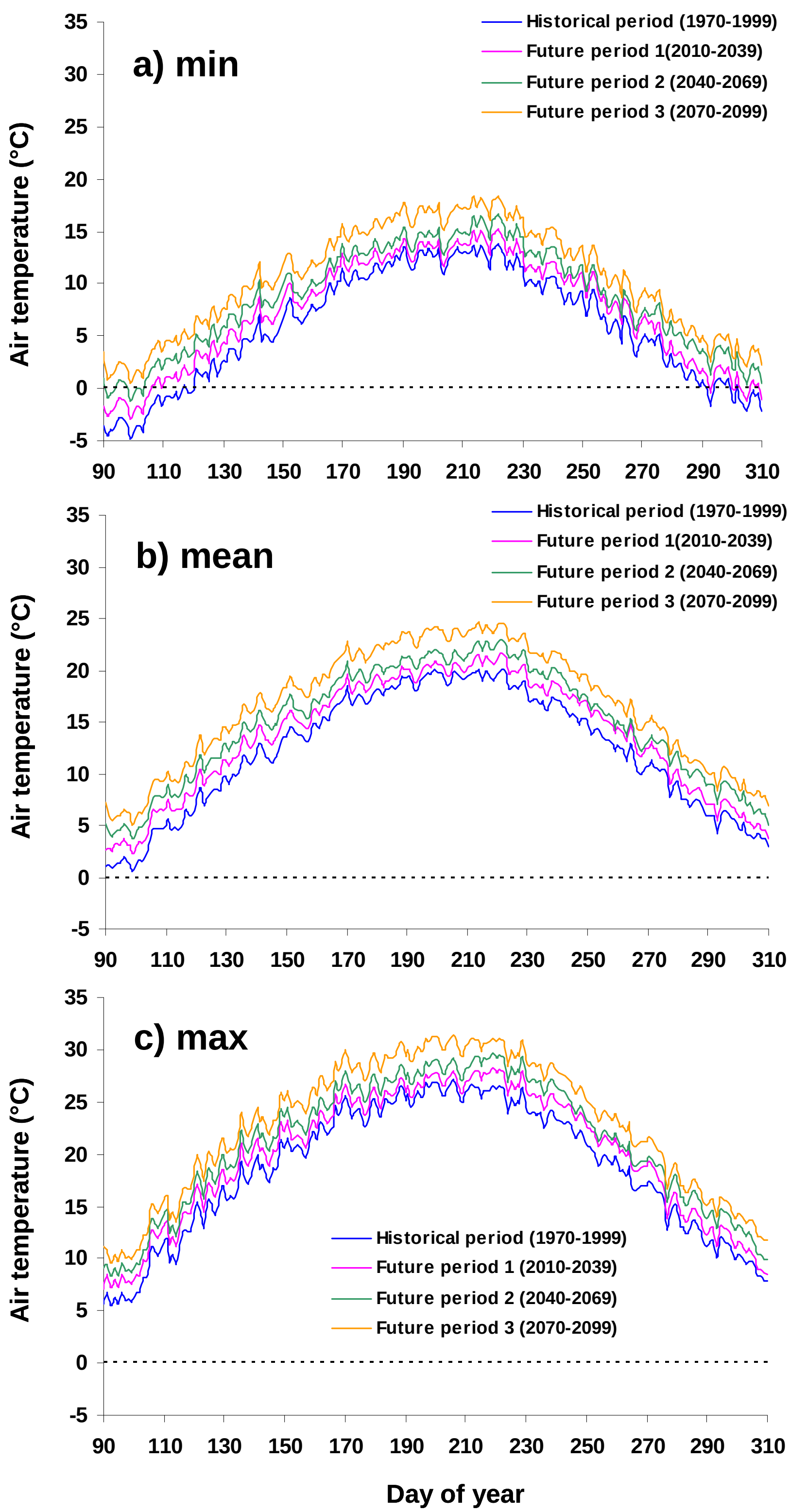


FIGURE 5. Average daily a) minimum, b) mean, and c) maximum air temperatures for the historical period (1970-1999) and the future period 1 (2010-2039), period 2 (2040-2069), and period 3 (2070-2099) for the Little Southwest Miramichi River.

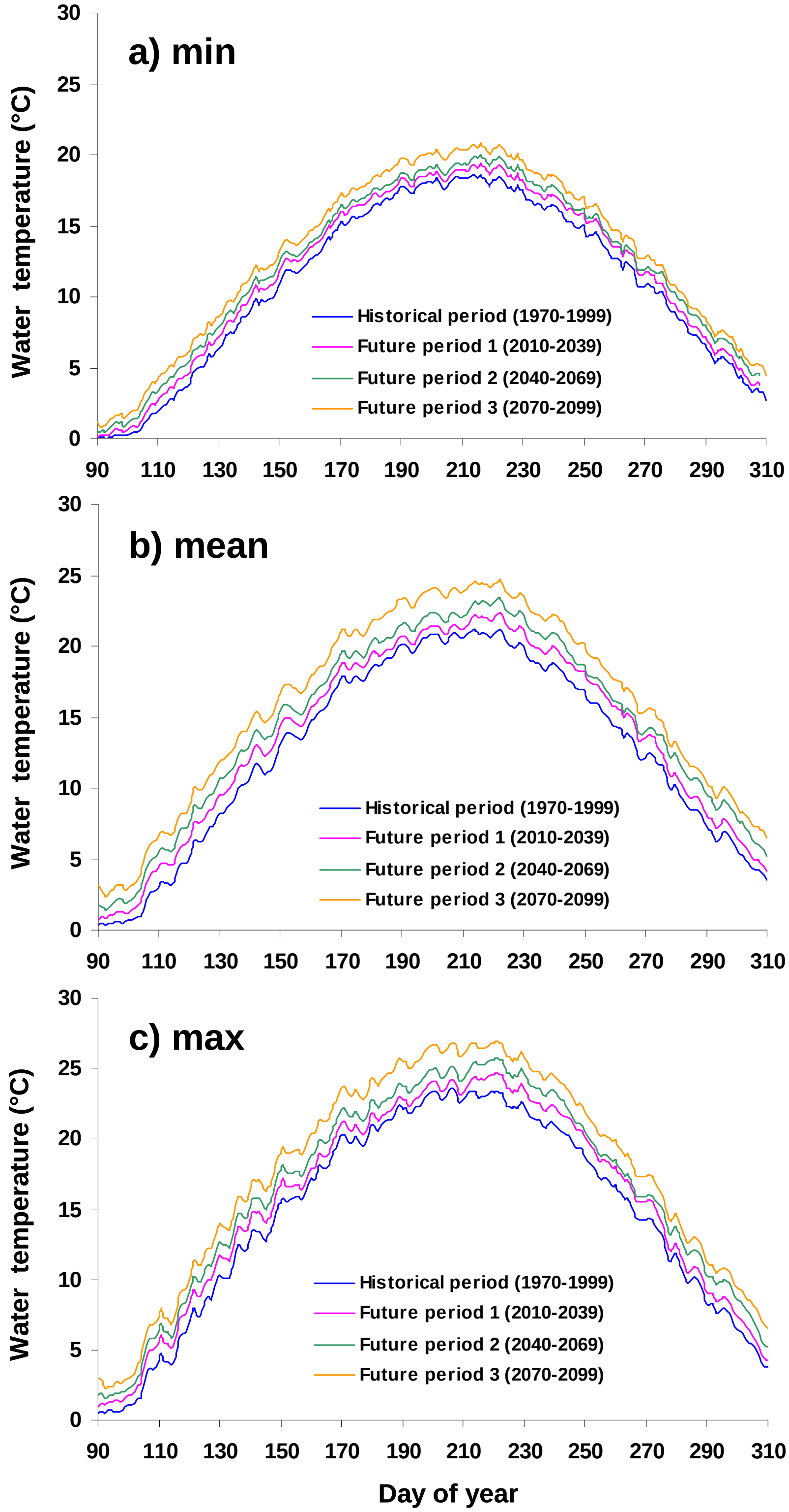
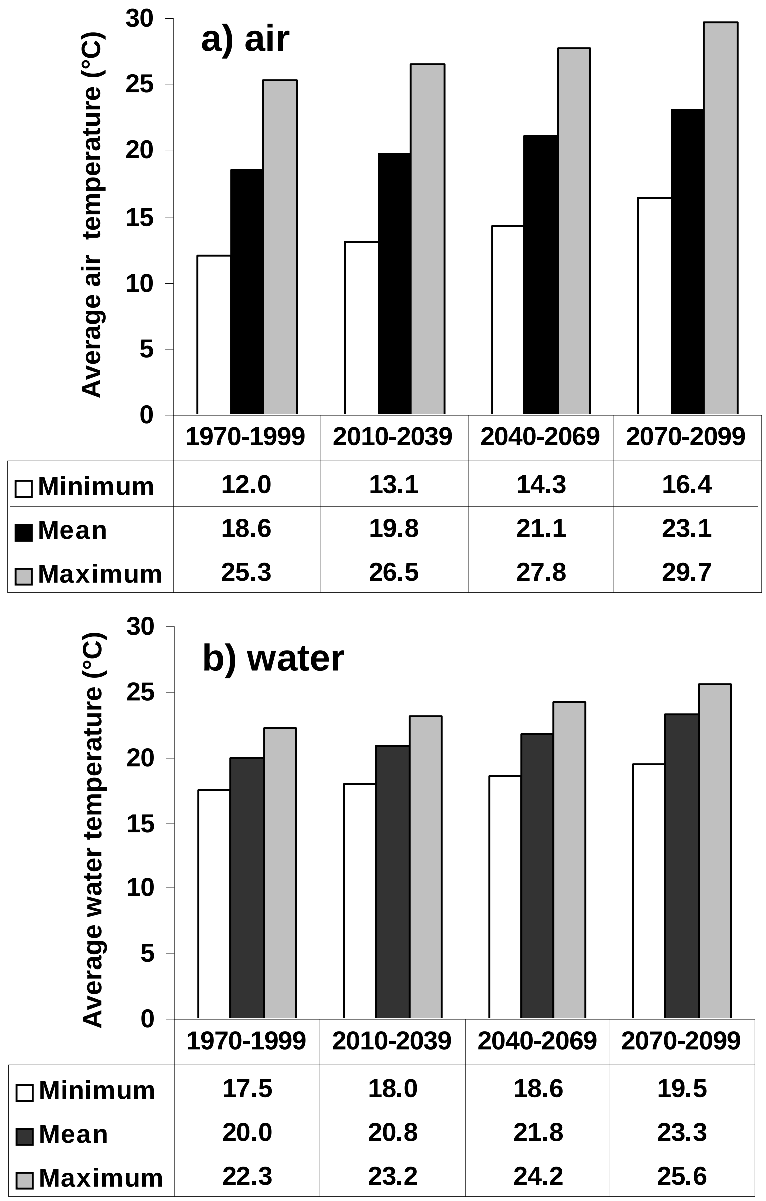


FIGURE 6. Average daily a) minimum, b) mean, and c) maximum water temperatures for the historical period (1970-1999) and for the future period 1 (2010-2039), period 2 (2040-2069), and period 3 (2070-2099) for the Little Southwest Miramichi River.



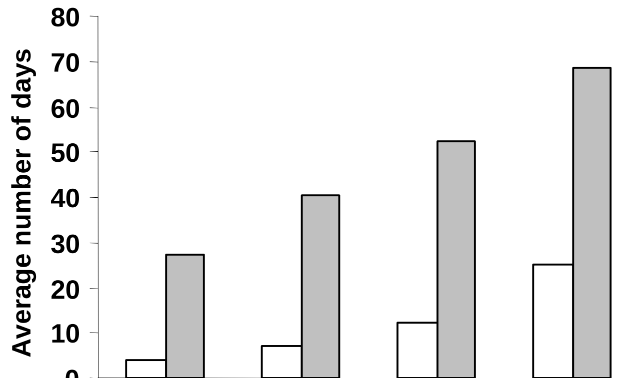
a) air

	1970-1999	2010-2039	2040-2069	2070-2099
Minimum	12.0	13.1	14.3	16.4
Mean	18.6	19.8	21.1	23.1
Maximum	25.3	26.5	27.8	29.7

b) water

	1970-1999	2010-2039	2040-2069	2070-2099
Minimum	17.5	18.0	18.6	19.5
Mean	20.0	20.8	21.8	23.3
Maximum	22.3	23.2	24.2	25.6

FIGURE 7. Average minimum, mean, and maximum a) air temperatures, and b) water temperatures, for the summer (July and August; day of year 182 to 243), for the historical period (1970-1999) and future period 1 (2010-2039), period 2 (2040-2069) and period 3 (2070-2099) for the Little Southwest Miramichi River.



	1970-1999	2010-2039	2040-2069	2070-2099
Tw-min over 20°C	3.8	7.0	12.3	25.0
Tw-max over 23°C	27.3	40.6	52.3	68.6

FIGURE 8. Average number of days per year where minimum and maximum water temperatures exceed critical temperature (20°C and 23°C, respectively) for the historical period (1970-1999) and for future period 1 (2010-2039), period 2 (2040-2069), and period 3 (2070-2099).