MID AND HIGH LATITUDE HYDROCLIMATOLOGY:

A MODELING STUDY OF THE OBSERVATIONS AND FUTURE TEMPERATURE TRENDS IN THE FRASER AND LENA RIVER BASINS

by

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ABSTRACT OF THE DISSERTATION

Mid and High Latitude Hydroclimatology:

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The global hydrologic cycle is a complex physical system connecting ocean, land and atmosphere, and rivers are the conduit which connect all of these media. There have been several studies on the impact of climate change on river flow, but relatively few long term studies focusing on the impact of climate change on river temperature. This dissertation examines the potential impact of climate change on river temperatures for mid and high latitude Northern Hemisphere locations. Present trends in temperature of the Fraser and Lena Rivers are extended by using a global climate model to project how river temperatures in the basins might change by the year 2100. During the second half of the 20th century, observations indicate that river temperatures in the Fraser River are increasing and extreme temperatures are more frequent. This can negatively affect the reproductive fitness of Pacific salmon during their upstream migration to their spawning beds. The model projects that the observed warming trends will continue to 2100 and that the frequency of extremes, particularly temperatures above 18°C, will increase the

risk to the salmon population. During mid summer, the model projects that the frequency of days with temperatures above 18°C will increase from 3.8 days per month now to 21 days per month by 2100. For the Lena River, the model projects that river temperatures will increase during the summer by 2.0°C–3.0°C by 2100, with the largest increase (approximately 4.5°C) at the mouth of the basin in late September. There are also changes in the timing of the peak summer river discharge which occurs earlier in the spring. This study is a useful starting point in understanding future water resource requirements and overall ecological fitness in the Fraser and Lena basins.

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And mostly I want to thank my wife and my best friend, Rita. Her many years of support through all of my classes, labs, and many, many late nights of writing, while at the same time keeping the family running smoothly, is something that I will always be grateful for. You have put a lot of things for yourself on hold, and now it is your turn.

This dissertation is dedicated to my children, Neelam and Navin. My hope is to instill in them a love for exploring and lifelong learning….always having a good book within arms reach is the first step in the journey. May science help to create for them a better world.

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Chapter 1

INTRODUCTION

Each year, additional evidence is gathered that supports the consensus that human activities are affecting the Earth's climate (IPCC, 2001; IPCC, 2007). The 2001 Intergovernmental Panel on Climate Change (IPCC) report stated that global surface air temperature (SAT) has risen 0.6°C ± 0.2°C during the last century, and increases will likely be larger through the end of the current century; the 2007 IPCC report provided further evidence to support this statement. While the science continues to strengthen, many uncertainties still remain regarding (a) how and when these changes will manifest themselves during the 21st century, (b) which regions are likely to be positively and negatively affected, and (c) how society can act without complete information (Oppenheimer, et al., 2007).

One of the most interesting aspects of Earth system science is that it has evolved so that one can address problems at the interface of the biological, chemical, and physical sciences, and also apply this knowledge to real world problems that are timely and pragmatic. The nature of this research is highly interdisciplinary, and the study of climate change is a good example of the need for this interdisciplinary perspective. It is very important to understand how climate change might affect freshwater resources in the future as well as the potential impacts of these changes on people and natural ecosystems. This dissertation will focus on one aspect of future changes in freshwater resources.

In addition to new climate patterns, associated changes in other components of the Earth system are anticipated by the year 2100, such as alterations to the freshwater component of the hydrologic cycle (Miller and Russell, 1992). Climate change is expected to enhance the global hydrologic cycle (Wentz, et al, 2007; Oki and Kanae, 2006), leading to a more active precipitation pattern. While the spatial and temporal effects of climate change, the hydrologic response, and the effects on biota are difficult to quantify and future projections are uncertain, efforts must be undertaken to understand the general behavior of these global systems under different future climate scenarios in order to prepare for a world that relies heavily on goods and services provided through climatically dependant natural resources. If current temperature trends continue, the commercial and societal roles that freshwater resources will play in helping sustain economic growth and human health will become more apparent (Framing Committee of the Global Water Systems Project, 2004; Lammers et al., 2007). As a result, many empirical and modeling studies which address the myriad of connections between climate change, water resources and societal systems have started to emerge, each asking very specific yet related questions. Freshwater is critically important for all human activities and natural ecosystems, including agriculture, human health, and commercial activity. Changes in the availability and quality of freshwater resources may also have significant geopolitical implications in coming decades.

A changing climate will affect water resources as they are connected to human health. Beyond freshwater's economic dimension, water distribution, scarcity and quality are also both intricately related to human health, as the development and spread of waterborne disease is largely a function of the local weather pattern. When analyzing the incidence and distribution of zoonotic disease, understanding the role of water in vector transmission is crucial. Numerous human diseases, including shistosomiasis, cholera, dengue fever, yellow fever, malaria, and river blindness are all anticipated to increase with a warmer climate; malaria is an example of a vector-borne disease that is thought to have the highest sensitivity to climate change (World Health Organization, 2003; Patz, 2000). Bouma and van der Kay (1996) describe how the risk of malaria epidemics increases nearly 5 times in the year following an El Nino event. Therefore, the risk of more frequent El Nino events (IPCC, 2001) with future climate change will be a significant concern for public health planners. Hopp and Foley (2001) evaluated a model that simulated the dynamics of the *Aedes Aegypti* mosquito population, to examine how changes in climate might affect the global distribution of the dengue fever vector via changes in regional hydrology. Shaman et al. (2002) used a dynamic hydrology model to predict mosquito abundances as a function of surface wetness. Surface wetness was correlated to the increased presence of three disease carrying mosquito vectors in New Jersey. They concluded that using a dynamic model to predict temperature driven outbreaks is preferable over real time conditional monitoring using satellite data and weather station observations. Improving and expanding these models can have significant value to public health officials for preparing for future outbreaks at the interface of climate change and human health.

The global hydrologic cycle is an example of a complex physical system connecting ocean, land and atmosphere; rivers are one of the drivers in this cycle, and are a major component of the world's freshwater system. During the last 50 years there has been evidence that changes in the timing and magnitude of river flow have been affected by climate change (Milly et al., 2005; Yang et al., 2003; Foreman et al., 2001; Greene and Pershing, 2007). Several studies have evaluated the potential effects of climate change on the hydrologic cycle, and specifically changes in river systems. Some of these studies have focused on the potential effects of climate change in numerous basins, while others focus on a specific geographic region.

Najjar (1999) evaluated the water balance in the Susquehanna River basin, and analyzed how the river's physical characteristics have changed over most of the 20th century. The study also includes model projections of precipitation and river temperature under 1xCO_2 and 2xCO_2 climate conditions, and found that while the sensitivity to these parameters in a smaller basin such as the Susquehanna is high, that the results also contain significant errors. Applying the methods incorporated in larger scale models may resolve some of this error. Ferrari et al. (1999) examined the combined effects of climate change and river modification on river flow in the Aral Sea basin. They applied a modification to the river routing scheme embedded into a global climate model to examine the impact of climate changes and anthropogenic diversions on the flow of the two primary rivers feeding the Aral Sea. They concluded that in heavily regulated river basins, it is imperative to include both the anthropogenic and natural processes in order to properly assess future river flow.

Haddeland et al. (2007) examine changes in North American and Asian hydrology as a result of anthropogenic changes over the last 300 years, and evaluated them with a macroscale hydrologic model. They conclude that agricultural expansion is responsible for a 2.5% increase in North American annual runoff, and a 6% increase in Asia. The change in runoff is attributed to a combination of natural and man-made causes; runoff changes have been influenced by higher evapotranspiration rates (natural) and increased irrigation (anthropogenic), while they acknowledged that the anthropogenic contribution is minor when averaged over a continental scale.

Morrison et al. (2002) and Foreman et al. (2001) found a shift towards earlier peak flow volumes in the Fraser River between 1913 and 2000 (one-third and one-half total seasonal flow volumes), and Morrison et al. (2002) project this trend to continue as a result of future changes in climate. Peterson et al. (2002) document shifts in the Arctic water cycle, including increased discharge and decreased ice volume from the Pan-Arctic drainage basin, which includes the six largest Eurasian rivers (Lena, Yenisey, Ob, Pechora, Kolyma, and Severnaya Dvina). They show that river discharge anomalies between 1936 and 1999 have been increasing at a rate of 2.0± 0.7 km^3/year, and suggest that future warming will exacerbate this trend, while also noting the influence of the North Atlantic Oscillation (NAO) and the Northern Annual Mode (NAM); these oscillations are among the dominant features in driving circulation in the northern hemisphere and are closely related to regional temperatures.

Ye et al. (2003), Yang, et al. (2005), and Liu et al. (2005) each observed trends in river temperature and flow for rivers in the Lena Basin in Russia. In Ye et al. (2003), monthly discharge records from 1936 to 1999 were examined and the changes in the streamflow were documented. They found that the upstream subbasin locations where there is minimal human impact, exhibit a higher flow rate in winter, spring and summer, and a decrease in fall months. They attribute this to a climatological shift towards earlier spring conditions, triggering earlier snowmelt and permafrost degradation; they also connect these findings to regional climate warming over the observed time period.

It has been shown that northern hemisphere temperature and precipitation changes have contributed to higher freshwater inflows in the Arctic Ocean (Greene and Pershing, 2007; Lammers et al., 2007; Peterson et al., 2006). Greene and Pershing (2007) describe a shift in the atmospheric pattern in the 1980s and 1990s which led to a decline in the area and thickness of northern hemisphere sea ice, and cryospheric changes via melting permafrost, including increased discharge into the Arctic Ocean. Careful mass balance approaches need to be employed to make the large scale connections between ice loss and atmospheric conditions. Rial et al., (2004) underscores this point. Despite the evidence for increasing runoff accompanying higher air temperatures in the studies mentioned above, we can not assume that all positive temperature trends will lead to increased flow. In an earlier study, Aizen et al. (1997) examined climatic and hydrologic data from 110 locations across the Tien Shan region of Central Asia from 1940 to 1991. Their analysis documented positive trends in surface air temperature (0.01°C yr^{-1}) and precipitation (1.2 mm yr^{-1}); however, there was no significant change in runoff over the same time period, and they concluded that the type of precipitation is more important in projecting runoff for rivers where snowmelt is a primary contributor. They documented a decrease in snow cover over the study period, as higher temperatures lead to more liquid precipitation. Some of this additional precipitation may be lost to increased evaporation or infiltration to groundwater, therefore not contributing to higher runoff totals. These findings also supported the earlier study of Karl and Riesbame (1989), where they suggested that temperature fluctuations are not as important of a factor on runoff as was commonly assumed.

Milly et al. (2005) assess global continental freshwater availability, and project how future freshwater supplies will be affected by climate change. They have identified global trends in freshwater quantity and distribution, and using a 12 model ensemble, they project future runoff patterns by 2050. Their global analysis of the observed changes showed stronger increasing trends in streamflow at higher latitudes, and decreasing trends in the equatorial regions. They extended these assumptions by modeling global streamflow and freshwater availability through 2050. Most of the trends found in the analysis of the observations are extended to the middle of the 21st century. Using this approach, the authors project a 10-40% increase in runoff at the higher latitudes of North America and Eurasia, and a 10-30% decrease in runoff for southern Europe, the Middle East and southern Africa.

Nijssen et al. (2001) discussed improvements in the ability to represent atmospheric and land surface processes at continental and sub-continental scales through the use of macroscale hydrologic models. The authors suggested that the implementation of improved land surface parameterizations may serve as a link between global atmospheric models and hydrologic systems on large spatiotemporal scales. They tested the models on simulating the hydrographs of 26 river basins, and found that calibration of certain model parameters decreased the relative root mean square error in monthly flow projections from 62% to 37%, and generated an overall improvement of streamflow simulations.

Georgakakos (2003) assesses the skill of using global climate models to assess regional scale hydrologic changes. He found that using an ensemble, as Milly et al. (2005) does, offers a skillful method to project seasonal hydrologic patterns in several regions of the United States, and that these same methods are useful in water resource studies at a scale similar to the breakdown in the U.S. climate divisions (http://www.cdc.noaa.gov/USclimate/map.html).

In addition to the projected changes at the northern latitudes, current climate trends have already altered the hydrology of high latitude regions (Comiso and Parkinson, 2004; IPCC, 2008; IPCC, 2007). High latitude northern rivers are an important component of the polar hydrologic cycle, and the effects of climate change on polar hydrology are likely to be significant because the sensitivity of the hydrologic cycle in far northern and southern latitudes may be higher than in other parts of the world (Yang et al., 2005; Peterson et al., 2002; Arora and Boer, 2001). As seasons change, the freeze/thaw cycle is a significant controlling factor of the Arctic water balance, and stream temperature is closely related to a discharging river's thermal characteristics (Yang et al., 2005).

Permafrost changes have also resulted in larger freshwater discharges into the Arctic Ocean over the last 3 decades (ACIA, 2005; Lawrence and Slater, 2005). Several recent studies have documented changes to the hydrologic cycle, an observed decrease in permafrost areal extent, and that active layer thickness (ALT, which describes the upper 'active' layers of soil which thaw and freeze each year) has been increasing (Lawrence and Slater, 2005; Jorgenson et al., 2001; Zhang et al., 2005). As the rate of permafrost loss has been increasing, additional freshwater volumes have then become available as inflows to the Arctic Ocean; this has contributed to the 7% increase in Arctic inflows observed between 1936 and 1999 (Peterson et al., 2002). There are cascading effects from additional freshwater inflows as well. The higher concentration of freshwater inflows reaching the Arctic Ocean affects sea ice formation, and may exhibit potential impacts to the thermohaline circulation (Arnell, 2005).

Kuhl and Miller (1992) used a global model to examine seasonal river runoff for several of the world's major high latitude river basins where modeled discharge was found to increase with climate change. Van Blarcum et al. (1995) calculated monthly river flow for nine high latitude rivers using present climate and 2xCO_2 climate simulations. They estimated that under future climate conditions, mean annual precipitation and monthly river flow increase in each of the basins, and higher flow rates are projected to occur earlier in the spring months. The projected changes in snow mass were mixed among the basins; snow mass decreases were projected in North America, but increases were projected for Asian rivers.

Arora and Boer (2001) investigated the potential effects of future climate change on runoff and streamflow at 23 of the world's large river basins, 10 of which are located at mid to high latitudes. They examined changes in mean discharge and seasonal streamflow, and also modeled future conditions using the Canadian Centre for Climate Modeling and Analysis (CCCma) global model. While they found that utilizing the model provided useful scenarios, there were limitations relating to coarse model resolution and errors in modeling future climate. However, they provided suggestions that have been incorporated into subsequent modeling studies, including focusing global modeling on only large basins, improving model parameterizations of land surface processes, and incorporating better regional climate simulations into the global analysis.

While there have been many studies of changes in river flow, there have been relatively few long term studies that focus specifically on the impact of climate change on river temperature. Further, of those studies that have examined climate change and river temperatures, the focus has usually been on smaller rivers and streams rather than regional to continental scale basins. Webb and Nobilis (2007) present an analysis of 20th century river temperature changes in the Danube River, which flows through central Europe. They found that river temperatures rose and fell in concert with air temperatures, and the pattern exhibited a strong correlation with the phase of the North Atlantic Oscillation, particularly in winter months.

Morrison et al. (2002) and Foreman et al. (2001) examined changes in river temperature that correlated with surface air temperatures for the Fraser River basin in North America. They found increasing 20th century river temperature trends are consistent with observed atmospheric warming. In Yang et al. (2005), Lena River basin temperature changes from 1950 to 1992 were identified through the analysis of temperatures that were collected every 10 days during the ice free season. Their analysis described warming river temperature trends in the early season across the entire basin, and a combination of warming and cooling trends during the summer months for the unregulated subbasins. For the regulated subbasin, they found a more significant increase in temperature during the early and late season, however, they specifically address reservoir regulations as a primary cause of this warming, also described in Liu et al. (2005). Yang et al. (2005) examined river temperatures at five locations in the Lena basin from 1950 to 1992, and their analyses showed a consistent warming of river temperatures in unregulated subbasins in early summer across the basin, and mixed results for the mid to late summer periods. Liu et al. (2005) also analyze Lena River temperatures over the same 1950 to 1992 period, and extend their analysis to understand the influence of climate changes on river thermal conditions. They correlated monthly mean surface air temperature and precipitation with river temperatures at the basin's outlet. Their work showed that there is a significant (95-99% confidence) positive correlation between air and river temperature, with the strongest relationship evident in the late summer months.

In the Lammers et al. (2007) investigation of Russian river temperature variability, temperature observations for 17 river basins were combined with river discharge at the stations between 1929 and 2003 to estimate the Pan-Arctic energy flux, in order to better define the contribution of north flowing Russian rivers to the Arctic Ocean. Part of this study assessed both atmospheric and river temperature trends. Despite the observed positive trends in air temperature, they did not observe a similar increase in river temperature across the Russian pan-Arctic. While Sinokrot and Stephan (1993) state that air and water temperatures move in concert, the results from Lammers et al. (2007) challenge that assumption, and provide questions for future basin wide river temperature studies.

Of the limited number of observational studies that relate climate change to river temperature, there are even fewer studies that attempt to model these changes. Beyond the physical climatological variables, very little is understood about the effects of climate change on aquatic ecosystems. The most recent IPCC report (2007) documents 28,586 significant changes in global terrestrial ecosystems; however, the same report documented only 85 changes to freshwater and marine systems, nearly all of which were related to climate change (Richardson and Poloczanska, 2008). This disconnect between the terrestrial and aquatic components of climate change highlights a problem, as well as an opportunity for new research. Morrison et al. (2002) model future hydrologic conditions that could affect salmon populations in the Fraser River basin. Their study projects a modest (+5%) flow increase, a peak flow decrease (-18%), and a mean water temperature increase (+1.9°C) for the 2070-2099 period. They also address the potential negative impacts to Pacific salmon, and predict their susceptibility to higher water temperatures will have a significant effect on reproductive fitness. Their work is summarize by stating that the projected flow rates should be benign to salmon health, but projected temperature changes may have serious implications on salmon population survival. They also suggest that future work should utilize different Global Climate Models (GCMs) to examine climate change scenarios, and that the models should be run from May to September, rather than starting in July.

For both the Fraser and Lena River basins, increasing river temperature trends that have been observed throughout the 20th century; these trends may be partially the result of climate change. Understanding the observed trends in the context of the changing climate is important, and it provides an opportunity to project how these conditions may change by the end of the century. The purpose of my dissertation is to extend and expand upon this existing body of knowledge, and to specifically examine river temperature changes for these two river basins at mid (Fraser) and high (Lena) latitude northern hemisphere locations. As a result, research efforts can begin to assess how select hydrologic variables in these regions might be affected by the end of the present century as a result of a changing climate. The research builds upon previous studies of changes in river temperature; primarily the Morrison et al. (2002) and Yang et al. (2005) papers by addressing questions about future river temperature in both basins by the end of the 21st century. This is done by using a GCM to examine river temperature and flow in the two above mentioned basins. Observations for river flow and temperature in each basin are examined and compared to a present climate/control version of the GCM. The model's future climate projections are then examined to investigate the potential hydroclimatological changes for the end of the century.

To accomplish the research objectives, both observations and models are utilized. The observations are examined to validate the model for the last half of the 20th century. This is followed by examining the model's temperature at the end of the 21st century, and the differences between 21st and 20th century temperatures are noted and summarized. During the initial stages of this research, sensitivity studies were performed to assess the model's performance in representing river temperature and flow for several large rivers around the world. However, for this dissertation, the Fraser and Lena River Basins were emphasized. While historical river flow data is available for several large rivers around the world, similar long term records of river temperature have proven difficult to obtain. The Fraser and Lena basins are two basins for which we have accurate historical observed river temperature and flow measurements.

I will address the following specific questions as part of this study:

- How have monthly river temperature and flow been changing in the Fraser River Basin, and how might we expect these variables to change during the 21st century?

- What does the observation of daily Fraser River temperature fluctuations tell us about the observed long term trends and the interannual variability during the 20th century? What can we expect to see by the end of the 21st century? Do we expect to see an increase in extreme temperatures as a result of future climate changes?
- How have monthly river flow and interannual river temperature been changing in the Lena River, and how will they change during the 21st century?
- Within the Lena Basin, are the observed seasonal variations identified in Yang et al. (2005) also evident in the model's river temperatures, and what assumptions can be made about future trends at the end of the 21st century?

Chapter 2 provides an overview of the observations and the climate model which are used in this study. In chapter 3, the model's Fraser River temperature trends for summer months are compared with observations from Morrison et al. (2002). The trends are extended to the end of the 21st century. In chapter 4 the model's daily temperature is compared to the observations, and trends in extreme temperatures are extended to the end of the 21st century, with a discussion on the potential impact of river temperature change to Pacific salmon. Chapter 5 shifts to the Lena basin, where an analysis is provided on modeled 20^{th} century river temperature trends for a high latitude basin, and evaluate the modeled temperature changes through 2100. While each of the three aforementioned chapters contains a discussion of the results, Chapter 6 synthesizes the work described in these three sections, and provides an overview of the pertinent results and the path forward for future research.

Chapter 2

OBSERVATIONS AND GLOBAL CLIMATE MODEL

2.1 Observations

The observed data used in these experiments were obtained from several sources. The Fraser River, which originates in the Canadian Rockies, is the largest Canadian river to discharge into the Pacific Ocean. Flow is dominated by snowmelt runoff in the spring, and the seasonal pulse of freshwater (the spring freshet) is the largest contribution of annual snowmelt runoff, occurring in June. Flow in the Fraser demonstrates a relationship with larger scale geophysical forcings. The phase of the North Atlantic Oscillation (NAO) is correlated with Fraser River flow during the second half of the 20th century; in addition, significant correlations are found between Fraser river temperature and CO_2 concentration, length of day, El Nino Southern Oscillation (ENSO) indices, and the Pacific North American Oscillation index (PNA) (Ferrari, 2008). The Fraser is impacted by human activities, including pulp and paper mills and constructed dams for hydroelectric power, but most of the human modification occurs in the lower basin.

Observed monthly flow and temperature for the Fraser River is found in Morrison et al. (2002), and supporting data were also provided by the Institute of Ocean Sciences in British Columbia, Canada (river flow) and Fisheries and Oceans Canada (river temperature). Historical daily observations of Fraser River temperature and flow were provided by Environment Canada (2008) and Fisheries and Oceans Canada/Simon Fraser University (FOCG, www.dfo-mpo.gc.ca). The recording station for the Fraser River is located at the Hope/Hell's Gate location, which is approximately 6.0 km upstream from the basin's mouth (see Figure 2.1 for a map of the Fraser River Basin). River temperatures are available from July through mid September, as this coincides with the period when salmon migration in the Fraser River occurs. The first study utilizes monthly data between 1942 and 2001. Following the monthly study, daily flow and temperature data were available from March through December, from 1912 through 2007. The first half of this data series included several gaps in the observations. The 1961 to 1980 period was selected as the present climate period primarily because observations over this 20-year period are complete, with no missing data points.

Monthly flow observations for the Lena River were obtained from the Regional, Electronic, Hydrographic Data Network for the Arctic Region [R-ArcticNET (v3.0); www.r-arcticnet.sr.unh.edu/v3.0/). Observations were obtained for the Lena's outlet, as well as for two of the upstream subbasins, the Aldan and Upper Lena tributaries. This online database maintains historical streamflow for all of the major sources (over 3,700 monitoring gauges) of Arctic Ocean freshwater inflows, which cover the entire pan-Arctic drainage system. One of the reasons for establishing this comprehensive database was to provide an accurate historical baseline time series for comparison with model values. In addition to the monthly flow, flow and temperature for the Lena Basin recorded at a frequency of once every 10 days were obtained from Yang et al. (2005) and Liu et al. (2005). This data provide better temporal resolution than the monthly data, and are therefore more suitable for analyzing long term trends and comparing to model results.

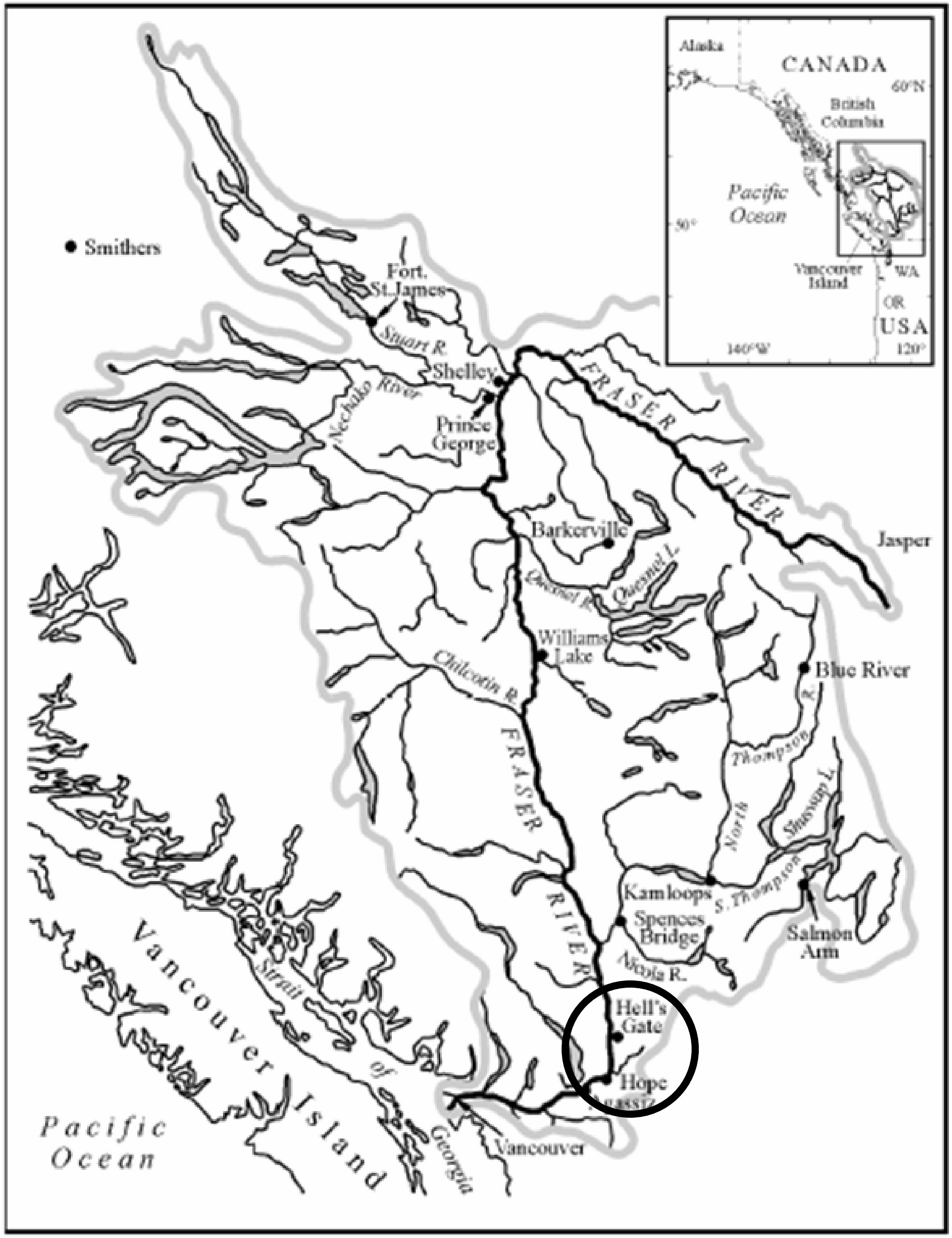


Figure 2.1. Map of the Fraser River Basin, modified from Morrison et al. (2002). The monitoring station location at Hell’s Gate/Hope is circled, upstream from the basin’s mouth.

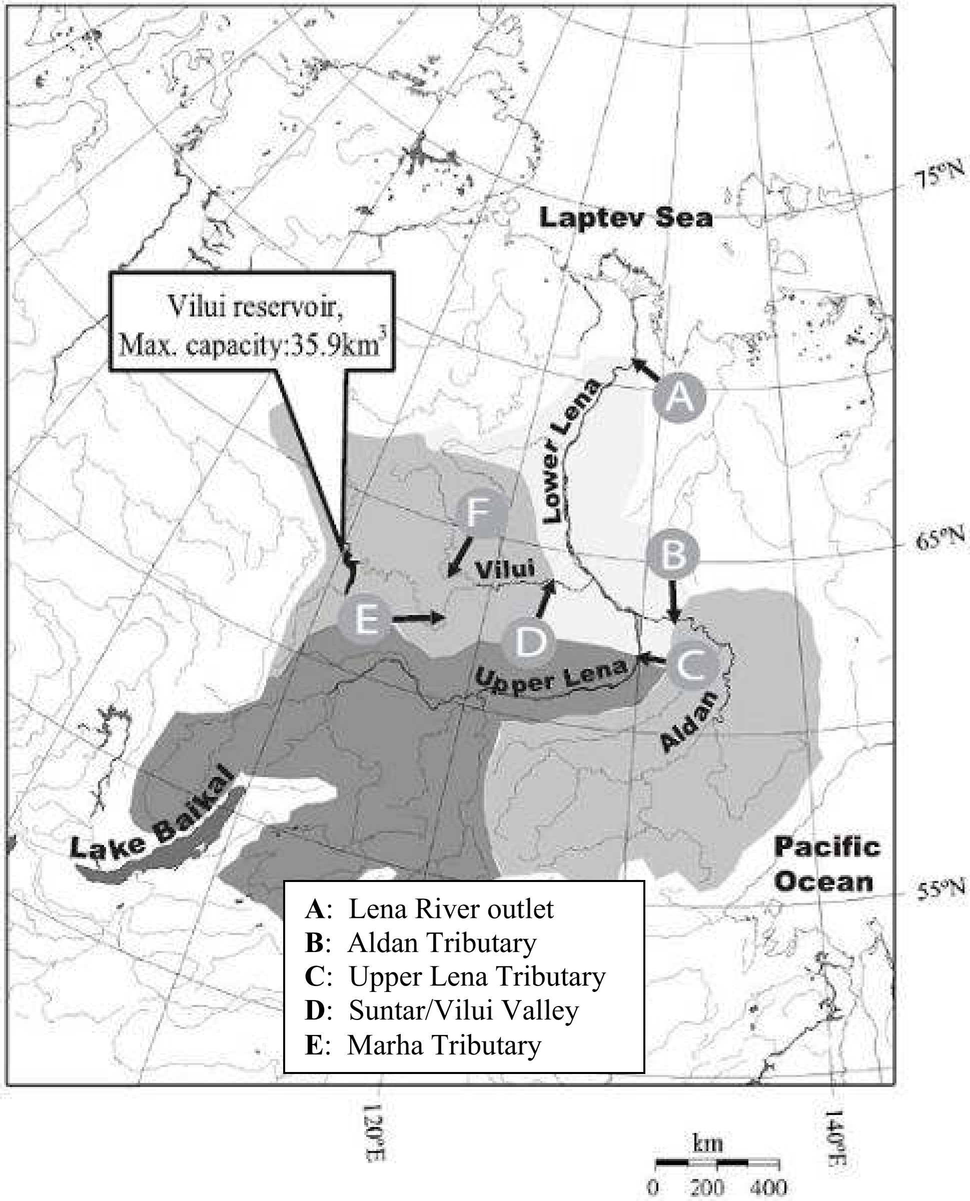


Figure 2.2. Map of the Lena River Basin, modified from Liu et al. (2005). This study focuses on locations A, B, and C.

Historically, several hydrologic parameters have been monitored at northern Russian gauging stations since the 1930s by the Russian Hydrometeorological Services Division and the former Soviet Union's State Hydrologic Institute. In addition to flow monitoring, many stations recorded river temperature at a frequency of three times per month, and measurements were taken two times on each observation day (State Hydrologic Institute, 1961; Liu et al, 2005). Examination of the historical data show that most of the lower Lena's seasonal flow is heavily influenced by snowmelt runoff in the late spring and early summer, with June being the month of peak flow. There is typically very low flow through the winter months when surface air temperatures are well below freezing. Temperatures consistently above the freezing point in mid to late spring trigger the large snowmelt that culminates in the high discharge in June. In most years, the data show that there is more flow generated between the three months of May through July than the total for all other months combined.

2.2 NASA GISS Global Climate Model

The atmospheric model used in this study is the NASA Goddard Institute for Space Studies (GISS) General Circulation Model. The version of the GISS global coupled atmosphere-ocean-ice model used here has been used for the IPCC Fourth Assessment Report simulations, the previous version of which was described in Russell et al. (1995). Both the atmosphere and ocean use the C-grid numerical scheme of Arakawa and Lamb (1977) to solve the momentum equations. The base model resolution is 3° x 4° in latitude and longitude with 12 vertical layers in the atmosphere and up to 16 in the ocean. A map of the global model's 3° x 4° grid with river flow direction is shown in Figure 2.3. The atmosphere and ocean are coupled synchronously every hour. The atmospheric model uses Russell and Lerner's (1981) linear upstream scheme to advect potential enthalpy and water vapor. All significant atmospheric gases and aerosols are used to calculate the radiative source term. The GISS ocean model has a free surface, employs the linear upstream scheme for the advection of heat and salt, and uses the K-profile parameterization (KPP) of Large et al. (1994) for the vertical mixing. The model also calculates at each hourly time step the flow of mass, potential enthalpy, and salt through 16 narrow (sub-grid scale) straits in response to the oceanic pressure gradient between the grid boxes on either end of the strait. Freshwater is added directly to the ocean by net precipitation and/or river flow. There is a four-layer thermodynamic sea-ice model, and sea-ice advection is based on the scheme described in Miller and Russell (1997).

River discharge is calculated directly as part of the model simulation using the river routing scheme of Miller et al. (1994), and a more complete description of the model can be found here. The volume of water mass entering a grid box will be affected by several variables, including topography, soil and vegetation type, and atmospheric physical variables which may either enhance or suppress microclimatological processes. Over time, lake mass above the sill depth of a grid cell flows to its downstream neighbor and eventually to the ocean. Sill depth is defined as the depth at which water can’t flow out of a grid box, and for rivers, this occurs when mass is greater than zero (Miller et al., 1994).

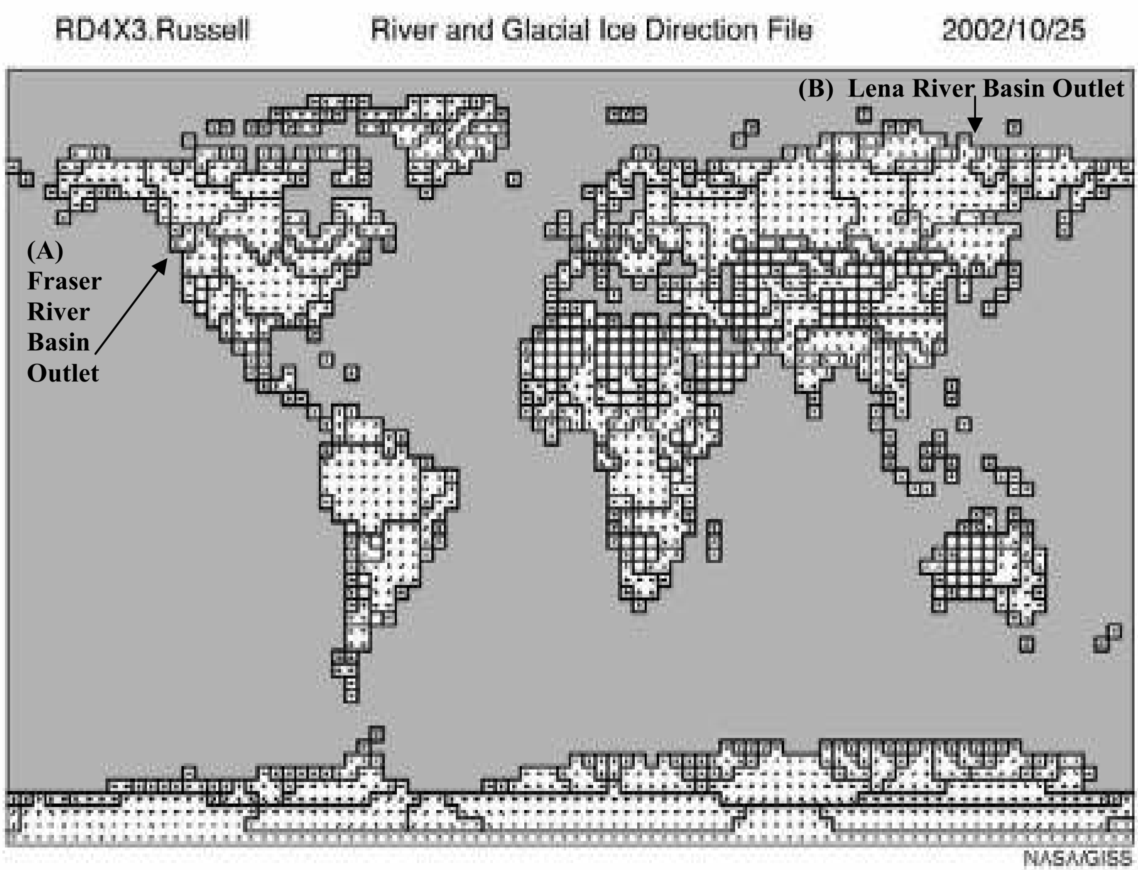


Figure 2.3. Map of the NASA GISS GCM's 3° x 4° grid, with river flow direction for water exiting a grid box indicated by the arrows. The Fraser (A) and Lena (B) basins are identified.

The volume and rate that the water exits a particular grid box is a function of these variables described above. The directional movement of water exiting a given grid box is determined by the river flow direction files, which are shown in Figure 2.3. The temperature of the upper layer of the river is given by

(1) $$T = H / M \bullet Cp$$

where Cp = 4185 J/kg ºC is the specific heat capacity of water. The river temperature, in turn, affects some of the heat flux terms in Eq. 3.

Lakes/rivers contain an upper mixed layer and possibly a second layer whose masses and heat contents vary in time. Mixing between the two layers is calculated each time step based on stability and surface stress. The rate of change of mass, M, in the upper layer is given by

(2) $$dM/dt = P + S + Rin - E - Rout + X$$

where t is time, P is precipitation, S is source runoff from the land fraction, Rin is input river flow, E is evaporation, Rout is output river flow, and X is mixing of mass from the second layer. The heat content, H, of the upper layer is given by

(3) $$dH/dt = QP + QS + QRin - QE - QRout + QX + SW - LW - QH$$

where QP, QS, QRin, QE, QRout and QX are the heat contents transported by the respective processes in Eq. 1, SW is incoming short-wave radiation, LW is outgoing long-wave radiation, and QH is the sensible heat flux. Source runoff comes from the land component of the same grid cell, which consists of both surface and underground components.

In this dissertation, model simulations are examined from 1850 to 2100. The simulations include a control with constant 1850 atmospheric composition and a greenhouse gas (GHG) experiment with observed greenhouse gases and tropospheric sulfate aerosol burden from 1850 to 2003 followed by IPCC's SRES (Special Report on Emissions Scenario) A1B GHG and sulfate scenario (considered a middle emissions scenario) to 2100 (http://aom.giss.nasa.gov/IN/GHGA1B.LP). Because models may have systematic biases such as overestimating precipitation fields, we obtain the temporal changes in climate variables (e.g., temperature, precipitation, river flow) by showing the differences between the future climate experiments and the 1850 control simulation.

Each section in the dissertation will stress the importance of using a combined approach consisting of empirical analysis and modeling. Each of the model experiments shows that there are historical trends upon which to build a central, theoretical hypothesis, which examines how we expect river temperatures to change by the end of the 21st century. The hypothesis is then validated with the GCM results, and the appropriate results and potential future scenarios are discussed. It is important to note that the model is not tuned to any specific river basin, but has been adjusted globally as described in Miller et al. (1994). In contrast to a downscaling approach which takes global climatological data from a GCM and constructs regional models for basin and subbasin processes, no specific adjustments have been made to the model to represent the physical processes at the sub grid level at either basin, and the model output is the result of running the model as a global simulation.

Chapter 3

MONTHLY RESULTS FOR THE FRASER RIVER

3.1 Introduction

In this chapter, historical temperatures for the Fraser River for the last 60 years are reviewed, and future river temperatures are projected with the GCM. As mentioned in chapter 2, a new feature in the Goddard Institute for Space Studies climate model is utilized, which allows for the direct online calculation of river temperatures through the year 2100. This allows river temperatures to be calculated directly as part of the global simulation. The presentation in this chapter follows that in Ferrari et al. (2007). The online results are compared with the offline results of Morrison et al. (2002). The characteristics of the Fraser River basin are discussed in section 3.2, results for the 20th century are given in 3.3, and the projections for the 21st century are given in Section 3.4. A summary and discussion are found in Section 3.5.

3.2 Fraser River Basin

The Fraser River in British Columbia has its headwaters in the Jasper National Park region of the Canadian Rocky Mountains (Figure 2.1). It has a basin area of approximately 217,000 km^2 and flows for 1370 km before discharging into the Strait of Georgia (Thompson, 1981). Most of the flow is dominated by snowmelt runoff in the spring. The Fraser River is an important component of the Canadian fisheries and aquaculture industries, as it is a major spawning ground for Chinook and Sockeye salmon, which account for a large percentage of Canadian Fisheries Stocks (Morrison, et. al, 2002). As the salmon complete their life cycle by returning to their geographic birthplace by migrating upriver to their spawning grounds, the temperature of the river plays an important role in their success, and ultimately the reproductive fitness of the species.

It has been demonstrated that there is a strong relationship between river temperature and salmon mortality; higher than normal water temperatures correlate with higher mortality rates (Crozier, et al., 2007; Morrison, et. al, 2002; Gilhousen, 1990). Warmer water speeds the metabolic rates, thus depleting their energy as they swim upstream, as well as increases susceptibility to disease (Morrison et al., 2002). River water temperatures above 18°C can negatively affect spawning rates (Gilhousen, 1990), temperatures remaining between 22°C and 24°C over the course of several days can be fatal for salmon (Servizi and Janzen, 1977), and temperatures above this range can cause death in hours (Bouke et al, 1975). Therefore, potential changes in river conditions, specifically temperature, could have ramifications on the immediate and the long-term survivability of Pacific Northwest salmon, as well as many other species that comprise this important freshwater ecosystem.

Since changes in river characteristics should be anticipated in light of continued climate change, it is important to develop an understanding of how the associated natural resource base will be affected; in the case of the Fraser, this base is the health of the salmon population. The future possibility of elevated river temperatures, earlier peak flows, and lower summer flows will all be factors in the success of the annual salmon migration. In Morrison, et al. (2002) the authors determined that there were detectable trends in both the annual flow as well as in the summer river temperatures in the second half of the 20th century, and suggested a possible link with observed increases in surface air temperatures. They state that mean summer river temperatures have increased at a rate of 0.22ºC per decade between 1953 and 1998 (Morrison et al., 2002). The observed river temperature increase is approximately 0.11ºC per decade when examined from 1942 through 2001; however, this record is partially incomplete as some of the early years are missing data. According to Foreman et al. (2001) who analyzed flow records from a gauge at Hope from 1912 to 1998, peak flow for the Fraser is occurring earlier in the year. Among the report's notable findings:

- The Julian day marking 1/3 and 1/2 of the annual cumulative flow is occurring earlier (equivalent to 11 and 9 days per century respectively),
- Peak flow arrives earlier in the year after El Nino events, and
- Total river flow tended to be higher following a La Nina winter.

Foreman et al. (2001) state that we can assume that as climate changes, the trend in earlier peak flows and lower summer flows is likely to continue.

Morrison et al. (2002) extended the summer temperature trends of the Fraser River through the 21st century (1953-2000) by downscaling output generated from two global climate models (the Canadian Centre for Climate Modelling and Analysis model (CGCM1) and the Hadley Center for Climate Prediction and Research Model (HadCM2)) to sites in the Fraser River watershed. Using an offline approach, they then used the GCM output to drive a regional watershed model to predict future changes (2070-2099) in river flow and temperature at a site near the mouth of the river. They were particularly concerned with the acute physiological effects via temperature stress on salmon spawning in summer, so they also discussed the potential for climate change to affect salmon mortality. Placing the study in the context of ecosystem health that may be connected to climate change, as the health of salmon becomes particularly susceptible to water temperatures above 18°C, their study predicts the potential for salmon exposure to negative conditions to increase by a factor of 10.

3.3 Observed and Modeled Summer Temperature and Flow (1940-2000)

In this section, observed and modeled summer flow and temperature are examined for the Fraser River for the last half of the 20th century. Understanding the monthly, seasonal and inter-annual fluctuations in flow rate and temperature is important for a variety of industries ranging from aquaculture/fisheries management to hydro power generation. Observed flows were obtained from the Institute of Ocean Sciences in British Columbia, Canada, and are compared to a control version of the model as well as a greenhouse gas (GHG) simulation that also includes the simulated effects of increasing sulfate aerosols.

There are three reasons for the emphasis of this study on summer river temperatures. First, the ecological impacts on salmon are likely to be greatest in July and August. Second, the observed river temperatures cover the summer months (early July through mid September), so the analysis was restricted to the months where the most complete data are available. And finally, the climate model does not simulate river flow very well in winter for the Fraser River. Although the model's precipitation is higher than observed in all seasons, it is significantly higher in winter. This causes the model's river flow in winter to be higher than observations. However, since the Fraser is a small basin compared to other major global rivers, the outflow at the river mouth is not dependant on more than the previous month's conditions. For example, while July and August runoff in the Fraser basin is affected by June atmospheric conditions, it will not be affected significantly by conditions in April and May, as could be the case for a larger basin. Therefore, the model's poorly simulated winter flow is not a significant factor when trying to examine how summer conditions might be affected by climate change.

Figure 3.1 shows that the model's average monthly summer flow between 1940 and 2000 is in good agreement with the observed flow. The observations and the model both confirm that summer flow has been increasing during this period. Warmer temperatures may be responsible for more glacial melt and snowmelt runoff, As summer river flow is a significant factor in determining the ability of salmon to successfully migrate upstream to the spawning beds, it is important to examine this variable further in the context of future climate scenarios. While sufficient flow is vital, river temperature is perhaps more important for the reproductive success of northwest salmon, particularly during their upstream migration occurring in the summer months. Daily river temperatures were provided through Fisheries and Oceans/Canada, who monitor salmon spawning conditions during this period.

Figure 3.2 (a and b) show observed average summer temperatures at Hell's Gate (see location on Figure 2.1) for the last 60 years based on Morrison et al. (2002). The temperatures were recorded for the 1942-2001 period and usually include daily temperatures from July 1st through September 15th, as this is the most crucial period for upstream salmon migration. Some data are missing from the earlier years. These figures demonstrate that there are positive temperature trends in both July and August (+0.1°C and +0.2°C per decade respectively). The trends for both months are statistically significant at 99%, as discussed in Morrison et al. (2002). The observed average river temperature recorded at the Hell's Gate station from 1942-2001 was 15.77°C in July and 16.95°C in August. Not only will increasing surface air temperature raise the river temperature, but it will also affect the timing and magnitude of snowmelt runoff, which in turn will have ecological ramifications.

A comparison of modeled and observed temperatures for July and August is shown in Figure 3.3 and also in Tables 3.1 and 3.2. The observed monthly average temperatures in Table 3.1 are based on daily temperatures. The July and August observations are compared to the model's monthly temperatures. The GHG version of the model shows a small increase (statistically significant at 95%) for both July and August, which is similar to the observed, while there is little trend in the control run. The mean temperatures of the model are too high in July but in good agreement with the observed temperatures in August. It should be noted that river flow and temperature in the model are not tuned to specific river basins. It should be noted again that there are no specific adjustments to the model to represent physical conditions that may be specific to a particular geographic location. The model's river temperatures are close to the observations, and this provides confidence that the model's future climate projections including the addition of increased GHG concentrations can be extended to the end of the century.

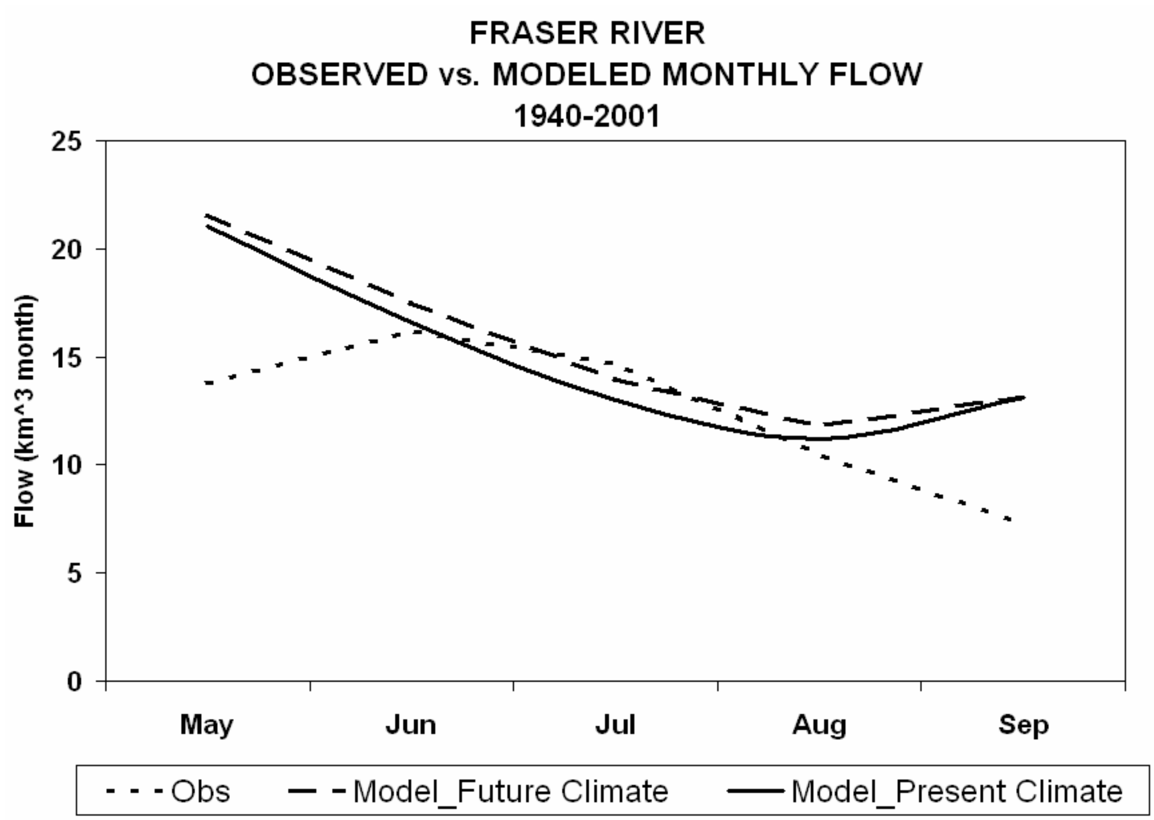
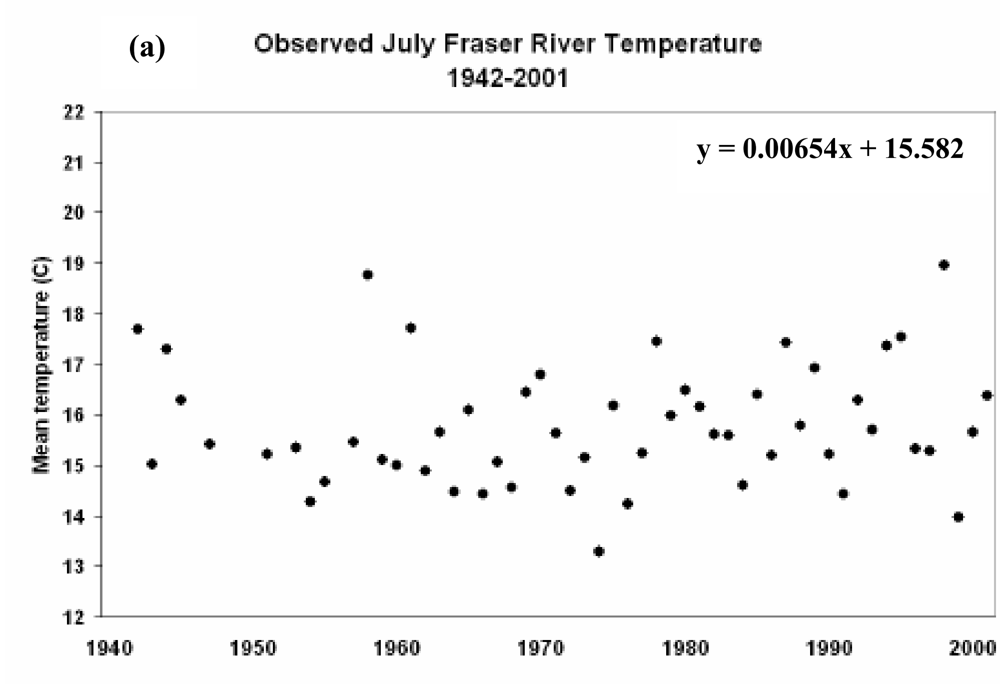


Figure 3.1. Observed and modeled summer monthly flow for the Fraser River Hell's Gate location, 1940-2000. The present climate/control simulation is run with the pre-industrial atmospheric concentrations of greenhouse gases. The future climate simulation (increasing GHG and tropospheric SO4 levels) is run for the same years, and shows an increase in temperature for the 20th century as a result of anthropogenic emissions.



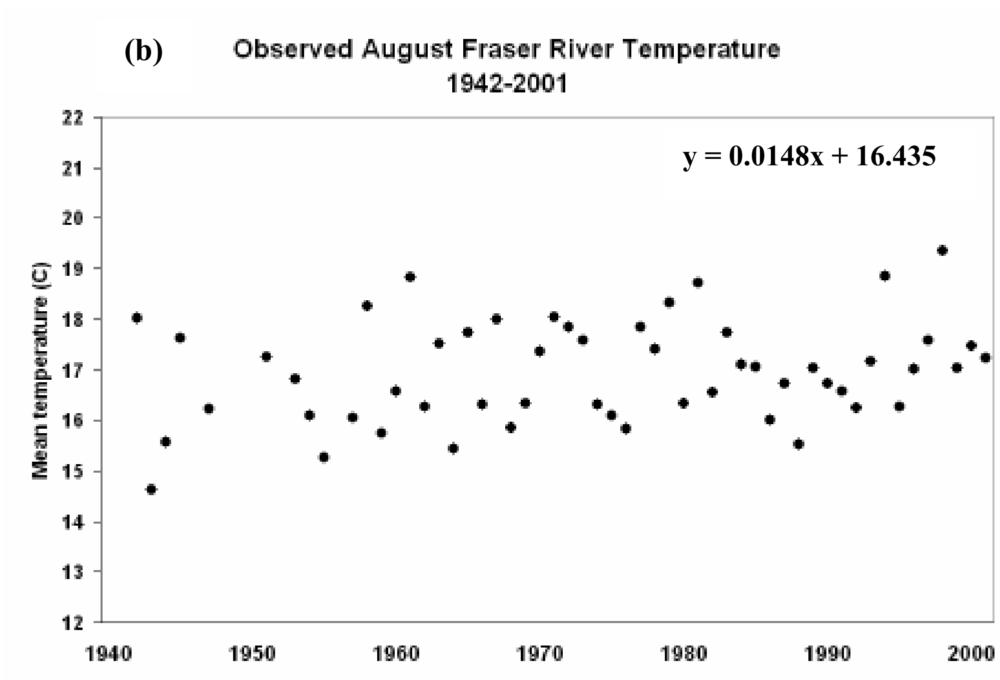


Figure 3.2. Observed Fraser River mean monthly river temperature between 1942 and 2001 for July (a) and August (b).

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TABLE 3.1. Observed and GCM Statistics, 1940 - 2001

	JULY			AUGUST		
	Obs	Control	GHG	Obs	Control	GHG
Average Temperature	15.77	17.22	17.51	16.95	17.37	17.72
Low Temperature	13.29	15.45	15.79	14.64	15.91	16.21
High Temperature	18.96	18.82	19.22	19.36	18.92	19.76
High departure from mean	3.19	1.59	1.71	2.41	1.55	2.04
Low departure from mean	2.48	1.78	1.72	2.31	1.46	1.51
Number of occurences when average temperature> 18C	2	4	8	9	8	12

Table 3.1. Notable observed and modeled (control and GHG) Fraser River temperature statistics for July and August, 1940-2001. The addition of greenhouse gases into the simulation leads to higher summer river temperatures in both months.

TABLE 3.2. Fraser River Temperature Changes (C) per decade for Observations and Model Output, 1940-2001

	July	August	JulAug ave.
Observed	0.07	0.15	0.11
Control	-0.09	-0.02	-0.06
GHG	0.16	0.09	0.13

Table 3.2. Observed and modeled Fraser River temperatures per decade. The GHG version includes an increasing temperature trend over the six decade monitoring period, consistent with observations.

In the control/present climate run for both months, Figure 3.3 shows that the modeled temperatures are in the same range as the observations. The increasing trend in the observed and GHG/future climate temperatures during the referenced time periods are statistically significant at the 95% and 98% confidence levels. Table 3.1 shows that both the observed and modeled future river temperatures exhibit an increasing trend in July and August, and more significant deviations above 18°C are apparent in the most recent years. As maximum temperature is an important factor regarding salmon migration, this could provide some insight on how the salmon migration and subsequent spawning rates could be affected under future climate scenarios. In the next section the global model is used to project how these Fraser River summer temperatures might change by the end of the 21st century.

3.4 Observed and Modeled Summer Temperature and Flow (1900-2100)

As an increasing trend in river temperature is evident during the time period examined in the previous section, the model's future climate simulation is examined next to see how river temperature might change during the present century. First, however, the summer flow during this period is evaluated, as river flow and temperature are closely related. Figure 3.4 (a and b) shows the temperatures from the control (present climate) and GHG (future climate) simulations for July and August between 1900 and 2100. When the control and GHG simulations are analyzed separately for the first and

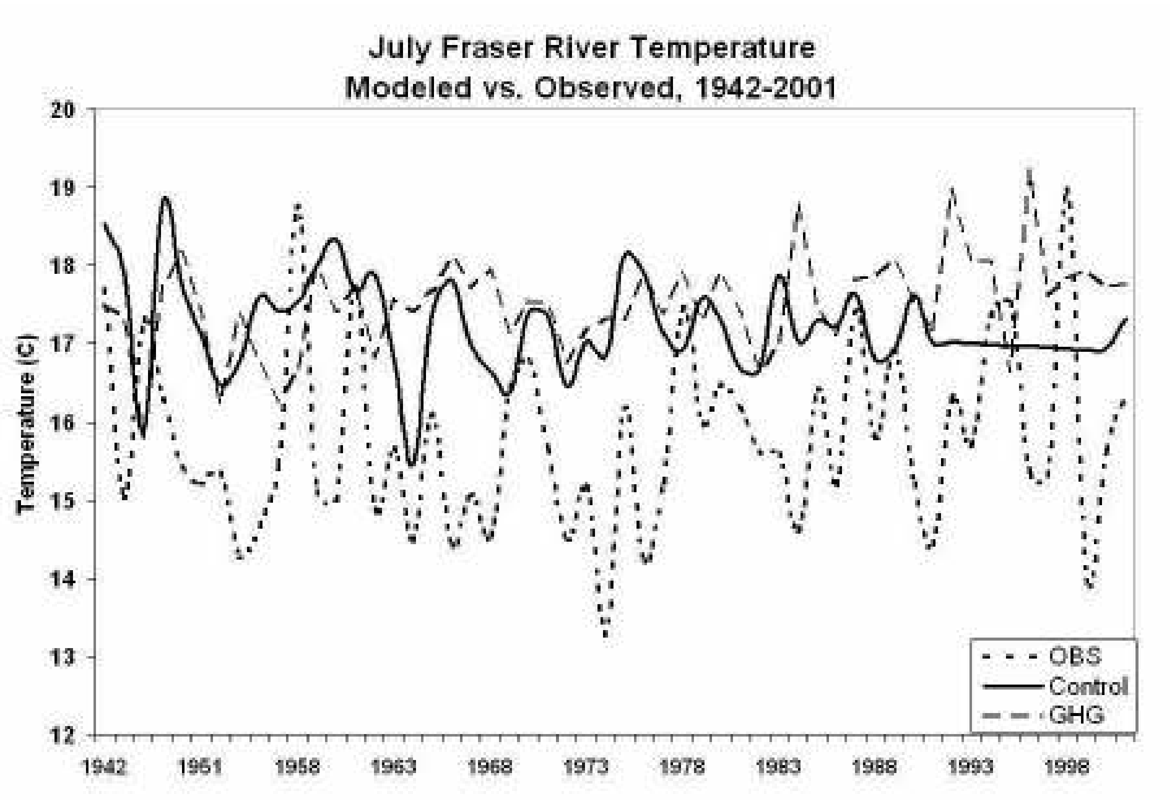

Figure 3.3(a). July Fraser River monthly mean temperature, observed vs. modeled (control and greenhouse gas versions) for the 1942-2001.

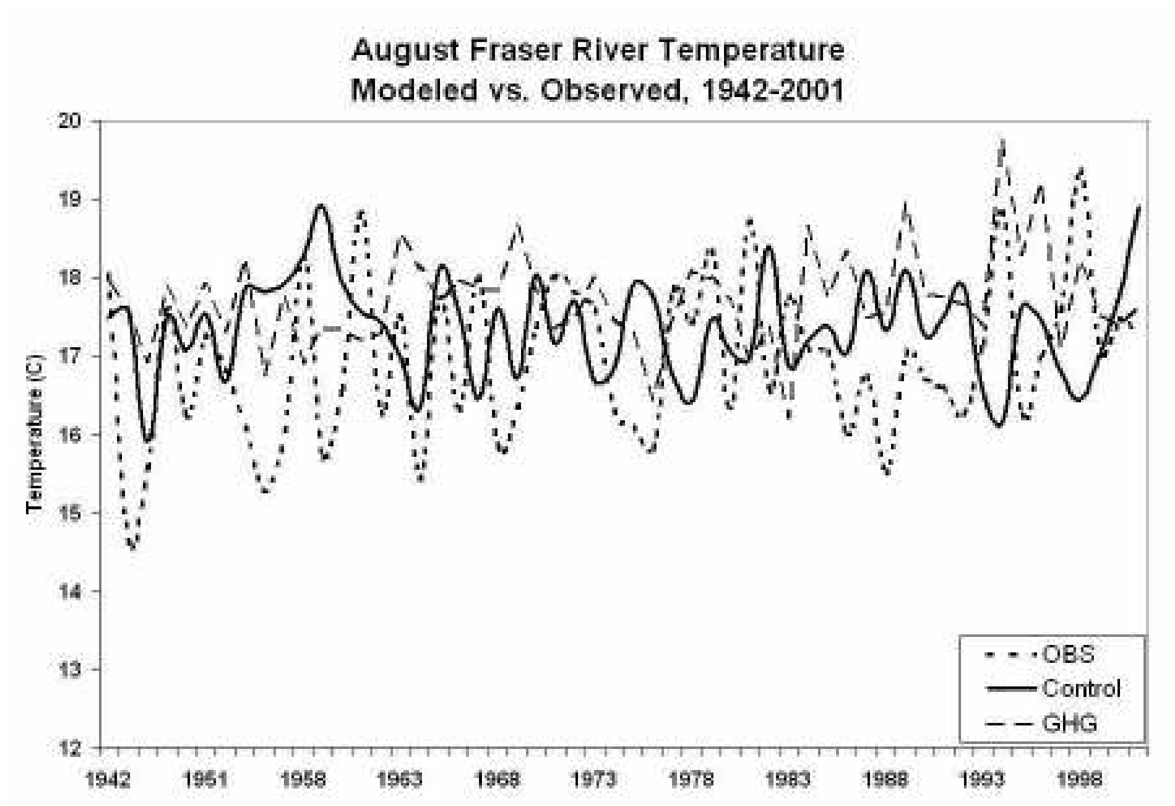

Figure 3.3(b). August Fraser River monthly mean temperature, observed vs. modeled (control and greenhouse gas versions) for the 1942-2001 monitoring period.

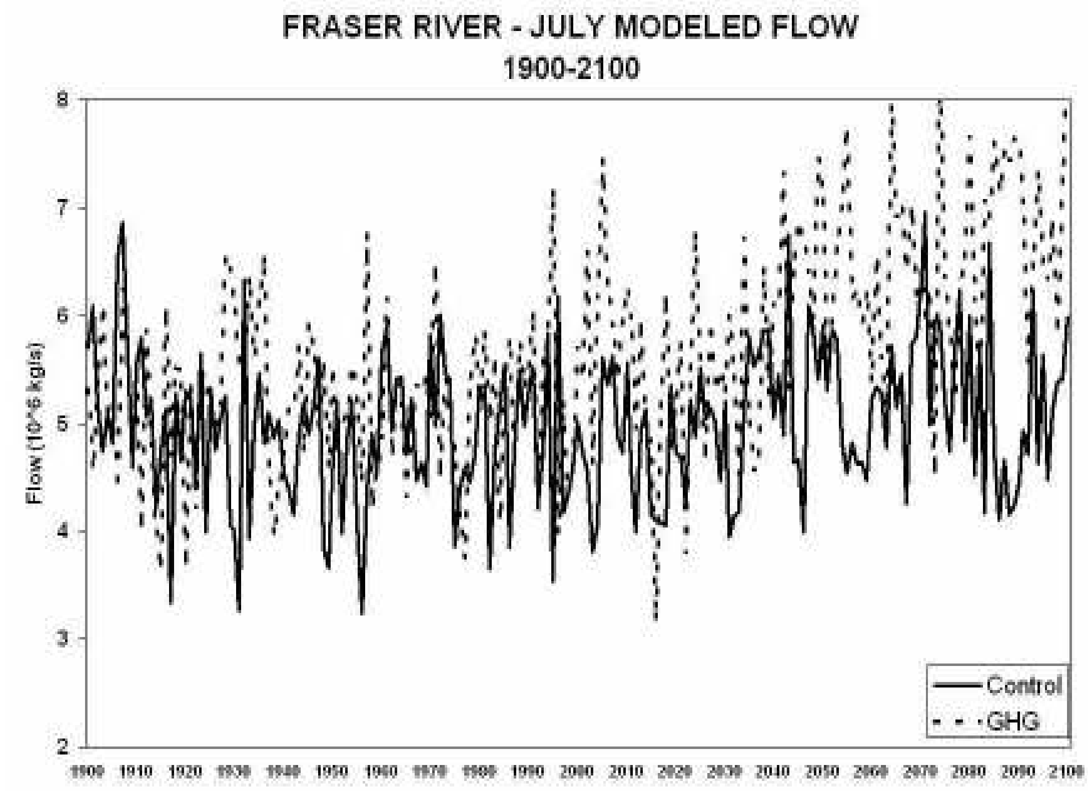

Figure 3.4(a). July Fraser River monthly modeled (control and greenhouse gas versions) flow for the 1900-2100 period.

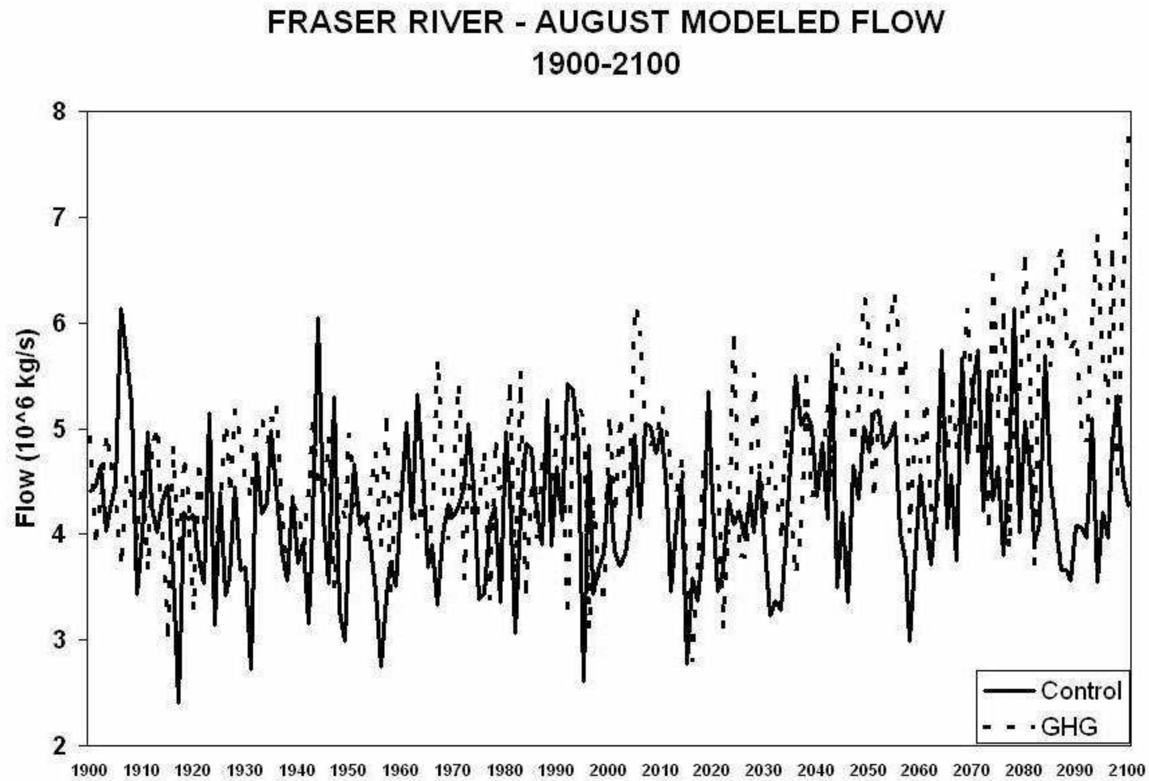

Figure 3.4(b). August Fraser River monthly modeled (control and greenhouse gas versions) flow for the 1900-2100 period.

second 100 years, both the extremes and range are similar between 1900 and 2000. However, during the second 100 years of this comparison (2001 to 2100), there is a significant increasing trend in the greenhouse gas induced temperatures, and the extreme flows are significantly higher than those generated by the control version in both July and August. The cause of the higher flow through 2100 may be a result of the GHG model generating more precipitation over the basin as a result of a warmer atmosphere. In addition to warmer temperatures contributing to higher early summer snowmelt runoff, higher surface air temperatures will enhance the water cycle, increasing evapotranspiration and subsequent precipitation, which will lead to higher rates of surface runoff. This leads to a more active flow pattern under simulated future warming conditions.

Arora and Boer's (2001) results showed that in middle and high latitude river basins, seven out of ten rivers exhibited an increase in mean annual discharge when the GHG projections (2070-2100) were compared with their control scenario. For example, the Mackenzie River showed a 20% increase in mean annual discharge, the Yukon River produced a 10% increase, and the Columbia River produced a 67% increase. Interestingly, in their study only one of the 13 tropical and low latitude rivers (Ganges River) produced an increase in mean annual discharge over the same period. With respect to the middle and high latitude projections, our findings for the Fraser River are consistent with those of Arora and Boer that increased GHG concentrations enhance the hydrologic cycle and influence higher flow rates in similar geographic settings.

Figure 3.5 shows the model's river temperature for July and August from 1900 to 2100. In both months, the control version contains a small negative drift in temperature.

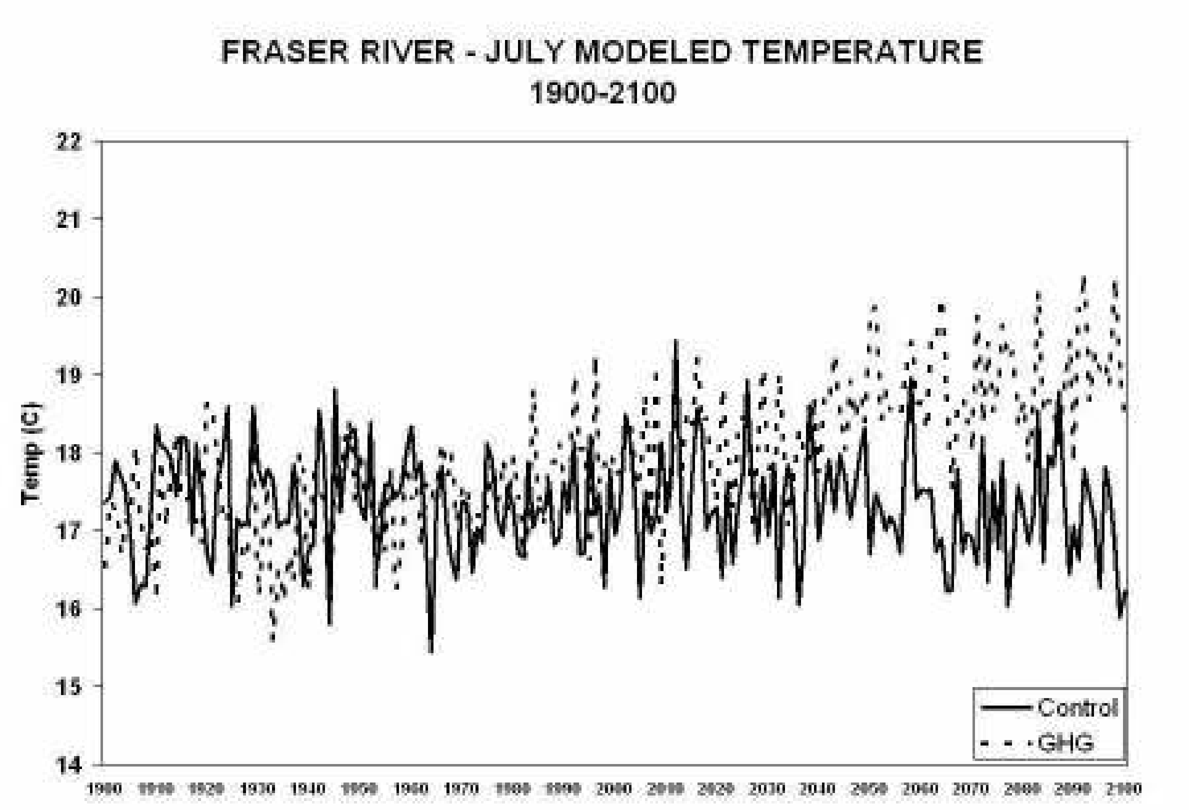

Figure 3.5(a). July Fraser River monthly modeled (control and greenhouse gas versions) temperature for the 1900-2100 period.

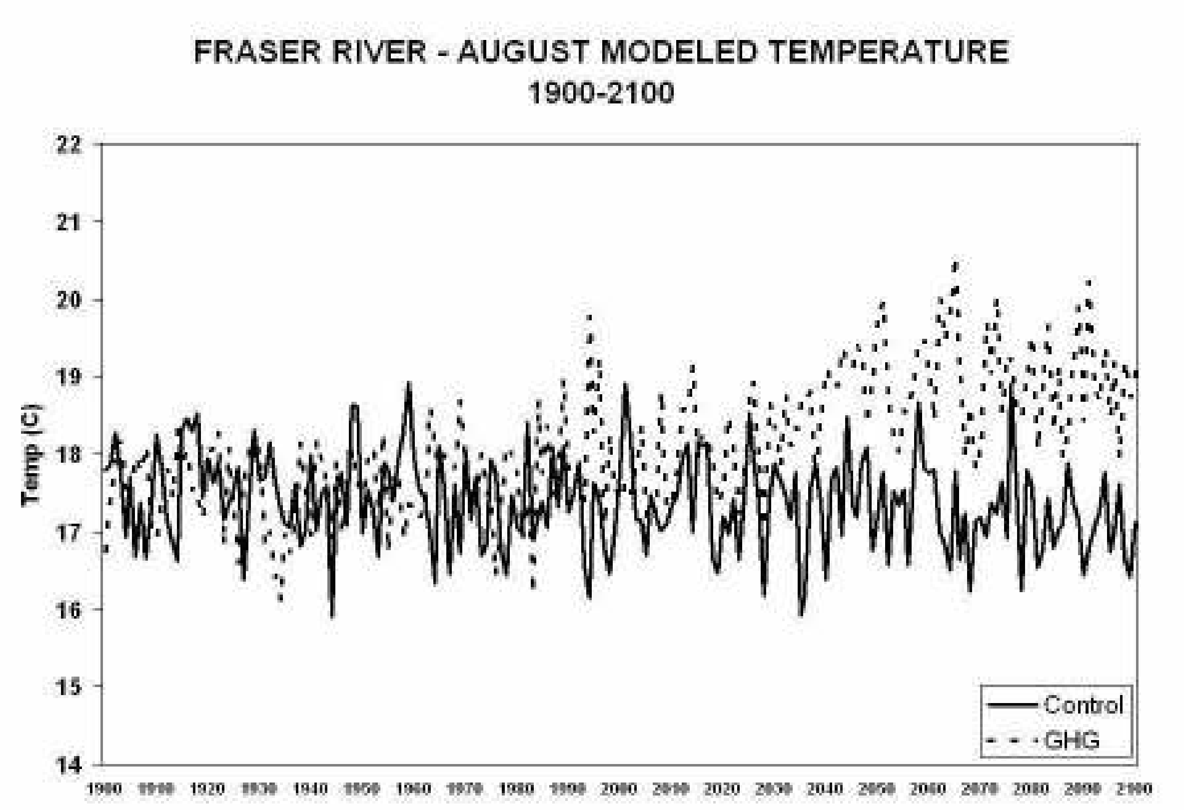

Figure 3.5(b). August Fraser River monthly modeled (control and greenhouse gas versions) temperature for the 1900-2100 period.

As noted with the flow comparison, the control and GHG simulations have similar values in the first half of this period, but the GHG simulation exhibits a significant increase in river temperature after 2030. For July and August, the temperatures between 2075-2100 are approximately 2.0ºC higher than in the present climate. Figure 3.6 shows the annual cycle of monthly river temperatures between 2070 and 2100 for both the control and GHG simulations. In all months, the river temperature is higher by the end of the century, with July and August being the months most likely to exceed the 18ºC threshold. Since these are average temperature projections, June and September will also be important, as there will likely be cases of extremes on the high side in these months as well.

3.5 Summary and Discussion

In this chapter, observations and a global climate model are used to examine how summer river temperatures and flow of the Fraser River changed during the last half of the 20th century and might change by the end of the present century. Although the model did not replicate the annual winter flow well, it did agree with the observed mean summer flow between 1942 and 2000.

The observed river temperature at the Hell's Gate station on the Fraser River shows an increasing trend during the last half of the 20th century (1942-2001). The average temperature during this period is 15.77°C in July, and 16.95°C in August. The model's mean summer river temperatures are in good agreement with observations, particularly in August. During this period, the observed river temperatures increased at a rate of 0.1°C per decade in July and 0.2°C per decade in August. The temperatures in

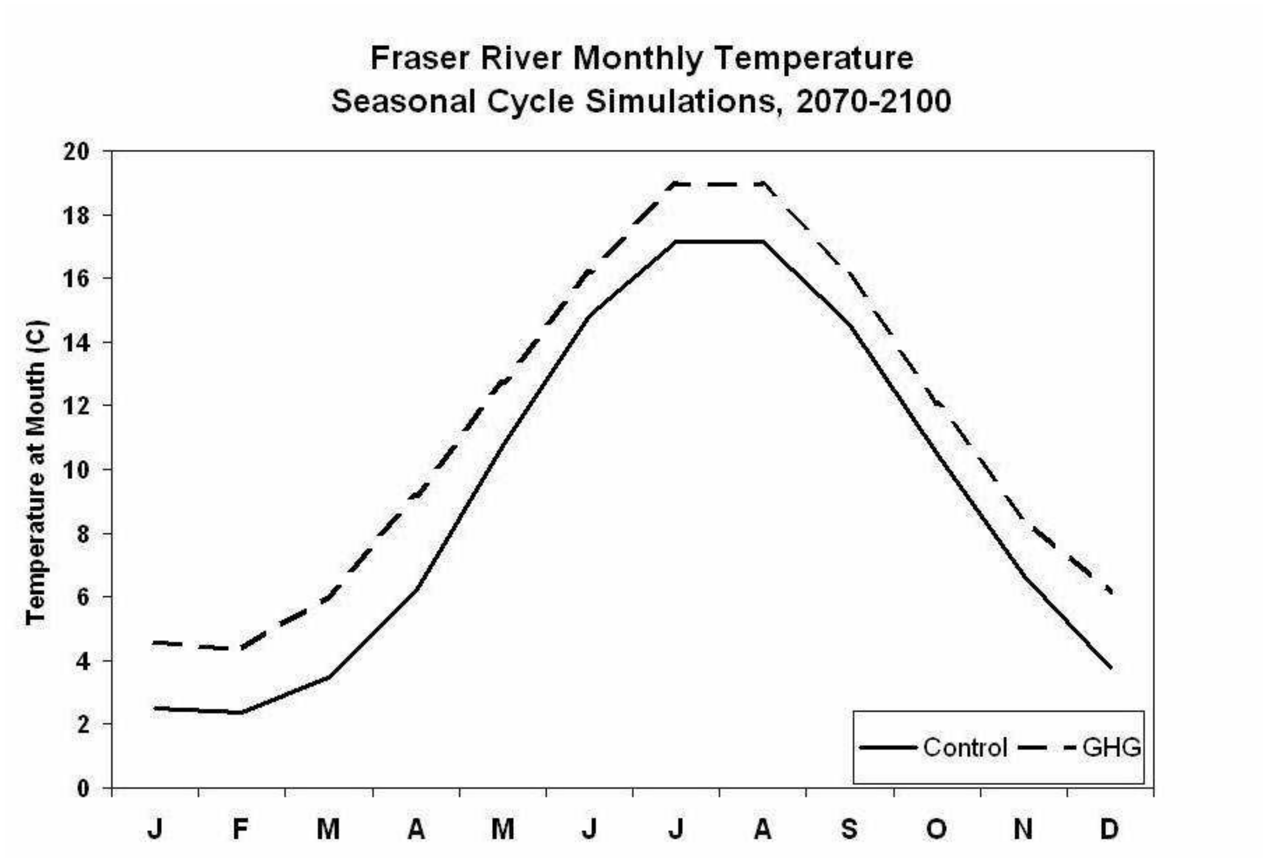

Figure 3.6 Fraser River monthly temperature seasonal cycle simulations for the control and greenhouse gas versions of the model, 2070-2100.

the model GHG experiment also increased, although at somewhat different rates, 0.2 °C and 0.1 °C per decade for July and August, respectively.

Since the model's summer flow and summer temperatures are close to observed values, the control version can be applied as a baseline for how summer river flow and temperature might change under current greenhouse gas projections through the end of the 21st century. Extending this to the end of the 21st century, allows for an assessment of how the hydrology of the Fraser River basin might be affected under future greenhouse gas scenarios, and how these changes might affect river ecosystems.

The online method in which river temperatures are calculated directly as part of the GCM simulation is used here. The river temperatures, in turn, feed back into the model's heat flux calculations, although the feedback is likely to be small for the Fraser basin because the water surface is only 4% of the total area of the model cells. The GHG simulation shows how temperature near the mouth of the Fraser River might change by the end of the present century. The current positive trends for warmer Fraser River temperatures and increased freshwater outflow are projected to continue and to significantly increase by the end of the century as shown in the GHG experiment. Most notable are the projected increases in river flow and temperature after 2030. The results indicate that river temperatures will increase in all summer months with the maximum increase of 0.14ºC per decade in August between 2000 and 2100. Although the focus here has been on summer months, the model indicates that by the end of the century river temperatures will increase in all months with little difference between seasons.

Morrison, et al (2002) performed an analysis which examined historic flows and temperatures in the Fraser River throughout the 20th century. They were particularly concerned with the effects of temperature change on salmon spawning in summer. They found detectable increases in both the annual flow as well as in the summertime river temperatures in the second half of the 20th century and suggested a possible link with climate change. They also found that peak flows resulting from snowmelt runoff are occurring earlier in the year. Morrison et al. (2002) extended these temperature projections through the 21st century by downscaling output generated from two global climate models to sites in the Fraser River watershed. Using an offline approach they then used the GCM output to drive a regional watershed model to predict future changes in river flow and temperature at a site near the mouth of the river. The online and offline changes through the year 2100 were compared, and the results are similar.

What will anticipated future temperature changes mean for the survival and fitness of mid-latitude and high-latitude, freshwater dominated ecosystems? When the observed trends discussed here are extended through the end of the century, the projected rate of temperature increase, may have significant impacts on the long-term fitness of the northwest salmon. Slower rates of river temperature rise may provide salmon with the opportunity to adapt to the changing physical conditions, and thereby reduce the potential negative impacts of temperature changes, allowing for some level of reproductive success. However, the rapid increases that the model projects in the latter portion of the 21st century may be too fast to allow organisms or communities to adapt physiologically or behaviorally. It is also important to remember that the projected river temperatures discussed in this chapter are average monthly values. Since extreme daily temperatures are not represented in the average monthly values, the modeled summer monthly temperature increases may underestimate the impact on mortality in the future. Although the results here provide some insight on how coarse scale models might be used to investigate specific biological effects, GCMs by their nature, are not intended to provide specific basin level characteristics where physical extremes (on spatial scales of kilometers and timescales of hours) can be the limiting biological factors. Future work should try to better assess and model the finer scale temperature variability (both spatial and temporal) and then link these physical conditions to ecosystem responses. The next chapter examines the daily summer temperature for the Fraser River, with a focus on the potential for extreme river temperatures to increase in the future.

Chapter 4

DAILY RESULTS FOR THE FRASER RIVER

4.1 Introduction

Water temperatures in the 18°C to 20°C range begin to negatively affect salmon mortality. This sensitivity to small changes in temperature becomes the foundation for this second experiment. While an analysis of monthly data is useful for examining the longer term trends, in order to assess the potential acute impacts of temperature induced physiological stress, it is necessary to examine the daily variables. Future climate regimes may lead to higher mean river temperatures, as shown in the previous chapter. However, while the monthly study projected higher mean future river temperatures, it did not focus on the potential for an increase in the frequency of extreme temperatures. The focal point of this chapter is to highlight the need for river temperature modeling at a better temporal resolution.

The work in chapter 4 extends the monthly analysis of Fraser River temperatures in the previous chapter to examine daily variability and extremes. For the daily study, observations of Fraser River temperature during the 'ice-free' months of June through September from 1953 to 2006 were analyzed. In addition to comparing the observed and modeled means as done previously, daily variability is shown through examining the standard deviations. This experiment extends the work of Ferrari et al. (2007), discussed in the previous chapter.

As in Ferrari et al. (2007), a new feature in the GISS climate model is utilized for direct online calculation of river temperatures. The model's river temperatures are compared with observations for the present climate, and then are extended to the 2081-2100 period by evaluating the model's output for the last two decades of the 21st century. Observed trends revealed in the daily data are also examined, and compared to the model's daily temperatures. Through an analysis of the model's temperatures, and the frequency with which temperatures exceed the physiological threshold temperature (18°C), an attempt to assess the future variability and the potential for heat stress by the end of the century is made. This analysis addresses problems related to both the physical and biological aspects of climate change. The findings here validate the use of the model for the intended purpose of projecting how future physical climate changes can exert an influence on habitat controlling, or fitness maintaining factors for these selected species. The verification of this work also allows for speculation on how anticipated changes in climate might affect the regional economy of the Fraser Basin.

The observational data sets and the climate model are briefly described in chapter 4.2. Results for the present and future climates are discussed in 4.3, the impact on salmon is found in section 4.4. A discussion and conclusions are given in 4.5.

4.2 Data and Methods

Observed daily river flow and river temperature are obtained for the Fraser Hell's Gate/Hope location. The version of the GISS global coupled atmosphere-ocean-ice model used in this experiment has been used for the IPCC Fourth Assessment Report simulations, the previous version of which was described in Russell et al. (1995). The observations for daily Fraser River flow and temperature are analyzed and compared to the present climate simulation for the 1961 to 1980 time period. The monthly analysis of

Foreman et al. (2001) addressed findings about the shifting hydrologic regime over the 20th century. As discussed in chapter 3, among their findings were that cumulative flow markers (1/3 and 1/2 of the cumulative seasonal flow) were occurring earlier in the season, and that peak and total river flow were significantly impacted during the years following El Nino winters. Ferrari et al. (2007) provided an understanding of monthly and seasonal hydrologic variability, but it is the daily fluctuations that can be most important when trying to predict potential impacts on biological systems. Monthly averages of river temperatures smooth out the extremes, and as we are ultimately concerned with the incidences of water temperatures that exceed 18°C, daily analysis becomes more appropriate. Depending on other factors such as time of year, age of fish, and stage in life cycle, the 18°C threshold does not need to be exceeded for a prolonged time period, as even short duration exposures can be fatal to the salmon population (Servizi and Janzen, 1977).

4.3 Results for the Present Climate

Figure 4.1 shows the observed (summer months) and modeled (all months) monthly river temperature for the present climate, defined here as 1961-1980. These monthly averages were obtained by averaging the daily temperatures for the 20-year period. Observed daily temperatures are only available for June through September, since much of the season experiences temperatures at or near 0°C. Figure 4.1 shows that the model's temperatures are close to the observations (OBS only available for June through September) for the present climate (1961-1980) period. August is the month of

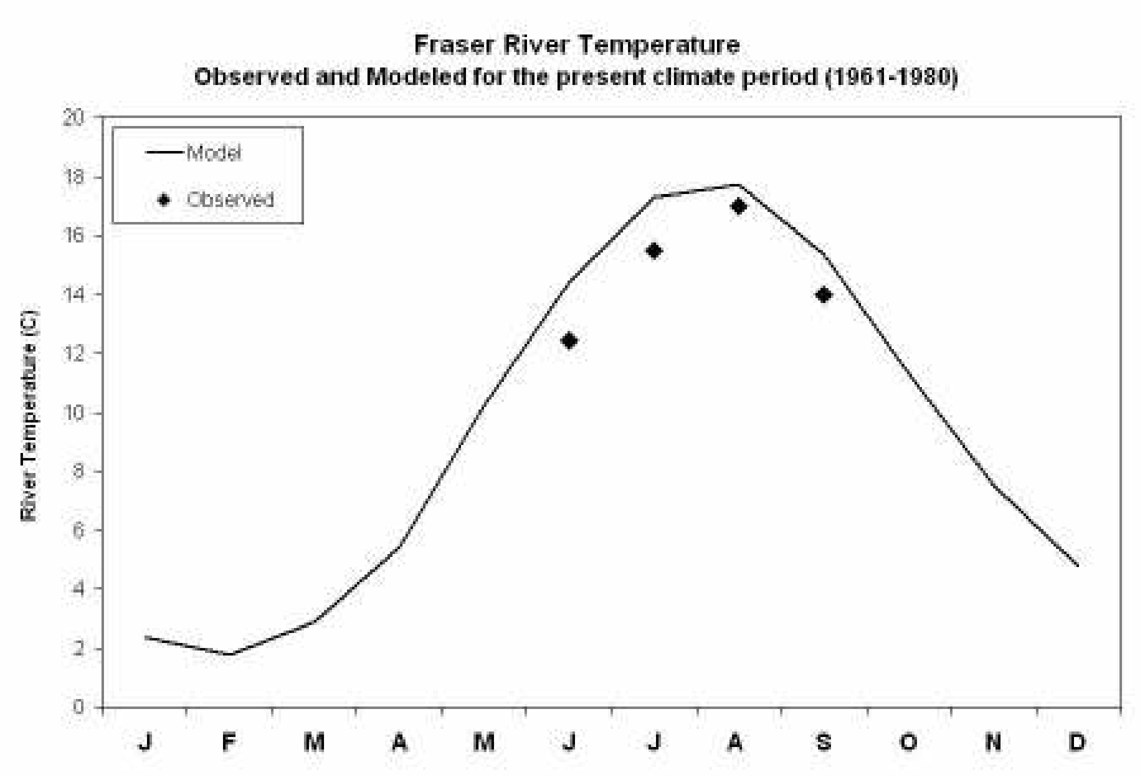

Figure 4.1 Fraser River observed and modeled present climate period (1961-1981) river temperatures. The model's temperatures are slightly higher than the observations for this baseline period.

peak river temperature after which there is a rapid temperature decrease in September. In chapter 3, Figure 3.1 showed how the model generates a similar discharge profile for the summer months, with an overestimation of runoff in May. However, the model's flow in June, July and August is consistent with the observations.

Figure 4.2 shows the decadal average of observed and modeled daily river temperatures for the two decades in the present climate period (1961-1970 and 1971-1980). In the early summer (June-July), the model generates river temperatures that are higher than observed. However, in August and September, the model's temperatures are closer to the observations. The higher early to mid-summer temperatures generated by the model are consistent with the monthly results of Ferrari et al. (2007). As shown in Figure 3.1, the model's river flow is higher than the observed flow in May for the present climate, and this higher spring flow likely affects June river temperature.

The model's daily variability is examined to see how daily river temperature might change during the present century. The model does well in replicating the observed temperatures for the 20-year period. In addition to the daily temperature comparison for each year, the observations for daily Fraser River flow and temperature are analyzed as groups of years within each climate regime, and then the results of the present and future climate experiments are compared. A comparison of the daily observations (1966-1970) to the model's daily temperatures for the same years is shown in Figure 4.3. This figure shows the observed and modeled daily river temperatures from June through September between 1966 and 1970; the pattern is consistent with the other years during the 1961-1980 present climate period.

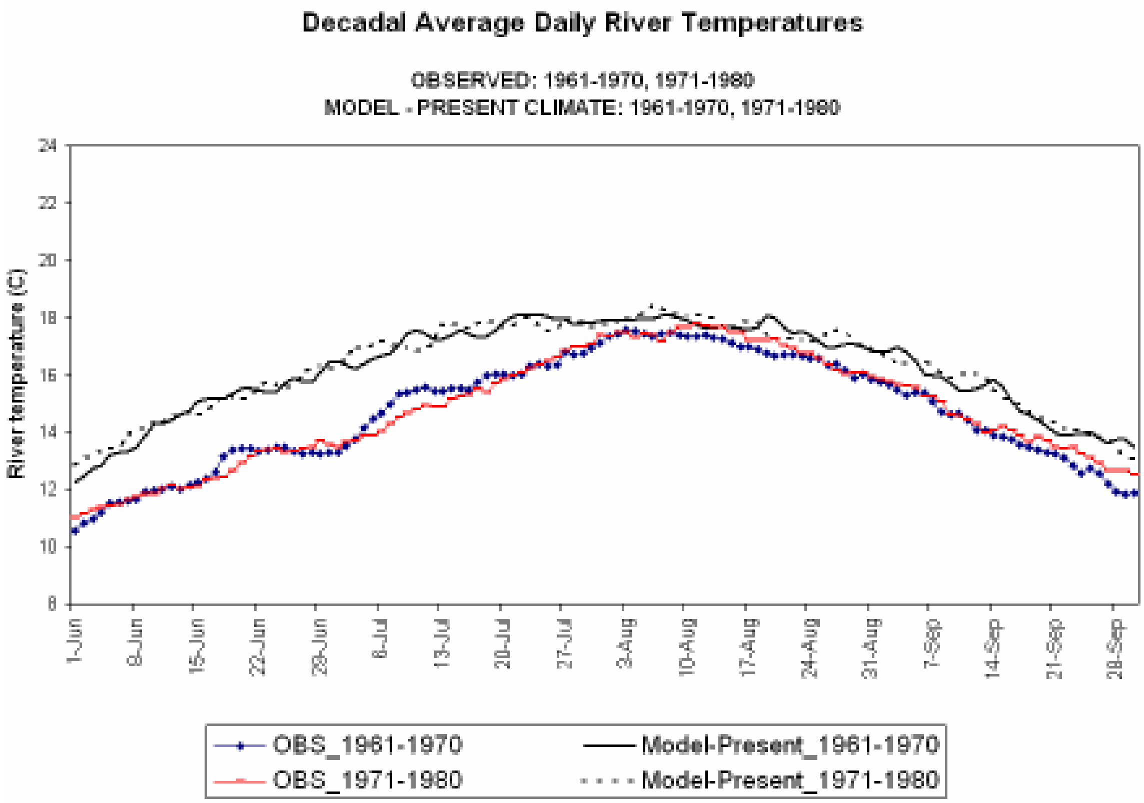

Figure 4.2 Decadal average Fraser River temperature, Observed and Modeled for the 1961-1970 and 1971-1980 time periods.

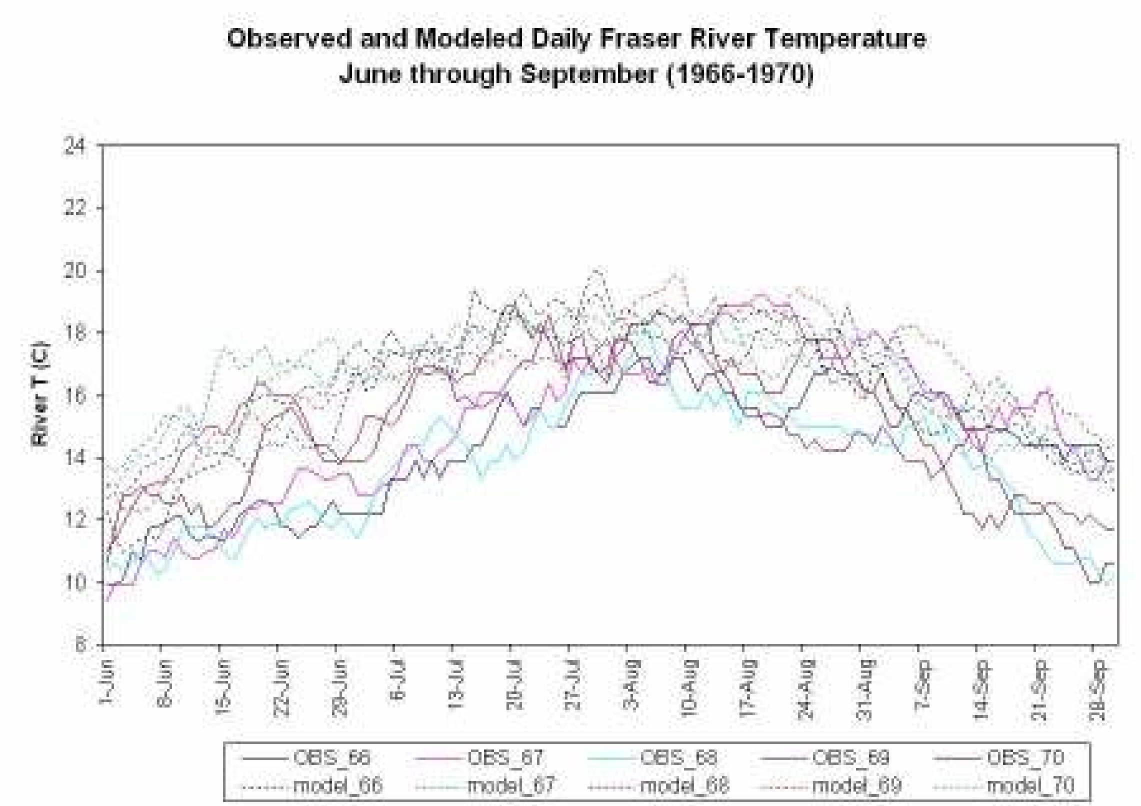

Figure 4.3 Fraser River observed and modeled daily river temperatures between 1966 and 1970. While the model's daily temperatures are slightly higher than the observations, the mid summer period (July 20 - August 20) is very similar.

The model does well in replicating the seasonal daily temperatures, although the temperatures are consistently too high in early summer as discussed above. However, the most important result from this comparison is that during the mid-summer period (20 July to 20 August), the model's mean temperature of 17.87°C is close to the observed mean temperature of 17.04°C, adding to the model's confidence. While the model does not generate higher interannual variability in river temperature during the mid summer period, it does produce more variability in early and late summer, and includes more +18°C days than the observations. The next section examines the model's future projections of temperature at the end of the 21st century.

4.4 Results for the Future Climate

In this section, model's results are examined to identify the potential effect of increasing greenhouse gas concentrations on daily river temperatures and their variability between 2080 and 2100. As with the present climate temperatures in the previous section, the decadal model temperatures are shown for two decades during both the present (1961-1980) and future climate (2081-2100) time periods in Figures 4.4 and 4.5. Referring to the model's present climate as a baseline, average river temperatures are expected to increase, and the anticipated increase is most notable during mid-summer. This mid summer period (20 July to 20 August) is also where the daily present climate model temperatures are close to the observations. Further, there is an extended period during which the model projects the average decadal temperatures to remain well above the 18°C threshold, which have ecological implications.

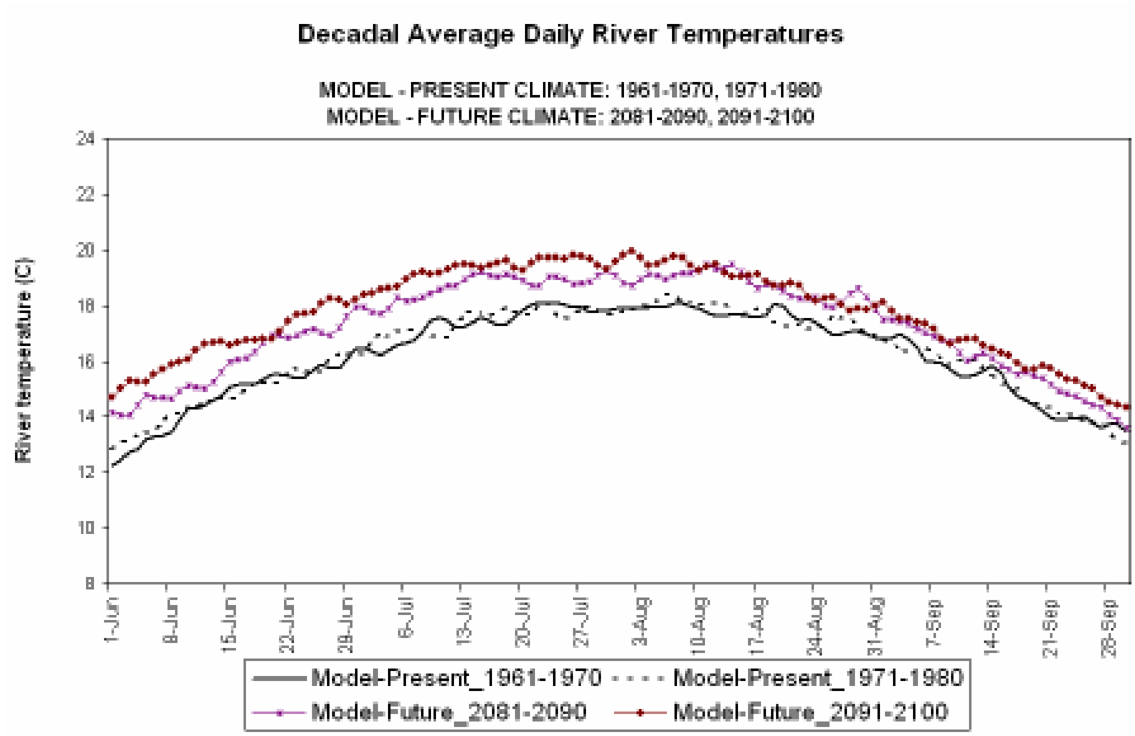

Figure 4.4 Decadal average Fraser River temperature, Modeled present climate (1961-1980) and future climate (2081-2100) time periods.

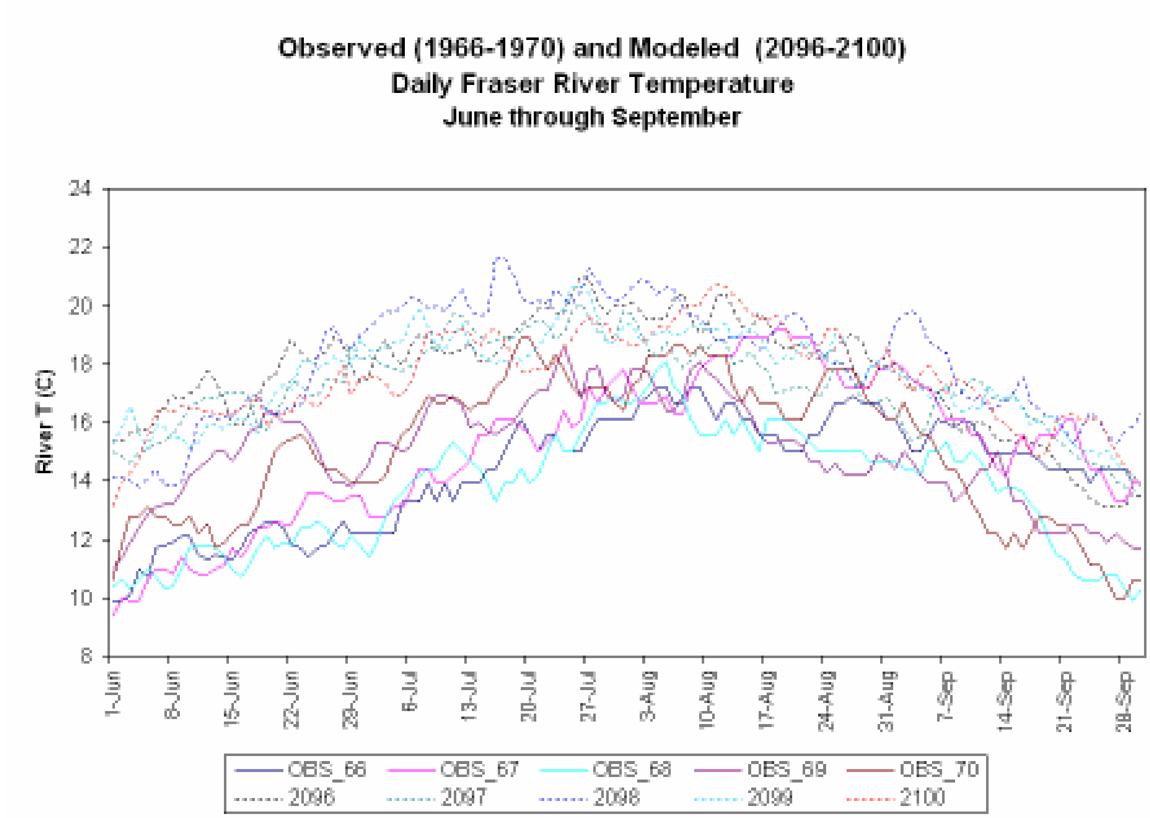

Figure 4.5 Fraser River observed and modeled daily river temperatures between 1966-1970, and 2096-2100. Again, the model's daily temperatures are slightly higher than the observations, the mid summer period (July 20 - Aug 20) is very similar.

Figure 4.5 examines the model's daily temperature projections for the end of the century (2096-2100) and compares these to the daily observations between 1966 and 1970. There are several important details to note from this figure. The model's future climate scenario indicates that temperatures are higher throughout the entire summer season from June through September. In addition, there is a prolonged period of days when temperatures are significantly higher than 18°C. During mid to late summer, in addition to the increased expectations of daily elevated river temperatures, the period when warm waters are anticipated is extended, so the summer season appears to be getting longer by starting earlier, as well as ending later. The observations during the baseline period reveal a relatively small number of days above the 18°C level, but the model projects a high number of days where the critical temperature is reached and exceeded. This can have a significant detrimental impact on the health of Pacific salmon, as well as other species whose physiology and reproductive cycle can be threatened by changes in physical environmental variables (Servizi and Janzen, 1977).

In addition to the absolute temperature results, the overall decadal temperature variability in both present and future climate scenarios is addressed in Figure 4.6. Here, the observed standard deviations for each summer month during the 1961-1970 period are compared with those from the model's present and future climate scenarios. The standard deviation for the present climate model is greater than that for the early summer observations, while temperature variability between the model and the

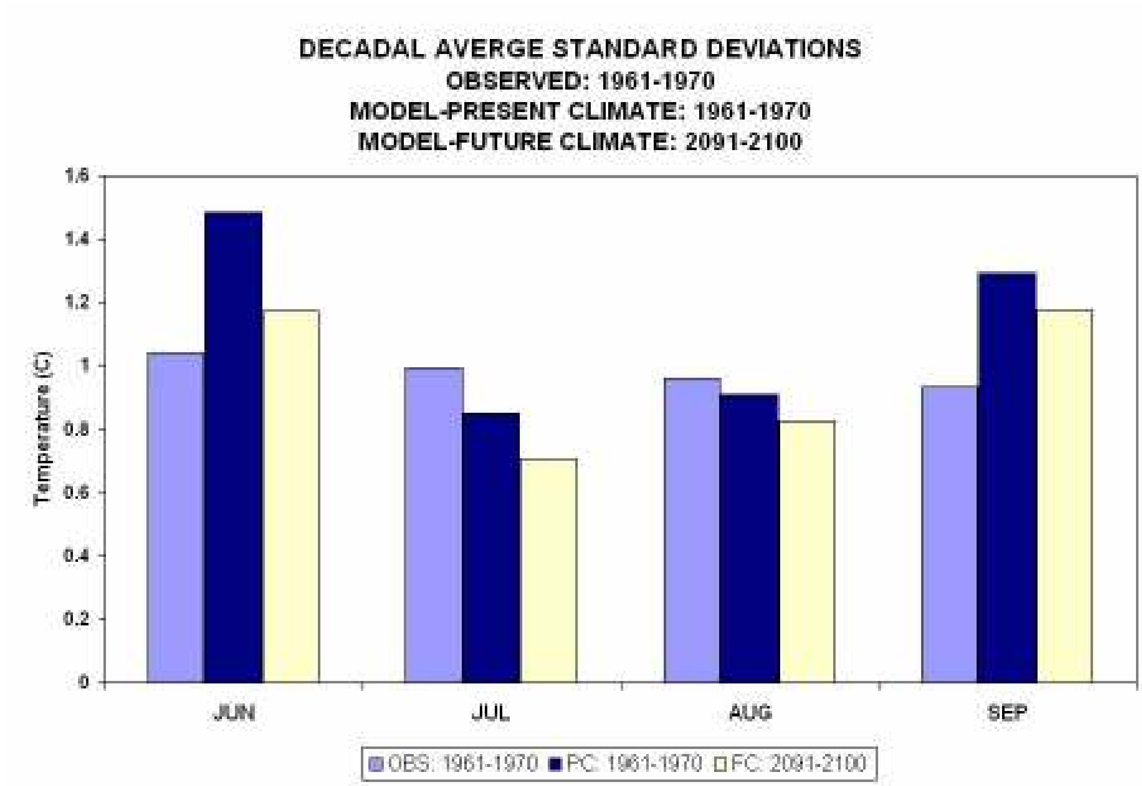

Figure 4.6 Decadal standard deviations for summer river temperatures for present climate (observed and model) and future climate (model). The future climate simulations standard deviations are similar to the observations, so we expect the variability to be similar to the present climate.

observed becomes closer during mid summer. In early summer, the model's present climate simulation is generating more temperature variation from the mean temperature early in the summer; the variability then becomes closer to the observations in mid summer. The model's standard deviation again is higher in September, indicating more interannual variability in the late summer season. The lower standard deviations in the model's future climate projections (vs. present climate) suggest that the daily variability in temperature between June and August will decrease, in spite of anticipated elevated mean temperature. While overall mean river temperatures are expected to trend higher, the variability is not expected to increase over present climate levels during the summer months by 2100. Less variability may not be as detrimental to salmon fitness, as a slower gradual increase may provide more opportunity for adaptation.

Since salmon survival is highly dependant on absolute temperature extremes, it is important to examine in more detail the potential frequency of river temperatures that exceed 18°C as climate changes. Figure 4.7 shows the number of days that observed and modeled river temperatures exceed 18°C for the present climate, and Table 4.1 shows the number of days when river temperatures exceed 18, 19 and 20°C for each of the decades shown. The model's future climate scenario shows increases for each of these physiological thresholds by the end of the 21st century (624, 353, and 114 exceedences of 18°, 19° and 20°C, respectively, between 2091 and 2100). The model also projects changes to river flow which accompany the higher river temperatures; more daily variability in flow, represented by higher standard deviations in daily flow when the future climate flow is compared to the model's present climate. Extending this to the end of the 21st century, the anticipation of future climate can be detrimental to salmon health

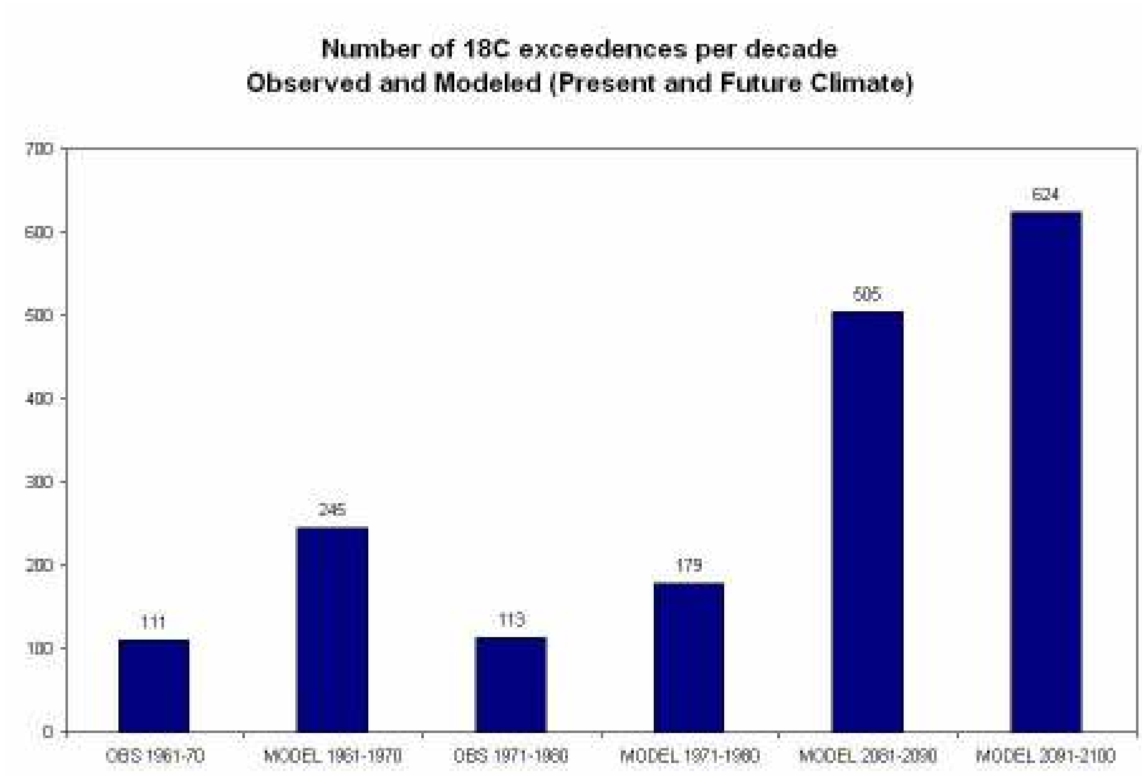

Figure 4.7 This plot shows the observed and modeled monthly number of days within each period where Fraser River temperature exceeds 18°C. The future climate simulation anticipates a significant increase in days where this threshold is crossed, potentially posing a serious risk to the Pacific salmon population.

	No. of days above 18C	No. of days above 19C	No. of days above 20C
OBS 1961-70	111	15	0
MODEL 1961-1970	245	41	4
OBS 1971-1980	113	19	0
MODEL 1971-1980	179	19	2
MODEL 2081-2090	505	253	51
MODEL 2091-2100	624	353	114

Table 4.1. Observed and modeled extreme temperatures for the present and future climate. In addition to the first column in Table 4.1 which shows that the model projects a significant increase in the number of days when Fraser River temperature is higher than 18°C, this table also includes the model's projections of days above 19° and 20°C for the entire summer season, which can have acute effects on salmon health.

not only from a physiological perspective (thermal limits), but also, the anticipated increase in future air temperatures may lead to a more variable river flow regime. Table 4.2 shows the number of days each year when river temperatures are expected to be higher than 1°C above the mean temperature. Because mean observed temperature for the present climate period is 17.04°C and the mean modeled temperature is 17.87°C, this table normalizes the data for comparing the potential for temperatures to exceed the 18°C threshold. The late 21st century projections for temperature to be greater than 1°C above the baseline mean temperature project that this threshold will be exceeded an average of 21 times per year under future climate conditions, compared to 3.8 days per year in the present climate. This projected increase of more than 5 times the baseline highlights the need to better understand the future hydrological characteristics in the Fraser basin, as it suggests increased salmon mortality under future climate conditions.

No. of days temp >mean +1°C	year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	ave # days yr^{-1}
Observed (1961-1980)	32	0	12	0	13	0	11	1	2	13	21	5	15	0	0	0	12	20	16	1	8.7
Present Climate (1961-1980)	0	0	1	1	15	4	5	1	0	1	0	0	14	10	5	3	0	7	9	0	3.8
Future Climate (2081-2100)	5	24	32	17	23	6	9	29	32	8	32	27	17	31	15	29	12	27	22	22	21.0

Table 4.2. Fraser River temperatures >1° above mean. Modeled and Observed river temperature for the present climate (1961-1980) are in closest agreement between 20 July and 20 August. Table 4.2 shows the observed and modeled number of days each year between these dates where daily Fraser River temperature was more than one degree higher than mean temperature. The same for the future climate period (2081-2100) is also shown. Mean observed temperature for this period is 17.04°C, and the mean modeled temperature is 17.87°C; mean future climate modeled temperature is 19.21°C.

4.5 Summary and Discussion

In this chapter, observations and a global climate model were used to examine summer river temperatures and flow of the Fraser River during the last half of the 20th century, and potential changes by the end of the present century. The results from chapters 3 and 4 will contribute towards making long range assessments on the hydrology of the Fraser River basin under future climate change conditions, and presents a method for identifying the potential impacts on Pacific salmon during the 21st century. Observations from an earlier study (Ferrari et al., 2007) were extended, which demonstrated how Fraser River temperatures exhibit an increasing trend during the last half of the 20th century to examine daily temperatures and their variability for both the present and future. The objective has been to project the frequency with which river temperatures will exceed critical thresholds in the future and discuss the potential ecological impacts on Pacific salmon. The model projects higher river temperatures, earlier peak flows, higher seasonal flows, and a significant increase in river temperatures above 18°C by 2100.

The model suggests that there will be an increase in extreme temperatures by the end of the 21st century. Observations for the present climate period (1961 – 1980) recorded an average of 8.7 days per year when river temperatures exceeded 18°C between 20 July and 20 August. However, the model's future climate simulation projects the 18°C threshold will be exceeded an average of 21 days per year during the 2081 – 2100 period. Further, the model projects a significant increase in open water season river temperatures above 19°C and 20°C (30.3 and 8.25 days per year respectively) from 2081

- 2100. As the 2004 scenario discussing Pacific mortality shows (CMU, 2008), higher river temperatures can have a significant impact on the health of a species. Because the model is projecting higher Fraser River temperatures and more temperature extremes during the coming decades, there is a higher potential for climate induced impacts on the fitness of the Pacific salmon population by the end of the 21^{st} century.

An extension of the present climate analysis allows us to not only develop an understanding of how the availability and distribution of water resources may change as a result of climate change, but also how changes in water resources may affect population distribution. While this study focuses on river temperatures that affect Pacific salmon, the approach will be useful in examining potential changes to numerous other species. Beyond the changes in river characteristics associated with anthropogenic climate change, this study also highlights the general relationships between climate variability and Fraser River temperature.

Chapter 5

MONTHLY RESULTS FOR THE LENA RIVER

5.1 Introduction

The purpose of this chapter is to examine the observed temperature trends (defined in Yang et al., 2005) of the Lena River and it's two major tributaries since 1950, and then project how river temperatures might change through the end of the 21st century by using the model's future climate temperatures. In addition to river temperature, the model's sensitivity to flow is also examined. Since the Lena River basin not significantly affected by human activities to the degree that many other large basins are due to the low population density of the region, it serves as a good basin to examine the effects of changes in physical conditions.

In this chapter, model simulations from 1850 to 2100 are reviewed. This chapter focuses on a high latitude river basin where snowmelt dominated runoff is an important part of the region's hydrology. The primary objective is to use the model to extend observed trends in river temperature trends through 2100, and this begins by comparing the model with observations for the 20th century. In contrast to the chapters discussing the Fraser River basin, this chapter focuses on a high latitude basin. This section includes a discussion of how river flow and temperature in the Lena basin have changed over the last 60 years, and how they might continue to change during the next 90 years. One useful component of this chapter is that it allows for an analysis of the Lena River basin's physical characteristics at 10 day resolution, which is better than the monthly studies which are conducted more often. While 10 day resolution data is not as good as continuous daily analysis, this still allows for developing a better understanding of changes in timing to both flow and temperature as a result of a changing climate.

In Yang et al. (2005), they discuss Lena River temperature trends, and make the assumption that rising river temperatures usually follow increases in air temperature when examined on a seasonal time scale (Sinokrot and Stefan, 1993). They examined the trends from four locations in the Lena watershed between 1950 and 1992, and concluded that that there was consistent warming in summer (open-water) river temperature that has occurred throughout the entire basin over this time period. They also noted a cooling trend in late summer temperatures. The authors attribute some of this to earlier snowmelt, with summer temperatures losing the influence of the colder influx of surface water. River flow was also examined in Ye at al. (2003) over a longer time period (1936-1999). In their work, the authors document a runoff increase in the winter and summer months, and a decrease in runoff in fall, which is indicative of an early start to the spring season.

Instead of looking at continuous daily observations, measurements were taken at a frequency of three times per month, and trends were identified from this data. The model is used to examine the river temperature on these same days (day 10, 20 and 30 of the ice free months), and quantify the trends. This is followed by utilizing the future climate simulation (2081-2100) to extend these assumptions, and then to project how river temperature in the Lena basin might change through the end of the 21st century. Again, as river flow and temperature are closely related, observed and monthly flow are reviewed to support the temperature projections for the three major tributaries of the Lena River basin (the Aldan River, the Upper Lena River and the Lower Lena River). By using the future climate scenario to project changes to temperature for the three rivers by the end of the 21st century, differences in temperature from the model's control (present climate) and future climate simulations are analyzed to identify potential changes in the Lena's hydrology by the end of the century. As noted in the Fraser daily experiment, developing a more complete understanding of temperature fluctuations and changes in the timing and magnitude of river flow, combined with effects of warmer river temperatures over the next several decades could pose significant challenges to the ecological fitness of fish species within the basin.

The Lena Basin and associated sub-basins are described in chapter 5.2. The observations and modeled flow and temperature are discussed in chapter 5.3, and the future climate projections of river flow and temperature are in 5.4. A summary and discussion of this final experiment is in chapter 5.5. The results of this study are useful in furthering our understanding of high latitude hydrologic processes as a function of changing climate, and can be extended to assessments of potential effects on aquatic ecosystems.

5.2 Lena River Basin

The Lena River basin is located in northern Russia (105° - 140°E, 54°N - 73°N) and has its headwaters in the Baikal Mountains of the Siberian Plateau (Figure 2.2). The area of the Lena drainage basin is approximately 2.43 million km^2 (Liu et al., 2005) and contributes 530 km^3 of freshwater to the Arctic Ocean each year (Shiklomanov et al, 2000; Peterson et al, 2002; Prowse and Flegg, 2000). The lower Lena originates at the confluence of the Aldan and Upper Lena Rivers (at approximately 130°E 64°N), where it then travels 1,300 km before discharging into the Arctic Ocean through the Laptev Sea at 73 N°.

The physiographic features of the basin are predominantly forested land, and the population for this region is less than 2.5 million people, or approximately 1 person per km^2 (World Resources Institute, 2002; Liu et al, 2005). This low population density makes the Lena basin a good system for study, as we assume minimal anthropogenic land-use impacts that might otherwise be present in a more heavily populated region. However, as some of the region is used for agriculture, there are modifications to the river in the form of dams or canals. The major large dam in the basin is located in the Vilui subbasin (112°15'W - 62°45'N) and is used for river regulation and hydroelectric power (Yang et al, 2005). Because the Vilui outlet is a regulated tributary and natural flow conditions are therefore not available, a comparison of the models conditions to the observations is not included at this location. In a separate study, Ferrari et al. (1999) used a coarser scale model that included a river routing scheme that was inserted into the model's equations to account for anthropogenic diversions in the Aral Sea basin. This technique can be revisited and used to assess the Vilui's hydrology as part of a future study.

5.3 Observed Summer River Flow and Temperature

This section includes an analysis of the observed and modeled seasonal patterns in river flow and temperature for two of the primary sub-basins within the Lena River basin, as well as near the Lena's point of discharge into the Arctic Ocean. Observed river temperatures at the three locations were obtained from Yang et al (2005), and Liu et al. (2005), and a more detailed description of the observations and hydrologic trends at each of the locations is described there. River temperatures were recorded at a frequency of two times per day (8:00 A.M. and 8:00 P.M.) and three times per month, on the 10th, 20th and 30th day of each month. Owing to the freezing conditions in fall and winter, flow and temperature in the basin are only collected during the 'open-water' ice-free season as discussed in Yang et al. (2005), which generally lasts from May through October. For the remainder of this chapter, when discussing the monthly river temperatures, the three periods of the open season are referred to as early summer (May 20 through June 30), mid summer (July 10 through August 10), and late summer (August 20 through October 20). As the Aldan and Upper Lena tributaries are largely unregulated river systems, we can project the future hydrologic behavior and also the potential biophysical and ecological consequences through the end of the next century with a much higher degree of confidence. To evaluate how the model can be utilized to project future river flow and temperature under different climate conditions, a comparison of the modeled and observed temperatures for the last half of the 20th century for each of the sub-basins is presented.

The analysis includes model variables that closely match the dates of the observed temperature readings discussed in Yang et al. (2005); this is accomplished by first comparing the model's values for the same day of the observation, with a present climate period defined as 1950 through 1992. This makes the comparison to the observations in the Yang et al. (2005) study more robust, and provides the baseline for a more useful projection of hydrologic conditions under future climate scenarios. As river temperature is closely related to river flow conditions, the monthly average observed and modeled streamflow are compared.

5.3.1 Aldan Tributary

The Aldan tributary drains a sub-basin with an area of 696,000 km^2, and contributes approximately one third of the Lena Basin's total flow (Liu et al., 2005; Ye et al., 2003). As a relatively unaltered tributary, the conditions can be considered natural conditions with minimal anthropogenic impact that might affect river flow and/or temperature. For the Aldan River, the observations were recorded at the Verkhoyanskiy Perevoz station (63.32 N, 132.02W). The model's flow is compared with observations between 1950 and 1975. The observations show that the Aldan tributary has very little flow from January through April, then exhibits a sharp increase in May, leading to peak flow in June (Figure 5.1 (a)). River flow then decreases steadily through October, followed by the return to winter with minimal flow through December. The model's monthly hydrograph is similar to the observed flow; the only notable difference is that the model's peak flow occurs in May, which is one month earlier than the June observed peak. The model also accurately generates the progressive decrease in monthly flow through the low flow winter period.

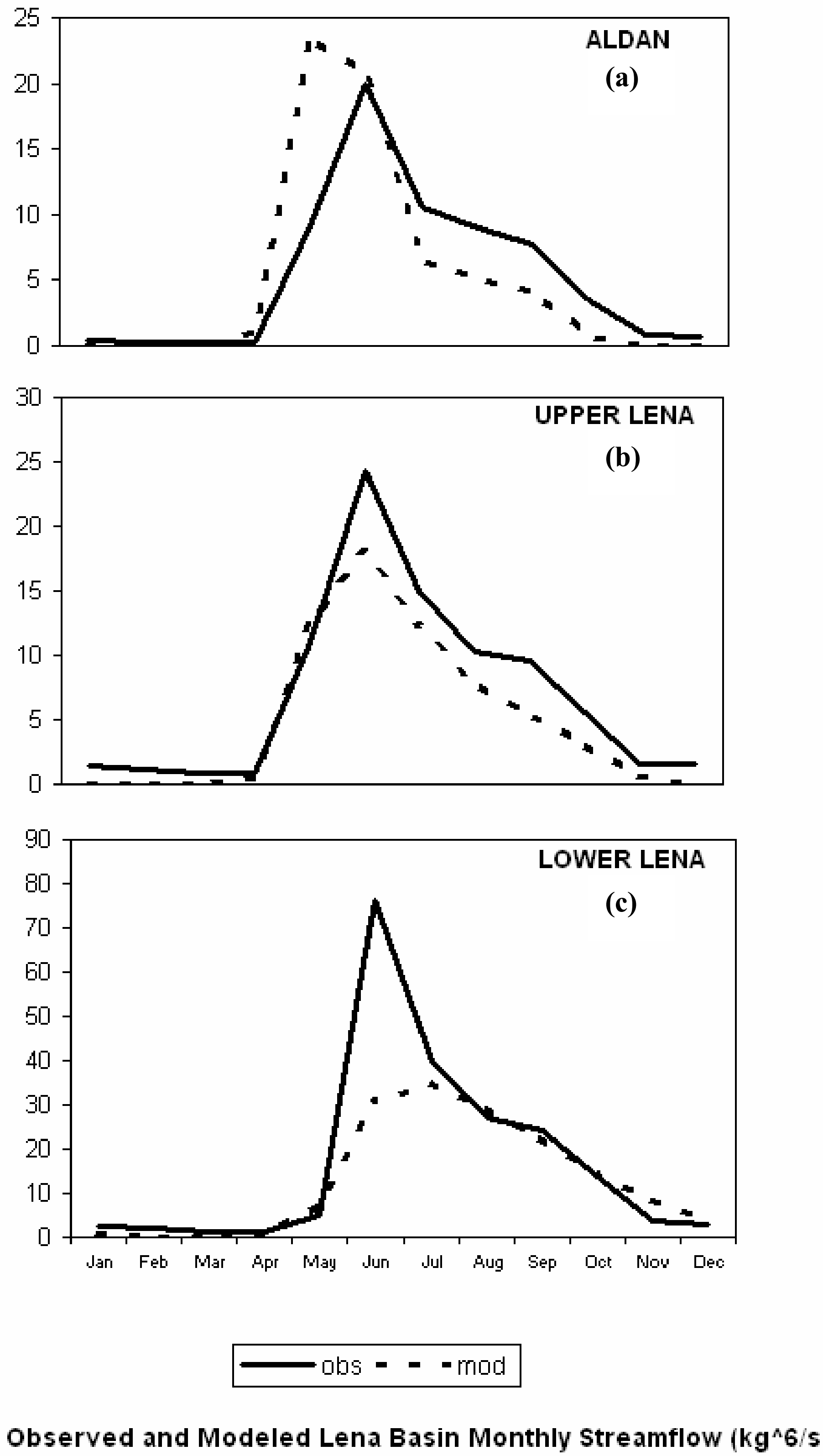

Figure 5.1 Observed and modeled present climate monthly streamflow, 1950-1975. The model's hydrograph is generally similar to the observations, while it does underestimate summer flow at the basin's outlet.

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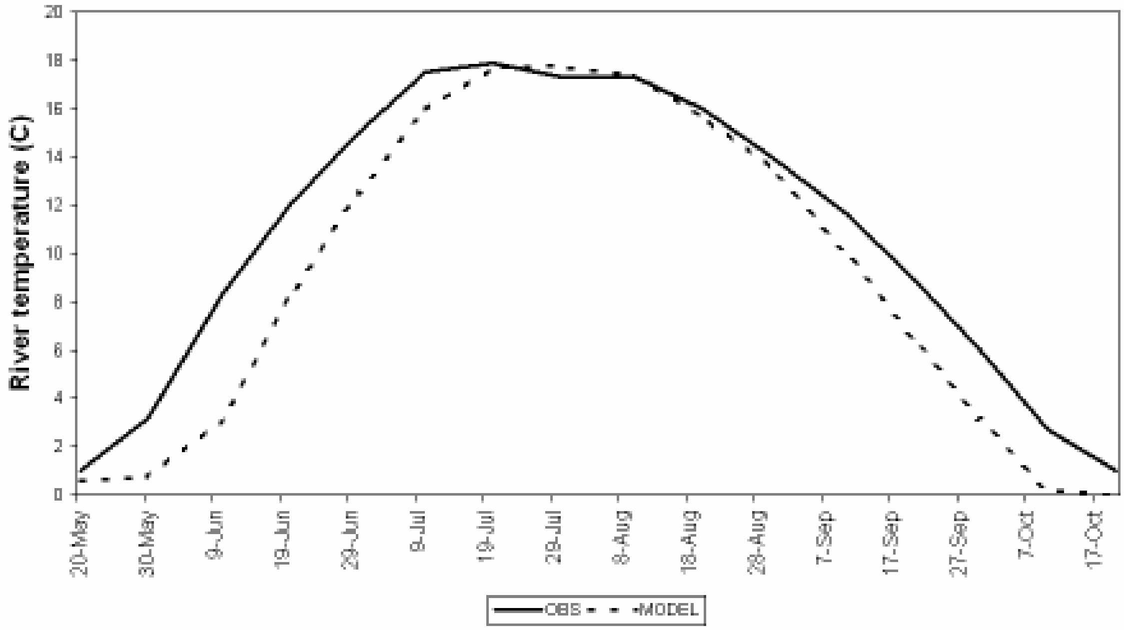
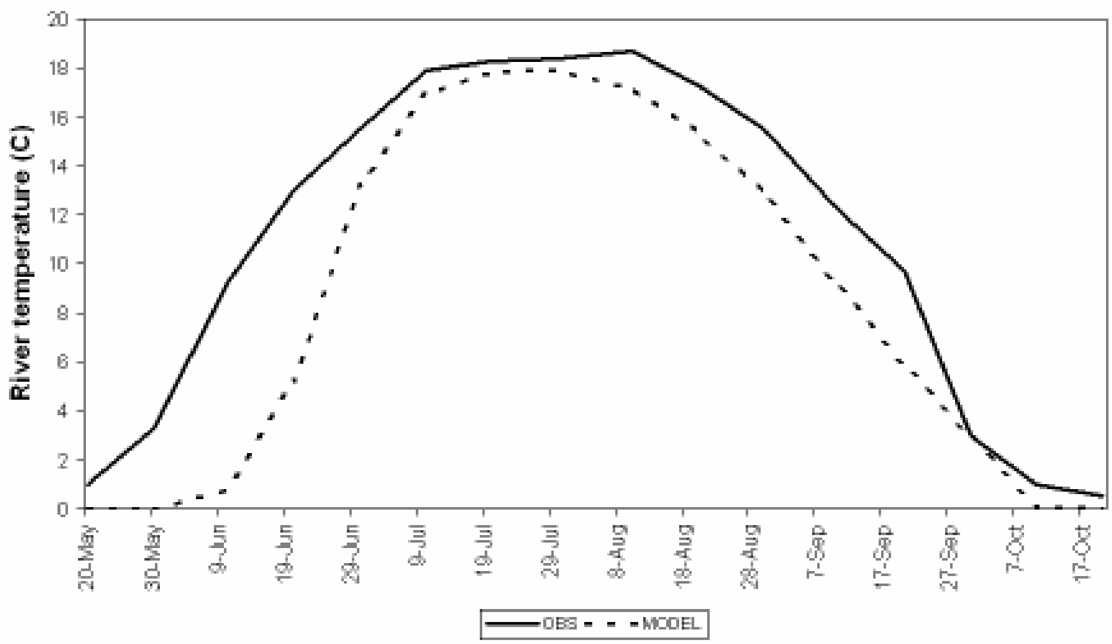
Present climate observations between 1950 and 1992 show that river temperatures for the Aldan tributary increase during early summer from below 1˚C to 15˚C, with an average temperature during this period of approximately 7.7˚C (Figure 5.2 (a)). This is followed by a stable period of high river temperatures in mid-summer when the average temperature is approximately 17.6˚C. The late summer period shows temperatures decreasing from 16˚C to near 0˚C, with the average temperature being 8.6˚C. While the model's early season temperatures are approximately 2.0˚C lower than observed, the mid to late season temperatures are consistent with the observations. While the observed temperature range during most of the period when the Upper Aldan is ice free is approximately 15˚C, the standard deviations are between 1.8˚C and 2.0˚C (Yang et al., 2005), indicating that the temperature for each of the sample dates during the entire observation period exhibited generally low interannual variability. The model's standard deviation range for the same portion of the open water period (20 June through 30 September) is 0.5˚C to 2.9˚C.

Yang et al. (2005) found strong statistically significant long-term warming trends in early summer, and cooling trends in late summer. In addition, there was a weaker increasing trend (at 12% - 47% confidence) observed during the mid-summer period. The early summer observed warming rates of between 0.1˚C and 0.7˚C per decade compare with the model's warming rates during the same period of between 0.3˚C and 0.8˚C per decade. The observations discussed in Yang et al. (2005) reveal a warming trend in the mid-summer period of July 10, 20 and 30 (0.1˚C, 0.14˚C, and 0.1˚C per decade, respectively).

5.2(A). Present Climate River Temperature Aldan Tributary



5.2(B). Present Climate River Temperature Upper Lena Tributary



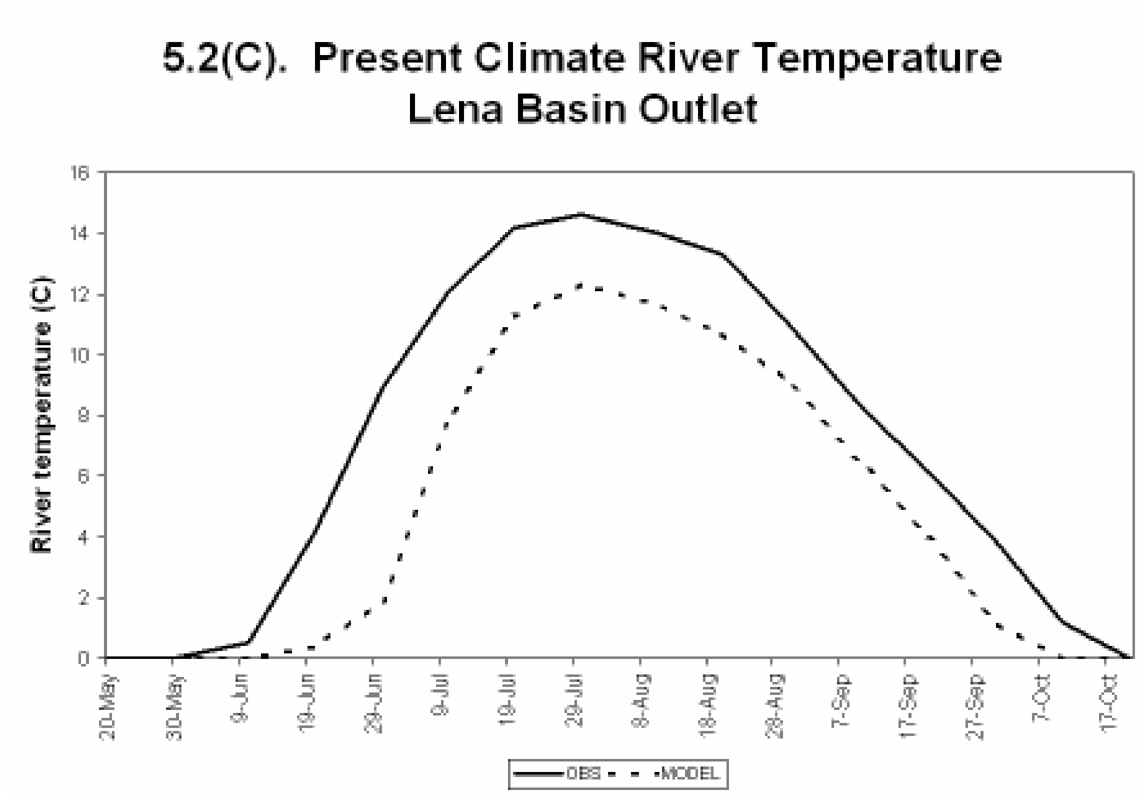


Figure 5.2 Observed and modeled Lena River temperature for the (A) Aldan Tributary, (B) Upper Lena Tributary and the (C) Lower Lena River Mouth. OBS: 1950-1992, MOD: 1961-1992.

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The model's warming trend is 0.16˚C and 0.14˚C per decade for 10 July and 20 July, but demonstrates a cooling trend of -0.3˚C per decade for 30 July. For 10 August, the observed cooling trend is -1.0˚C and the model's cooling trend is -1.3˚C. For the rest of the season (20 August to 10 October), the observations show cooling trends between -0.4˚C and -0.14˚C per decade. For this late summer period, the model still shows a warming trend between 0.2˚C and 0.9˚C. Yang et al. (2005) attribute the increasing/decreasing changes during the early/late ice free season to a shifting regime towards and early spring season. The model seems to account for the earlier seasonal warming, but may not be shortening the latter half of the summer season. While the model's present climate temperatures are lower than the observations for early and late summer, the seasonal profile is consistent with observations, including the peak in July; therefore the model serves as a good baseline from which to project future temperatures within the subbasin.

5.3.2 Upper Lena Tributary

The Upper Lena sub-basin, with an area of 897,000 km^2, contributes 42% of the total basin outflow (Liu et al., 2005). Figure 5.1(b) shows the observed and modeled (1950 – 1975) flow for the Upper Lena River station at Tabaga (61.83 N, 129.60W). As with the Aldan sub-basin, the monthly flow pattern is similar. Following winter, the observed flow in the Upper Lena tributary exhibits a sharp increase during May, leading to the peak flow in June. The model's flow is similar to the observed in this subbasin. The model's peak flow month occurs in June in agreement with the observed peak, and the overall monthly flow variability for the Upper Lena tributary is consistent with observations.

Figure 5.2(b) shows that the seasonal temperature variation is similar to that observed in the Aldan watershed; however, the average maximum river temperature occurs approximately 20 days later. Yang et al. (2005) found a similar trend (warming trends in the earlier months/cooling trends in later months), with the difference being that the warming trend was only found in the early season, and the cooling trend was in the mid to late season. The observations for the present climate show that river temperatures in the Upper Lena also range from below 1˚C to approximately 15˚C, and the average temperature is 8.1˚C. The mid-summer temperatures are stable between 17.7˚C and 18.6˚C, then in late summer, retreat from 17˚C to below 1˚C. The inter-annual variation is stable between 1.2˚C and 2.3˚C for most of the open water season (Yang et al., 2005). The model's standard deviations are slightly greater during the comparable mid-summer period (10 June through 10 October), ranging from 0.3˚C to 3˚C. Again, the present climate model replicates the daily temperature pattern and the observed seasonal temperature profile in all months but June, where temperatures were underestimated. It should be noted that the model consistently underestimates observed river temperatures in the summer months by between 1-2˚C. In June, the model underestimates observed temperature by more than 8.0˚C.

The analysis of the observations by Yang et al. (2005) confirmed statistically significant warming trends in early summer (20 May to 30 June), and cooling trends in mid to late summer (10 July to 20 October) between 1950 and 1992. The earlier observed warming trends of 0.14˚C to 0.7˚C per decade (significant at 93 to 98%

confidence) are again similar to the model's results of 0.14˚C to 0.9˚C per decade. The modeled temperature exhibits a cooling trend on 30 July and 10 August, followed by warming for most of the remainder of the season (20 August through 20 September). Here again, Yang et al. (2005) demonstrate through the observations an earlier spring melt. However, as with the Aldan, while the model's river temperature is lower throughout the open water season, the seasonal profile is similar. Further, while the absolute values are not replicated by the model, the simulations are consistent in their representation of the general observed pattern in both flow and temperature, with increases/decreases occurring at or near the dates seen in the observations.

5.3.3 Lower Lena Basin

The mouth of the Lena River is the point of discharge into the Arctic Ocean. River temperatures at the Kusur station (70.68E, 127.39W) play an important role in ocean mixing that occurs just downstream. Yang et al. (2005) note that the long-term temperature trends at the Lena's mouth are weaker than those evident in the observations at the upstream (southern) sub-basins. The characteristics are similar to those of the two subbasins, but are colder due to the more northern latitude. Lammers et al. (2007) still found that discharge into the Arctic has been increasing during the last 70 years. Figure 5.1(c) shows that while the model's present climate streamflow significantly underestimates June flow, the model's hydrograph is consistent with observations during all other months. The observed flow is very closely replicated in the model from January through May, and then again from July through December. The model's underestimation of total June streamflow may be related to the additional flow that is contributed by anthropogenic river management at the Vilui dam. As mentioned above, this dam is downstream of the two subbasin locations that we study in this paper, and river regulation through dam releases may account for this additional flow that is not captured by the model. Another factor related to the underestimation of summer flow is that the Lena's flow volume increases while the delta begins to form as it approaches the Laptev Sea; as such, tributaries that connect with the main river will contribute to the overall volume. The grid scale of the model may not account for the cumulative effect of the addition to smaller, higher order tributaries, hence the model's underestimation in summer river flow.

The observed river temperatures for the Lower Lena (Figure 5.2(c)) described in Yang et al. (2005) show increasing trends (approximately 0.24˚C per decade) during the early summer through June 20, which are in agreement with the upstream locations. The mid-summer observations (30 June and 10 July) demonstrate a cooling trend of approximately 0.24˚C per decade at the Lena's mouth, in contrast to the warming trends for this period at the upstream basin locations. This is followed by another observed warming trend (0.2 to 0.3˚C) from 20 July to 10 August. Other than warming for 30 September, no significant trends were detectable at the mouth of the Lena during late summer (August 20 forward). The model's trends at the Lena's mouth indicate a warming trend throughout the entire open water season. This is in contrast to the two upstream subbasins, where cooling trends are found during late summer. This is however, consistent with the observations, in which the trends were mostly increasing temperatures for all sample dates. The observed inter-annual variation at the Lower Lena is generally small, as the standard deviations are between 1.6˚C and 2.5˚C for much of the summer season. The model's standard deviations are in agreement as the values range from 1.1˚C to 2.4˚C between 30 June and 30 September.

Table 5.1 summarizes the differences in observed river temperature between the Lena River at the mouth (lower Lena) and the two upstream sub-basins (from Yang et al., 2005). In early summer, average river temperatures at the Lena's mouth were approximately 5˚C colder than the average temperature at the upstream stations. During mid-summer and late summer, the observed downstream temperatures were 4.0˚C and 2.7˚C lower, respectively. Part of this difference can be attributed to the colder surface air temperatures of the northern latitude/Lower Lena region. Another reason, particularly in early and mid-summer may be the result of increased summer snowmelt runoff. When average surface air temperatures are higher, this induces additional snowmelt runoff from the central region of the basin. This increase in snowmelt dominated runoff should be particularly apparent during the seasonal transition from April to May, when average surface temperatures shift from a below freezing range to above freezing. Moving to the summer months, as surface air temperatures peak and additional volumes of upstream snow is melted, the resultant infusion of colder fresh water into the watershed may decrease river temperature. In addition, warmer temperatures that affect permafrost contributions to freshwater were not explicitly considered in this study. Warmer surface air temperatures will increase spring and summer active layer thickness, contributing to significantly higher flow volumes throughout the open water season due to the release of additional water volumes that were previously locked in the upper layers of soil. The model may not be representing this permafrost contribution to runoff, therefore underestimating summer flow volumes.

Table 5.1. Observed open water Lena River Basin temperatures (deg.C) for the three locations for the early summer, mid -summer and late summer periods, 1950-1992. From Yang et al. (2005).

	Aldan	Upper Lena	Lower Lena
20-May	0.2	0.3	0.0
30-May	3.2	3.4	0.1
10-Jun	8.2	8.8	0.8
20-Jun	12.1	12.8	4.5
30-Jun	15.0	15.2	9.0
Early Summer Average	**7.7**	**8.1**	**2.9**
10-Jul	17.5	17.7	12.6
20-Jul	18.0	18.5	14.5
30-Jul	17.5	18.6	14.6
10-Aug	17.3	18.8	14.3
Mid Summer Average	**17.6**	**18.4**	**14.0**
20-Aug	16.0	17.0	13.0
30-Aug	14.0	15.0	10.5
10-Sep	11.6	12.2	8.3
20-Sep	9.0	9.5	6.1
30-Sep	6.3	6.6	3.8
10-Oct	3.0	3.2	1.6
20-Oct	0.5	0.8	0.2
Late Summer Average	**8.6**	**9.2**	**6.2**

It follows that the difference between downstream and upstream temperatures for early/mid summer are greater (colder) than the difference later in the season. Yang et al. (2005) and Liu et al. (2005) note that the long-term temperature trends at the Lena's mouth are weaker than those evident in the observations at the upstream (southern) sub-basins. Warmer trends (approximately 0.24˚C per decade during the period of record) are evident during early summer.

5.4 Projected Flow and Temperature through 21st century

In the section above, it was shown that the present climate the model performs well in representing monthly river flow and temperature at the three Lena River Basin locations during mid-summer, and does not perform as well in early summer. The model's ability to replicate the seasonal flow and temperature variability of the Lena River is consistent with observations. It is noted that as a basin where the flow and temperature are dominated by snowmelt, the model projects future climate (2081-2100) snow cover for the basin to decrease from present climate levels in the summer through early fall months. A future study can compare the model's representation of summer snow cover to observations to test this hypothesis. Figure 5.3 shows the model's projections for basin-wide percent snow cover for the present and future climate simulations. There is a projected decrease in snow cover beginning in April and May, and after the summer months, again in September and October. Figure 5.4 also shows the model's observed and modeled daily precipitation rate.

Fig. 5.3(A)

Aldan River Basin modeled percent snow cover:
Present (1951-2000) vs. future (2075-2100) climate simulations)

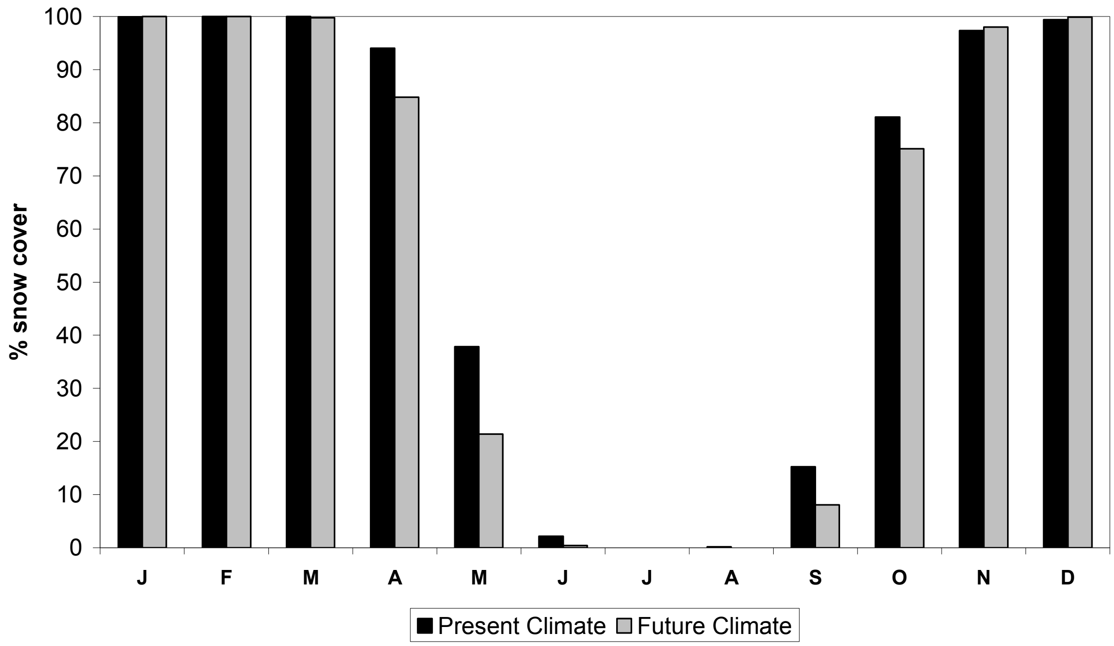


Fig 5.3(B)

Upper Lena River Basin modeled percent snow cover:
Present (1951-2000) vs. future (2075-2100) climate simulations

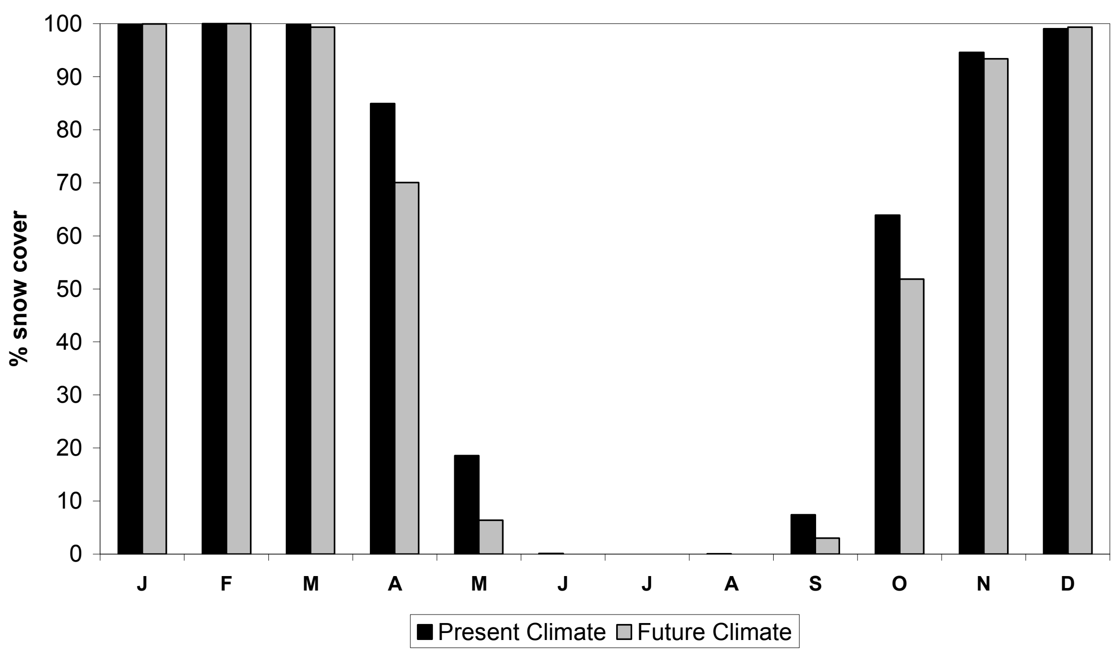


Fig 5.3(C)

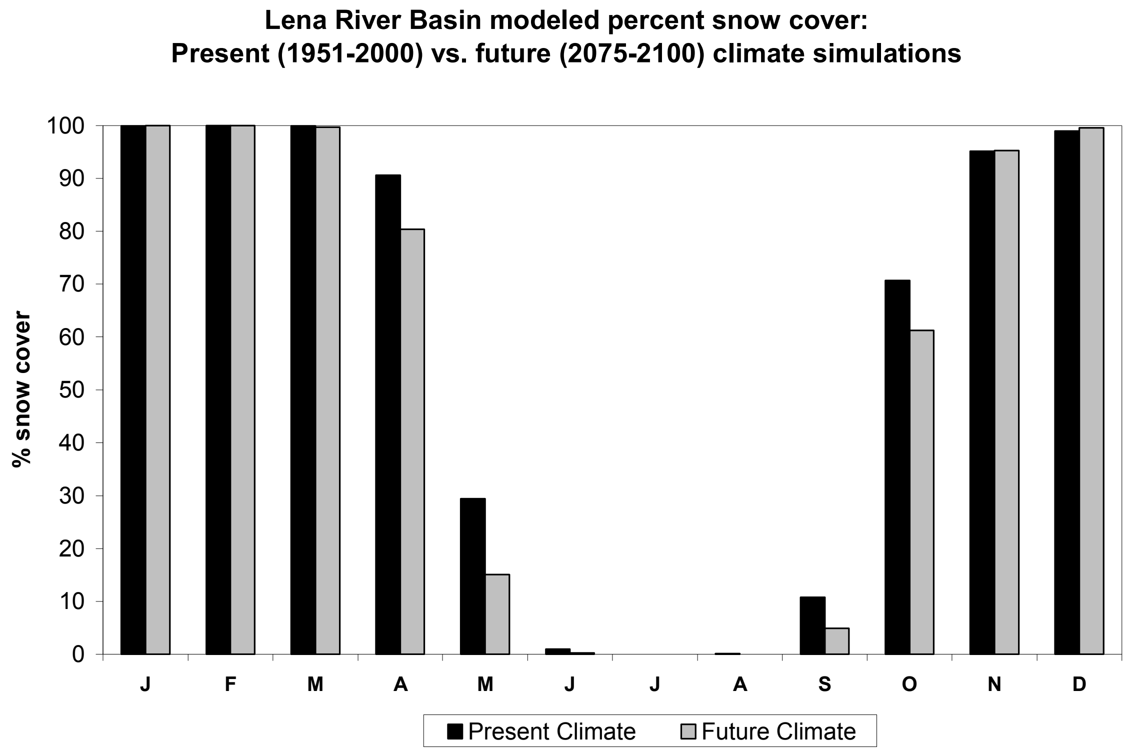


Figure 5.3. Modeled Lena River basin % snow cover for the present climate (1951-2000) and future climate (2075-2100) time periods for the (A) Aldan, (B) Upper Lena and (C) total Lena Basins. The model projects a decrease in snow cover and a later snow accretion in the future climate simulation.

Fig 5.4(A)

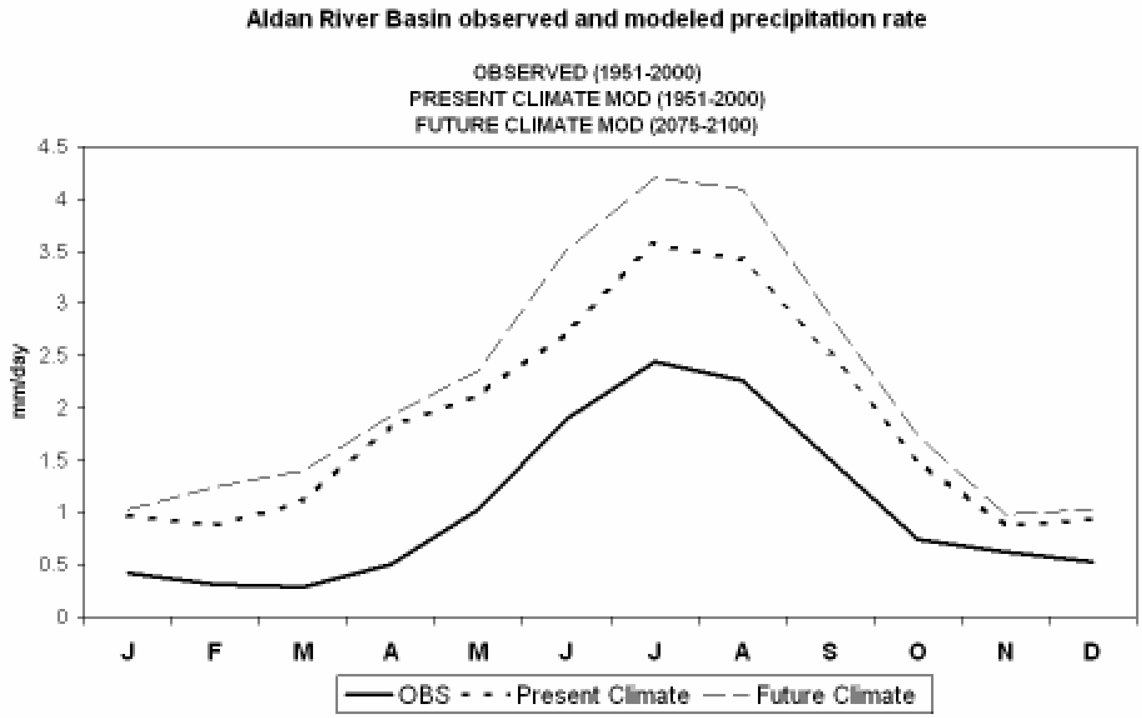


Fig 5.4(B)

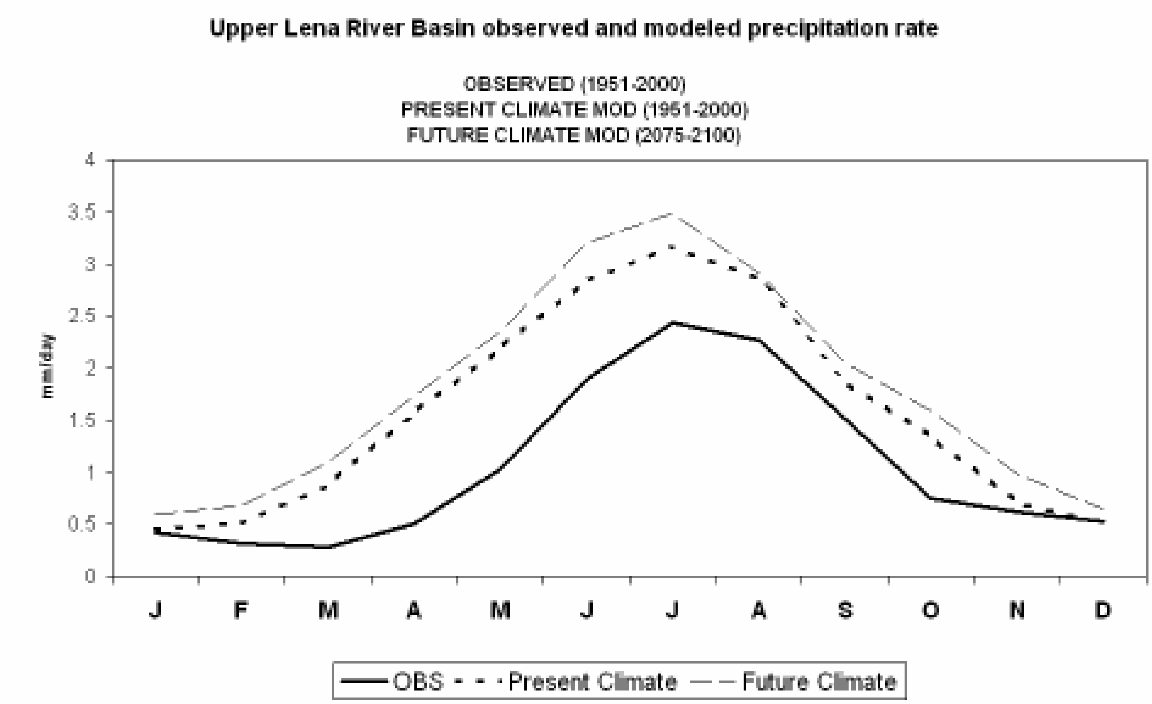


Fig 5.4(C)

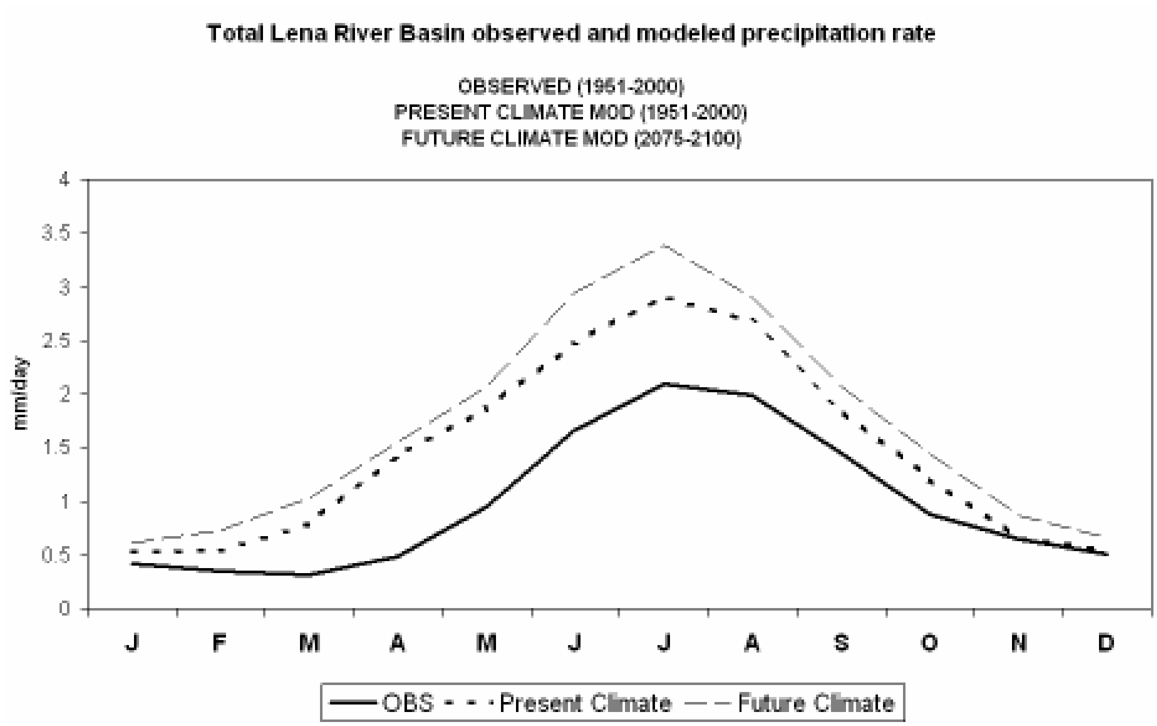
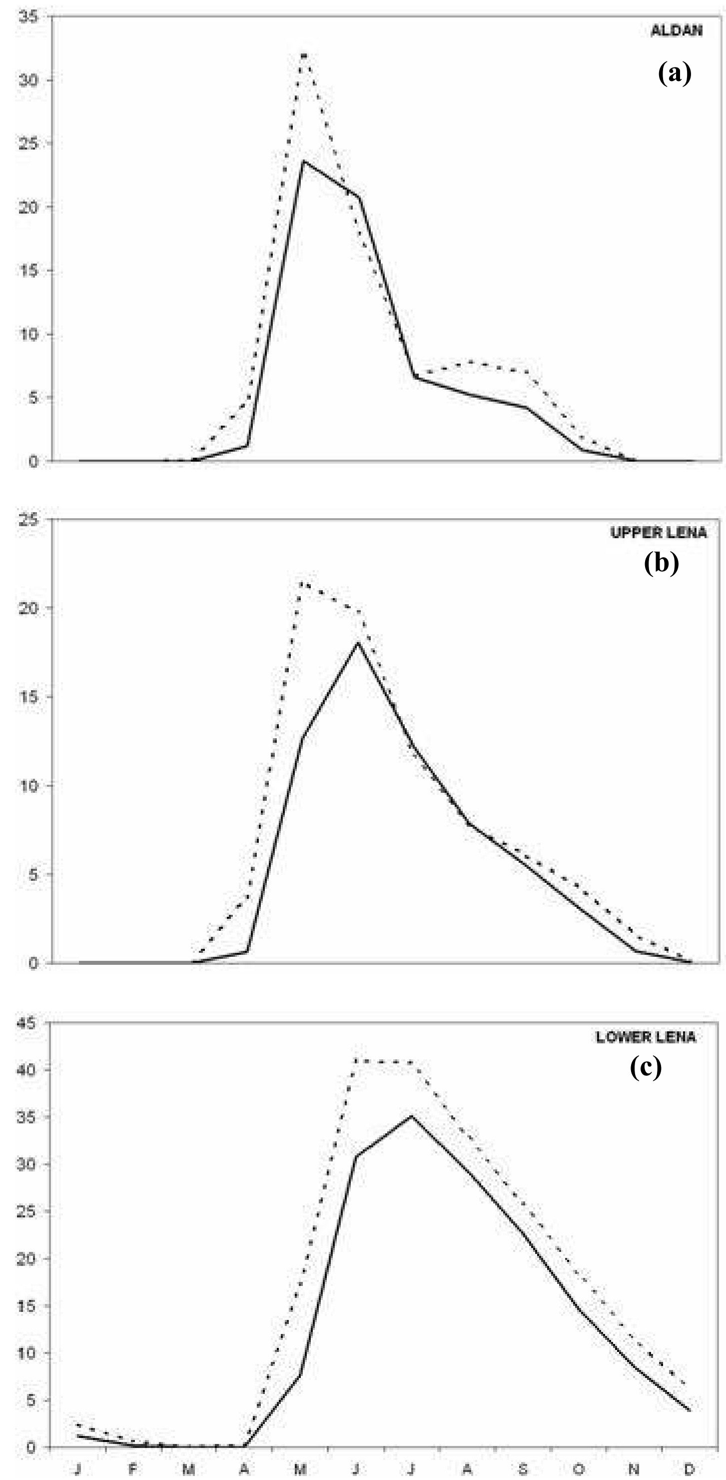


Figure 5.4. Observed and modeled Lena River basin precipitation rate for the present climate (1951-2000) and future climate (2075-2100) time periods for the (A) Aldan, (B) Upper Lena and (C) total Lena Basins. The model's precipitation field is too high for the summer months. Higher precipitation should contribute to an increase in summer streamflow during June through August.

Figure 5.4 demonstrates how the model's present climate precipitation rate (mm/day) is higher than the observed rate for the entire open water season. This does present a problem that will need to be studied as part of future research. It was discussed earlier in this chapter how the model's present climate flow at the basin's mouth is lower than the observed during the mid summer period. While it is reasonable to expect that the model's precipitation field is also lower, Figure 5.4 shows that the opposite is true. When extending the model's present climate results to 2100, it is noted that this is an area that will require further investigation, in order to more accurately project the basin's future hydroclimatology. In addition, while the modeled river temperatures are lower than observed, the overall pattern is similar with the exception of the month of peak temperature in the Lower Lena. The analysis is now extended by examining how the model projects river temperatures in the Lena Basin to change by the end of the 21st century. In addition to river temperature, the model's projections of future river flow at each of the locations for the same period is included.

5.4.1 Aldan Tributary

The projections of flow for 2081-2100 in the Aldan tributary are shown in Figure 5.5(a). The Aldan's flow is projected to be higher than for the present climate in April and May, similar for June and July, then higher again between August and November. The largest projected increase occurs during May, where the projected flow is approximately 40% higher than the present climate. The model's monthly future flow pattern is similar to that of the present climate, and the peak flow month (May) does not



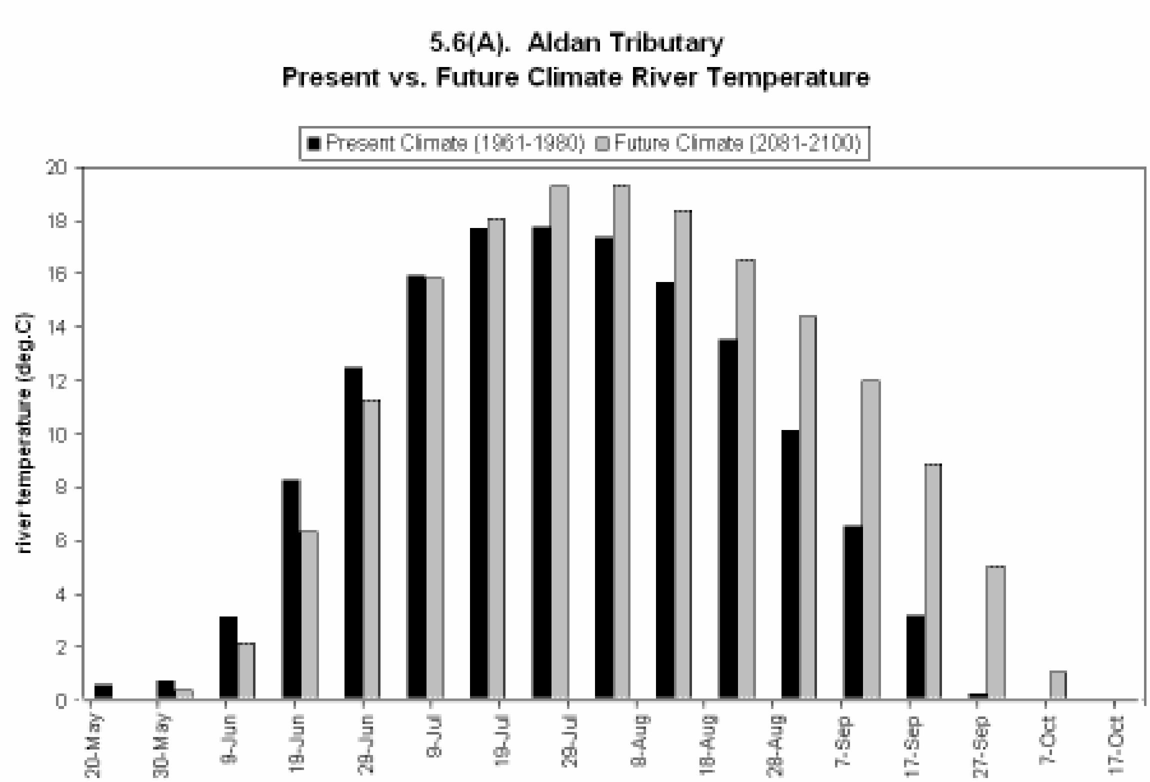
___ present climate _ _ _ _ future climate

Figure 5.5. Lena River basin projected flow for the end of the 21st century as compared to the present climate.

change between the 20th and 21st century simulations. As noted in Figure 5.1, the observed peak flow occurs in June, so the model generates peak flow one month early.

Projections of river temperature for the Aldan Tributary are notable, particularly for the early and late summer periods. Figure 5.6(a) shows the model's present and future climate river temperatures, and Figure 5.6(b) shows the projected changes at the same 10-day increments described in the previous section. The future climate river temperatures are consistently higher throughout the mid and late periods of the open water season, with the largest projected increase of 5.5˚C projected for late September. Following the early summer when the model temperatures are expected to be lower than the present climate, the temperature increases get progressively larger for each 10 day period through early October.

When the standard deviations for the present and future climate are compared, the interannual variability for both periods was found to be similar. Standard deviations for the present climate are 1.7˚C, 1.9˚C and 1.0˚C for the early, mid, and late summer periods, respectively. These compare to the future climate standard deviations of 1.8˚C, 1.9˚C and 1.1˚C for the same periods. Figure 5.7 depicts the July time series model temperatures for all three rivers from 1950 to 2100. Over this 150 year period, the Aldan River's July temperature is expected to increase at a rate of 0.24˚C per decade. The minimum July temperature is modeled to be 12.3˚C, and the maximum temperature is 20.9˚C (standard deviation of 1.8˚C). This analysis highlights another potential problem with climate change and future river dynamics. The Lena currently freezes during the early fall period, and the model accounts for this freezing. However, the model does not project the future Aldan river temperatures to cross the freezing threshold until



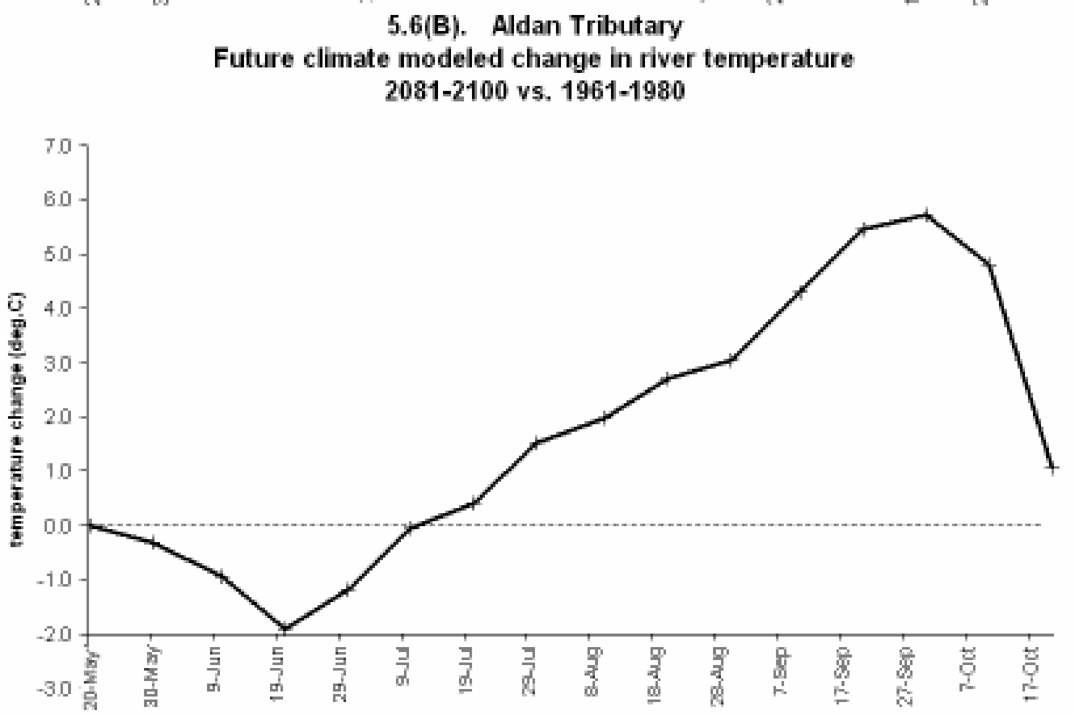
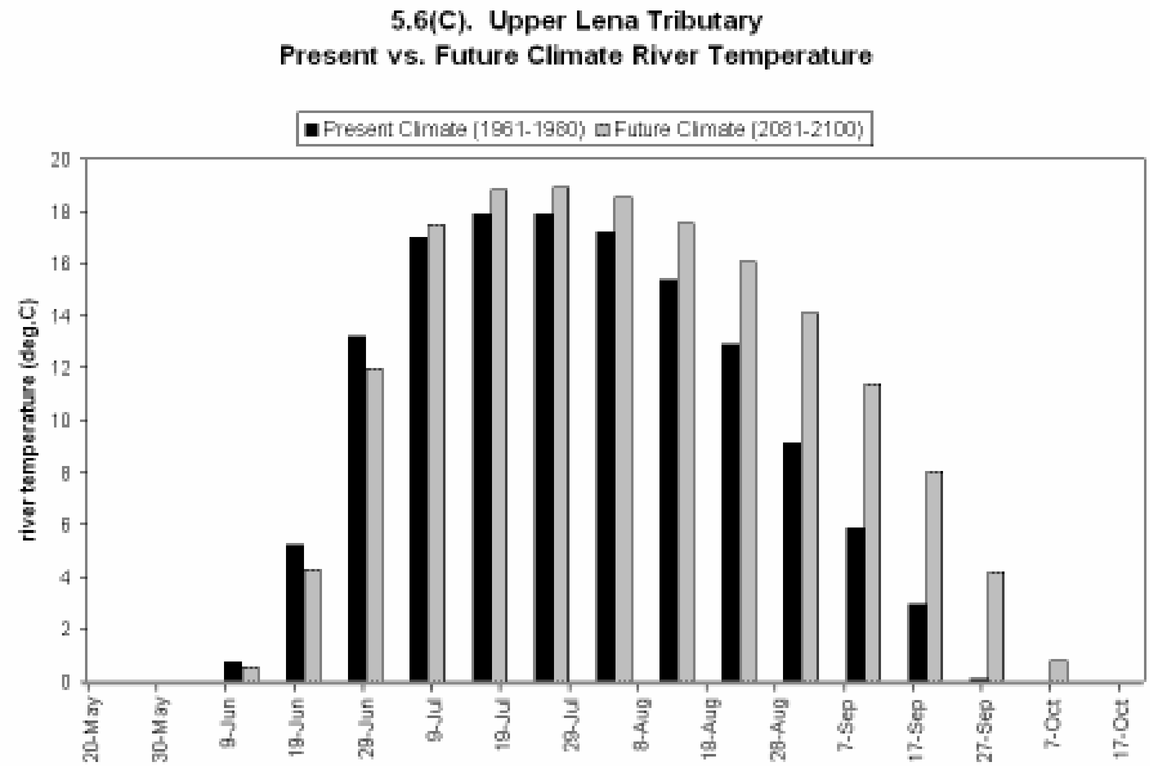


Figure 5.6(A-F). 5.6(A) shows the present and future climate river temperatures for the Aldan Tributary, and (B) is the projected river temperature changes for the end of the 21st century, compared to the present climate.



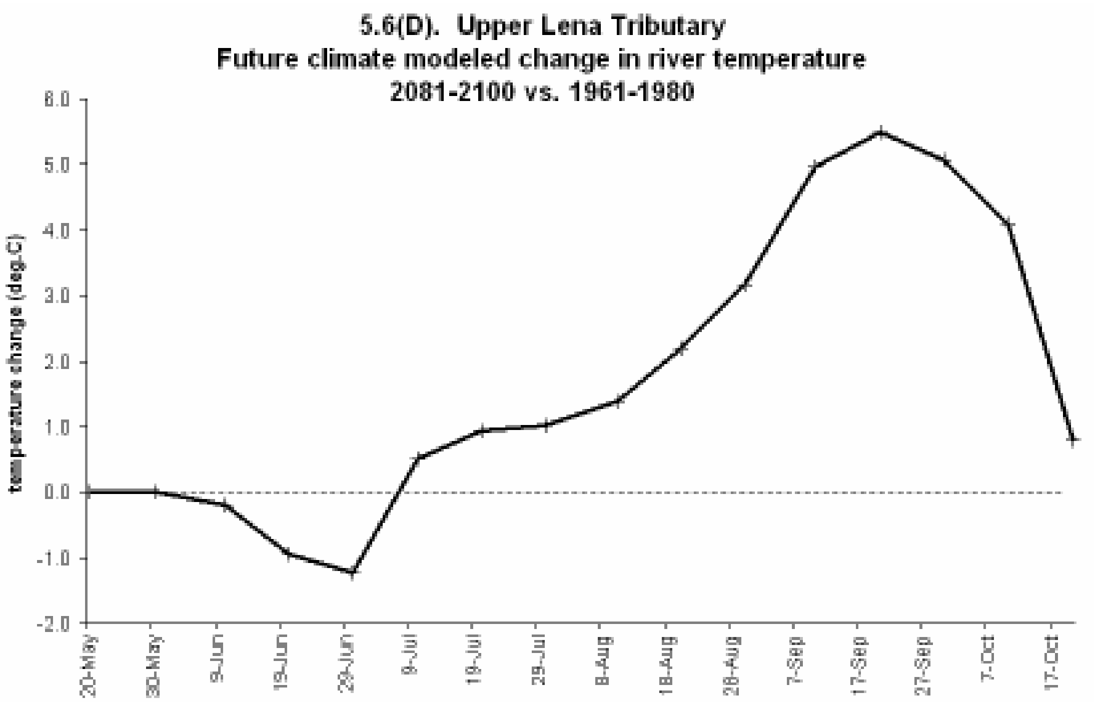
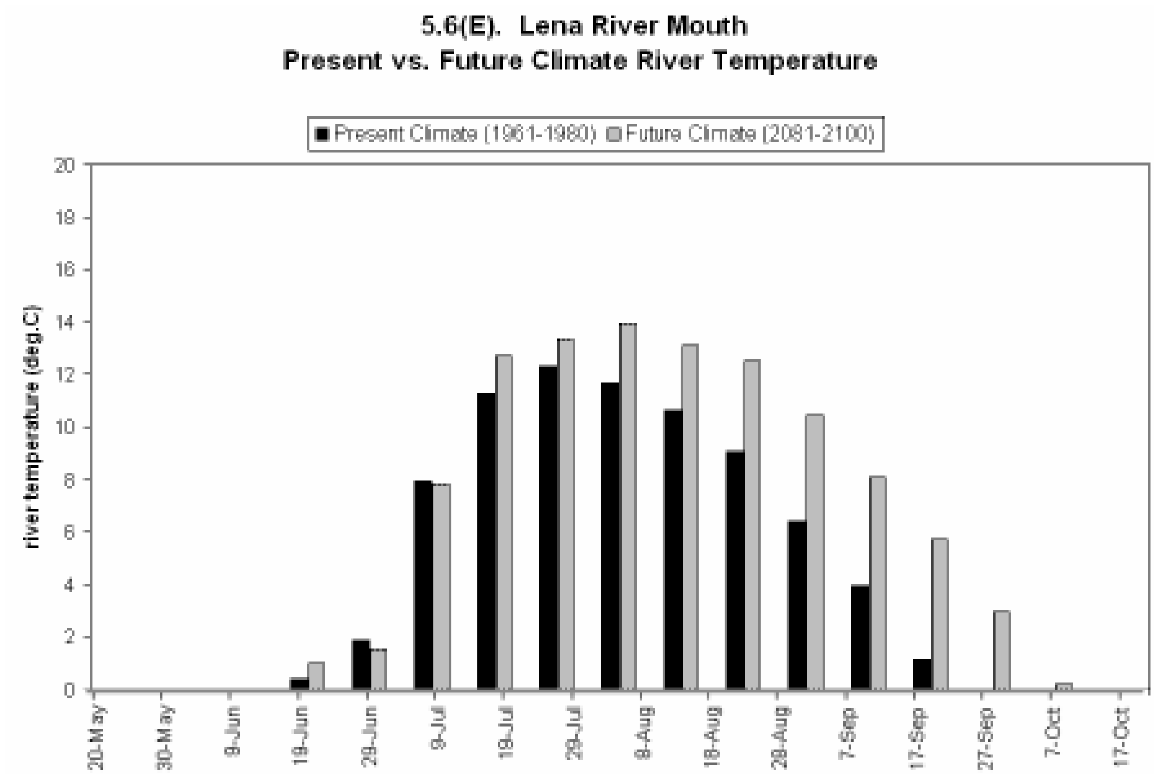


Figure 5.6(A-F). 5.6(C) shows the present and future climate river temperatures for the Upper Lena Tributary, and (D) is the projected river temperature changes for the end of the 21st century, compared to the present climate.



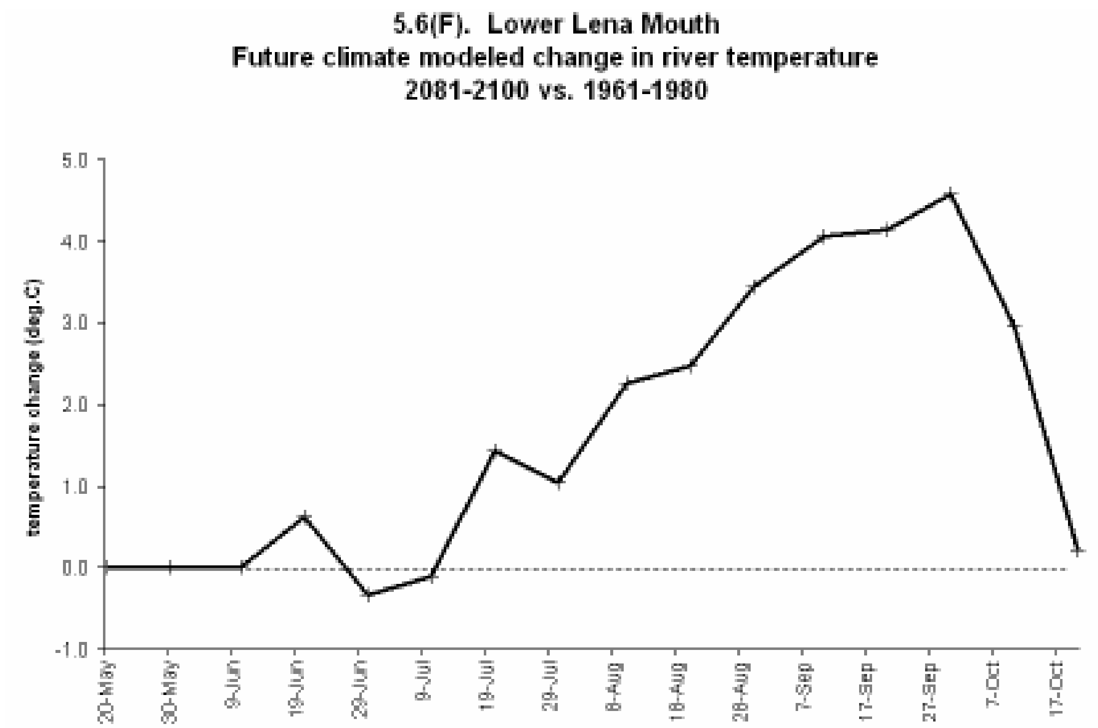


Figure 5.6(A-F). 5.6(E) shows the present and future climate river temperatures for the Lower Lena mouth, and (F) is the projected river temperature changes for the end of the 21st century, compared to the present climate.

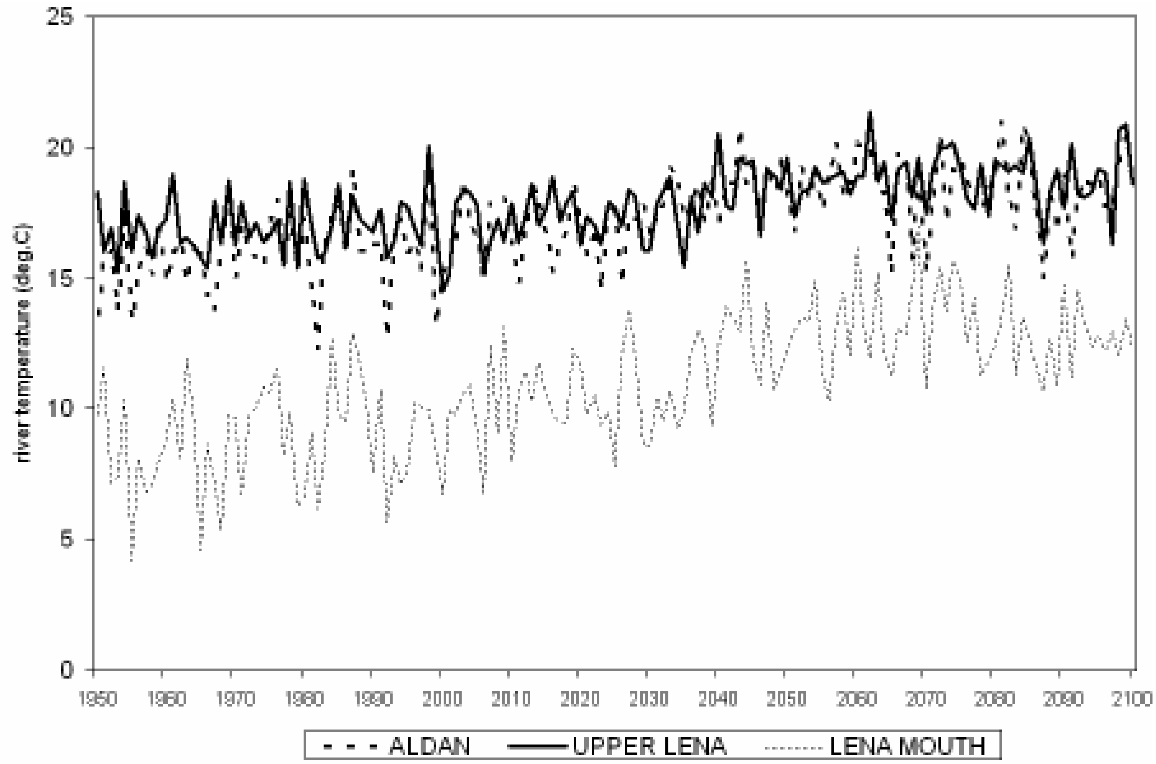


Figure 5.7. July Modeled River Temperatures for the Lena River at the mouth and the two upstream subbasins, 1950-2100.

November. This change in late season river thermal dynamics can be a significant change to the basins hydrologic regime. There could also be ecological impacts, similar to those discussed above in the Fraser River analyses. Examining the potential ecological impacts of targeted species in the Lena basin could be the focus of another study.

5.4.2 Upper Lena Tributary

The results for changes in flow in the Upper Lena are shown in Figure 5.5(b). Again, the late 21st century river flow is projected to be higher than 20th century flow, particularly in the first half of the open water season. The model projects monthly flow to peak in May, which is one month earlier than the June peak for the present climate. Flow increases the most during the April through May period, and after June, the flow is similar to that for the present climate, which is similar to the Aldan tributary.

As with the Aldan River, the model scenario for the Upper Lena Tributary produces an increase in river temperature above the present climate for approximately 2/3 of the open water season, as seen in Figure 5.6(C). The largest projected river temperature increase of +5.5˚C again occurs in late September (20 September), and the future climate shift towards significant warmer water deviations is more apparent during late summer, as seen in Figure 5.6(D). The projected interannual variability for all three summer periods is again similar to that of the present climate. The respective present climate standard deviations are 2.1˚C, 1.6˚C, and 1.1˚C for the early, mid, and late summer periods. Future climate standard deviations are 1.8˚C, 1.9˚C, and 1.0˚C for the same periods. In Figure 5.7, the projected rate of July temperature increase of 0.19˚C per decade over the 150 year period for the Upper Lena is similar to that of the Aldan

(0.24˚C). The interannual variability is projected to be slightly lower, as the standard deviation is 1.4˚C. Both of the Lena's subbasins do exhibit a sharper increase in temperatures in the latter half of this period, indicating that a more pronounced warming of upstream river temperatures is expected for the 21st century. The late summer contributions of warmer freshwater to the basin's mouth will affect the timing of ice formation, as well as influence the thermal profile in the Laptev Sea.

5.4.3 Lower Lena Basin

The projections for river flow at the mouth of the Lena Basin for the future climate period are compared to the present climate in Figure 5.5(c). The two time periods exhibit similar flow characteristics in the early months of the year, which are characterized by little to no river flow as a result of the more northern location's colder conditions. In May, the model produces more river flow at the basin' outlet, and higher flow rates are higher through December. The model's peak flow month is in June, one month earlier than the present climate peak flow (this is similar to the Upper Lena). The 21st century July peak flow rate is 17% higher than the present climate June peak flow.

The future climate results at the mouth of the Lena projects consistent river temperature increases over the entire ice-free season through 2100, seen in Figure 5.6(E and F). The largest modeled late 21st century temperature increase of +4.6°C occurs on 30 September. One feature that is different at the basin's mouth (vs. the two upstream subbasins) is that there is only one week where the model's future climate simulation projects lower river temperatures than those for the present climate (30 June). This suggests that river temperatures may be more sensitive to climate changes at higher latitudes. For August and September, the projected future river temperatures are approximately 3.5°C higher than those from the late 20th century. The outlook from this experiment is for consistently higher temperatures for the ice free season at the basin's outlet, with the largest projected temperature increase projected for early summer; future climate river temperature is expected to be approximately 2.1˚C higher than that of the present climate between early June and early October. As described in the two upstream subbasins, the interannual variability is not expected to change significantly, with the respective early, mid, and late season standard deviations for the present climate being 1.4˚C, 2.5˚C, and 0.9˚C. For the same periods, future climate standard deviations are expected to be 1.5˚C, 1.7˚C, and 1.2˚C.

While the upstream locations are important, it is the conditions at the mouth which are most valuable in understanding from the perspective of the Lena's thermal discharge load, and the potential implications on ice formation and the late season freshwater influx. The model's July temperatures at the basin's mouth demonstrate a more significant temperature increase by the end of the century. The rate of change at the mouth is 0.4˚C per decade, and the variability is much greater as the standard deviation for the July temperatures is 2.5˚C, vs. 1.8˚C and 1.4˚C for the Aldan and Upper Lena, respectively. When the projections are compared to those for the upstream subbasins, in early summer the observed river temperatures at the Lena's mouth are about 6˚C colder than the average temperature at the upstream stations. During mid-summer and late summer, the observed downstream (northern) temperatures are about 3.0-4.0˚C lower than that of the subbasins. Further, the largest projected temperature change between the present and future climate at the mouth occurs in late August and early September.

Recent papers have documented the rapid decline in Arctic ice cover (Stroeve et al., 2007), while others discuss the possibility of a 'Blue Arctic' during the 21st century (Comiso and Parkinson, 2004; Meier et al., 2005); as the model suggests that the warmer Lena River temperature by the end of the century are significantly above those from the present climate, the results from this study may be one contributing factor to such a Blue Arctic scenario, and therefore require further investigation.

5.5 Summary and Discussion

In this chapter modeled river flow and temperature were compared with observations for the present climate, followed by an analysis of how the physical variables have changed during the last half of the 20^{th} century for two sub-basins and the basin outlet within the Lena River basin. The GISS global climate model was then applied to project how the river temperature might change in the future in response to increasing atmospheric greenhouse gases. Included in this analysis was an assessment of the model's ability of the model to replicate future flow. While the model performs better for some basins than for others, the results for the present climate are generally consistent with observations. It is noted again that there has been no model tuning of river flow or temperature specifically for the Lena, or any other, river basin.

The observations collected during the 20^{th} century show that peak river flow for all three locations in the Lena basin occurs in June. The model overestimates early season flow in the Aldan, and underestimates mid to late season flow at all three locations, but it does well in replicating the seasonal river flow pattern. The model's river temperature is lower than observed summer river temperatures throughout the basin by approximately 1˚C to 2˚C, with the exception of June where the underestimation is larger. The model produced consistently higher summer river temperatures (approximately +4.0 to +6.0˚C higher than present climate) at all three upstream locations for the late summer period, and less significant increases during mid summer (+2.0 to +3.0˚C

The model's monthly present climate generally underestimates river temperature early in the open water season during the spring summer transition, but then does well in representing mid to late summer river temperatures at each of the three locations, with the most difficulty at the Lena outlet. However, even though the temperature projections may be lower, the seasonal progression of increasing/decreasing water temperature is replicated. This is a starting point in making projections about the basin's hydrology at the end of the century.

As polar regions play key roles in global environmental processes, it is important to understand the observed trend of increasing temperatures for rivers discharging into the Arctic Ocean from an ecological as well as a commercial perspective. Changes in river temperatures will likely impact the biological systems (Durance and Ormerod, 2007) in this environment; warmer waters will allow species which were not suited to warmer temperatures to adapt and expand their habitat into more northern locations. Therefore, it is appropriate to begin to assess these potential hydroclimatological changes and provide the societies that depend on these natural resources sufficient time to adapt. The model's summer temperatures follow a similar pattern to the observations, so the difference between late 21st century and late 20th century simulations can be used as a baseline for how summer river temperature might change under current greenhouse gas projections through the end of the 21st century. While our results provide some insight on how global climate models might be used to investigate specific hydrologic changes resulting from future climate scenarios, there is still a great deal of future work to be performed in this area. Two areas that were not fully examined in this study are (1) the role of the Vilui subbasin in the Lena basin's hydrologic profile, and (2) projected changes in permafrost, and how this will affect flow rates and water temperatures. Our analysis can be extended to other mid and high latitude river systems in an effort to project the potential effects of climate change on the behavior of all of the world's large river basins as well as to identify the potential biological and economic effects that may accompany these changes.

Chapter 6

CONCLUDING REMARKS AND FUTURE RESERACH

As more evidence for global climate change is added every year, there is no shortage of basic or applied research topics that relate the observed climatic changes to other environmental systems or variables. The purpose of this dissertation has been to focus on an important component of applied climatology that is receiving less attention – the effects of global climate change on river temperature. This component of global change studies has been underrepresented in the literature, and the intent of the research has been to build upon the few comprehensive analyses that have already been performed. Changes in river temperatures associated with climate change can affect ecological, economic and human health. Therefore, understanding potential hydrologic changes and the effects they may exert on other environmental systems is important, and timely. For this dissertation, I have presented an overview of the observed 20th century river temperature trends at one mid-latitude and one high latitude basin, and then projected future river temperatures to the end of the 21st century. Earlier studies which have focused on identifying the observed trends in the Fraser and Lena River basins have been extended along with projections of how the thermal regime may change in these basins by 2100.

I started by examining the monthly summer temperature trends in the Fraser River basin. The observed summer temperature trends from Morrison et al. (2002) were compared to the model's temperatures, with favorable results. Morrison et al. (2002)

discussed observed trends in 20th century Fraser River flow and temperature, and used an offline modeling approach to project long term river temperatures. Among their findings, were earlier peak flow milestones (0.11 days and 0.09 days earlier each year for one half and one third annual volumes, respectively) between 1913 and 2000, as well as an increasing river temperature trend of +0.22°C per decade between 1953 and 1998. Their model results identified positive river temperature trends, particularly in the 2070-2099 time period; they project mean summer water temperature to increase by 1.9°C. Morrison et al. (2002) also noted the potential for more river temperatures above 18°C; specifically, they note that the results of their model projections for the 2080 period, indicate that mean monthly temperatures at the start of the season in early July are approximately 17.6°C, which is higher than the observed baseline mean temperature (which is approximately 17.6°C) for the entire summer season. Water temperatures above this threshold begin to pose a threat to the health of Pacific salmon, a commercially important species in North American fisheries by degrading spawning success.

This work was extended by projecting river temperatures through the end of the 21st century with an online modeling approach. The model results show an increase of approximately 2.0°C above the present climate for both July and August monthly temperatures between 2075 and 2100. As the model projects Fraser River temperatures to increase in the coming decades, identifying the temperature extremes becomes an important question. This served as one of the focal points for the next phase in the research, which included an examination of daily river temperatures. Monthly averages tend to smooth out the extremes (both positive and negative), and critical biological temperature thresholds are not able to be identified in monthly time series. As such, a daily time series is more valuable if the objective is to examine the likelihood of temperatures to exceed certain physiological thresholds.

The next phase of the research extended the work on monthly temperatures by examining daily river temperature and flow profiles, and again projecting conditions through 2100. Observed and modeled daily flow for the present climate period are in good agreement between June and September. While the modeled daily temperatures are higher than the observations, they are comparable, particularly in mid to late summer, which is the most crucial time period for salmon survival in the Fraser River. When future climate river temperatures were analyzed, it was shown that the model projects higher river temperatures throughout the entire summer season. In addition, the number of days where river temperature exceeds the important physiological threshold temperature of 18.0°C increases significantly in the future climate scenario. The model's present climate temperatures (1961-1980) exceed 18.0°C 3.8 days per year, while the future climate (2081-2100) projections is for 21 days per year. While mean temperatures are expected to increase, variability, as measured by the standard deviations, is expected to decrease under future climate conditions.

The final experiment maintained the theme of studying climate induced late 21st century river temperatures, but moved to a high latitude basin. Among the few studies that have focused on long term analyses of observed river temperatures for Eurasian rivers, Yang et al. (2005) and Lammers et al. (2007) documented late 20th century changes in river temperature within the Lena River basin. The work of Yang et al. (2005) have been extended in this dissertation by replicating the observed present climate river temperatures using the model, and expanding their findings by projecting temperature in the Lena basin through 2100. The model underestimates the present climate Lena River Basin temperatures at the mouth and the two upstream subbasins, but does simulate a similar seasonal profile during the 'open-water' season. For the Aldan and Upper Lena tributaries, the model's present climate temperatures are similar to the observations during the mid summer period; however temperatures at the mouth are consistently lower. Looking to the late 21st century projections, the model produces an increase in river temperatures at all three locations for the mid and late summer periods during the open water season, with the most pronounced increases occurring in September The model projects the largest temperature increase between 20 and 30 September, where river temperatures are projected to be between +4.6°C and +5.5°C above that of the present climate. The results for the entire Lena basin suggest a longer open water season which can have effects on the thermal profile at the Lena's outlet.

The goal for this dissertation research was to build upon the relatively sparse literature at the interface of climate change and river temperature modeling, as few studies have examined potential changes in freshwater systems as a result of anticipated climate change. I have already begun extending the work contained in this dissertation by collaborating with researchers at the Fisheries and Oceans/Canada research unit. This group is attempting to project how anticipated changes in climate and river thermal characteristics in the Fraser basin will affect salmon fitness in the coming decades. Morrison et al. (2002) specifically addressed the impacts of elevated temperatures to salmon health, and this work will provide the foundation in constructing regionally specific population models, and river management schemes.

Future work that utilizes the model's projections as a foundation can be applied to numerous commercially or ecologically important problems. Analysis of observed trends and predictions of the future arctic water balance will result in a better understanding of the many interacting forces which contribute to northern hemisphere freshwater temperature and discharge. Assessing the economic and social impact of the anticipated changes will be an important topic in the coming decades, and this work will serve as a starting point in synthesizing all of these related topics, both in establishing baseline trends as well as projecting how conditions will change by 2100..

These are just a few of many reasons that highlight the need to better understand future freshwater conditions under changing climate conditions. Mid and high latitude river systems such as the Fraser and Lena basins are important components in the global freshwater cycle, and the methods used in this dissertation should also be extended to other large river basins. So, one of the primary questions guiding the research for this thesis is this: How might future climate change affect river characteristics in all of the world's major mid/high latitude basins? Future work should not only focus on the anthropogenic driving mechanisms, but also the physical forcings, such as the North Atlantic Oscillation and ENSO events. As with any study on future climate, this dissertation is only a starting point, as each section only generates more questions. The questions that have come out of this work keep the science moving forward, and also strengthen the interdisciplinary ties within the Earth System Sciences. Some portions of the work fall under basic research, while others are more applied. It is this multifaceted nature of global hydroclimatology, which blends the basic and applied sciences that makes the field intellectually stimulating, and vital for the survival of modern culture as well as the integrated global economy.

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SELECT PUBLICATIONS

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Global Climatology and 2008/09 Sugar Production. SugarAsia 2008. New Delhi, India, July 2008.*

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