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Climate Change in the Fraser River Watershed: Flow and Temperature Projections

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Abstract

An analysis of the historic flows and water temperatures of the Fraser River system has detected trends in both the annual flow profile and the summer temperatures. This study was undertaken to determine if these trends are likely to continue under the conditions predicted by various global circulation models. To do this, existing flow and temperature models were run with weather data that were derived from actual weather observations, but modified using changes predicted by the global circulation models.

The validity of the flow model results is supported by very close agreement with the historical record. The differences between model output and the historical record for mean flow, mean peak flow, mean minimum flow and peak flow day were not statistically significant; furthermore, there was only a 3-4 day shift in the occurrence of cumulative flow milestones. The temperature model's mean water temperature was only 0.2° C higher than the historical record.

For the period 2070 – 2099 the flow model predicted a modest 5% (150 m^3/s) average flow increase but a decrease in the average peak flow of about 18% (1600 m^3/s). These peaks would occur, on average, 24 days earlier in the year even though for 13% of the years the peak flow occurred much later as a result of summer or fall rain, instead of the currently normal spring freshet. In the same period the summer mean water temperature is predicted to increase by 1.9° C. The potential exposure of salmon to water temperatures above 20° C, which may degrade their spawning success, is predicted to increase by a factor of 10.

Trends in both flow and temperature in this study closely match the trends in the historical record, 1961 to 1990, which suggests that the historical trends may already be related to climate change. While the mean flow of 2726 m^3/s does not show a statistically significant trend, the hydrological profile has been changing.

Keywords: climate change, Fraser River, runoff, temperature, fish,

1 Introduction

Draining a watershed of approximately 217,000 $km^{2,}$ the Fraser River is the largest Canadian River that flows to the Pacific Ocean. With headwaters near Jasper, Alberta in the Rocky Mountains, the Fraser flows for 1370 km before it discharges into the Strait of Georgia Near Vancouver (Thompson 1981). The Fraser River watershed is a major spawning ground for Sockeye and Chinook Salmon, accounting for the majority of the Canadian stocks (DFO[1] 1999, DFO[2] 1999). Sockeye Salmon begin their lives in spawning beds distributed throughout the watershed. Eggs laid in these beds hatch in the following spring. After spending the next year in fresh water, they move into the ocean for a period of 2-3 years after which time they return to their original natal streams where they spawn and then die. On the migration back to the spawning beds the salmon are sensitive to the river water temperatures and there is a strong correlation between prespawning mortality and high river temperature (Gilhousen, 1990; Rand and Hinch, 1998; Williams, 2000). Temperatures between 22°C and 24°C over a period of several days can be fatal for salmon (Servizi and Jensen, 1977) and temperatures over 24°C can cause death within a few hours (Bouke et al., 1975).

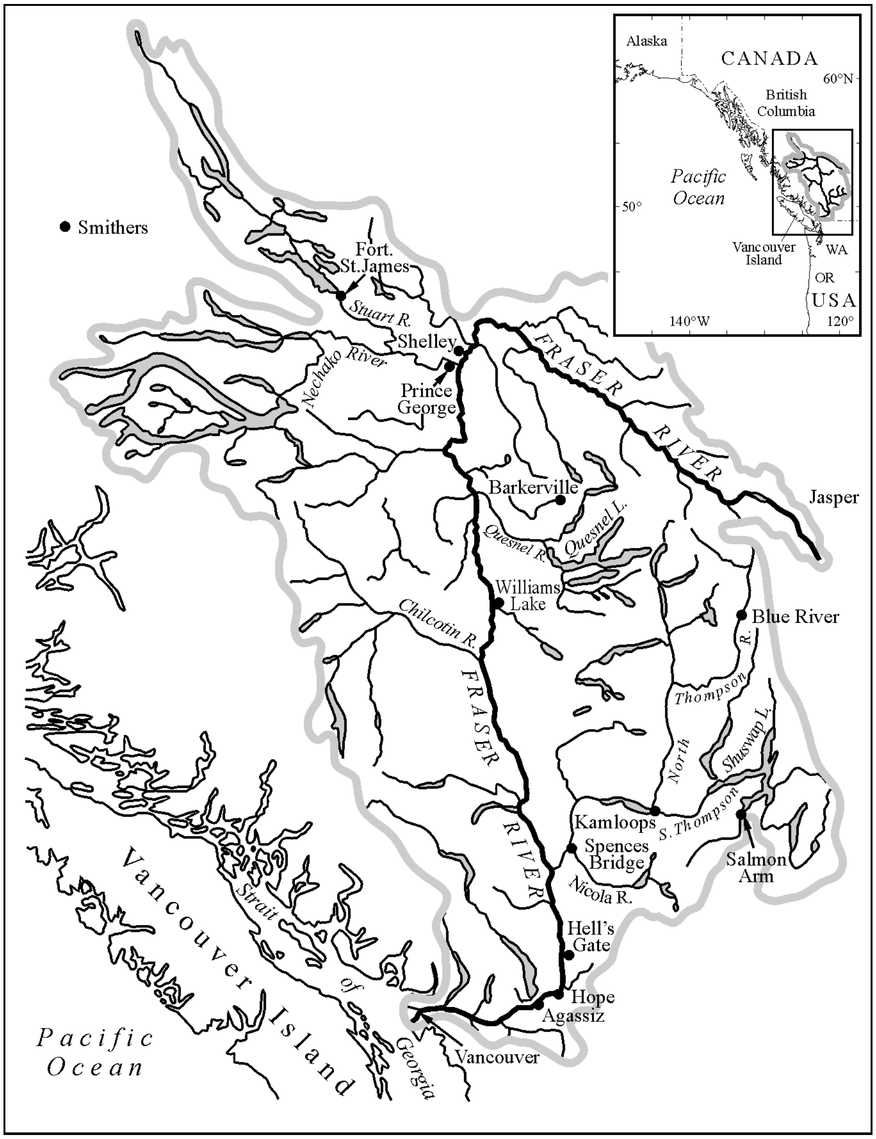

Fig. 1. Fraser River watershed

Even water temperatures as low as 20°C can have an adverse affect on spawning success rates (Gilhousen, 1990).

Daily flow records recorded at Hope since 1912 indicate that the Fraser River has been changing. The Julian day numbers by which one-third and one-half of the integrated yearly discharge occurred have been transpiring earlier (Fig. 2) in the year and the summer water temperatures have been increasing (Fig. 3) (Foreman et al. 2001). The river flows are highly seasonal with winter lows at Hope often below 1000 m^3/s and peak flows typically occurring in mid June in the range of 9000 m/s. These flows are primarily generated from seasonal snowmelt. The lowest flow recorded between 1913 and 2000 was 340 m^3/s on Jan. 8, 1916, while the highest recorded level of 15200 m^3/s occurred on

May 31, 1948 during a period of extensive flooding of the lower Fraser River.

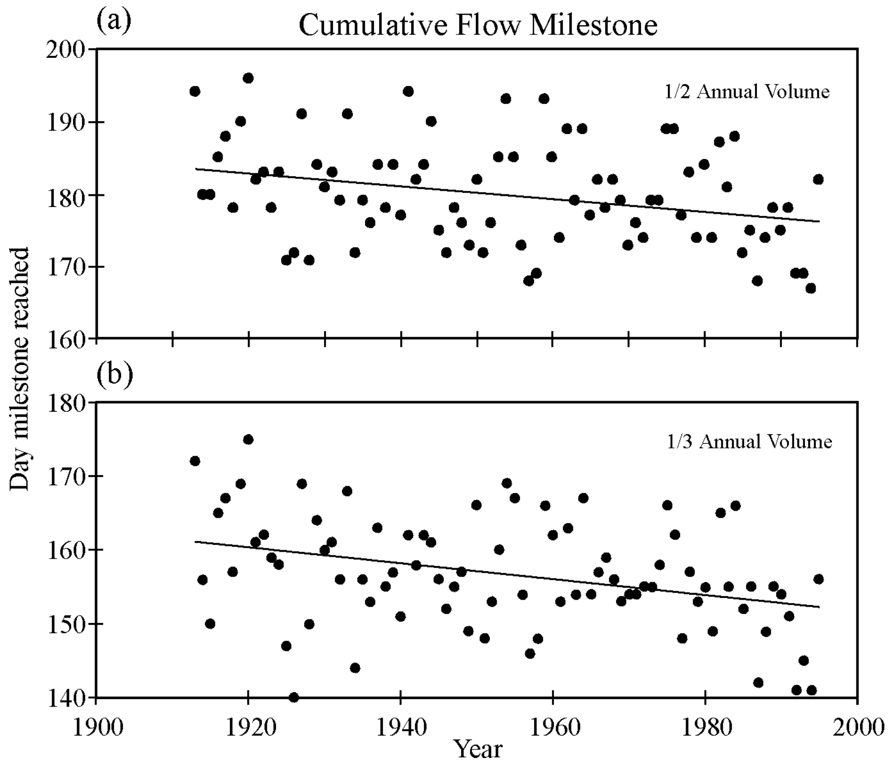

Fig. 2. Days of the year by which one-third and one-half the integrated yearly Hope discharge has occurred. Trend analyses suggest earlier progressions at the rates of 0.11 and 0.09 days per year, respectively with the statistical significance > 95% in both cases.

Summer water temperatures have been recorded manually at Hells Gate since the early ‘40s. Typically these recordings were made from July 1 through Sept. 15 but unfortunately in the early years there was much missing data. In this paper the river temperature comparisons are based on the manual data collected at Hells Gate between 1961 and 1990. Recently this activity was supplemented by the installation of an automatic data recorder at Qualark, a few kilometres down stream from Hells Gate. Of all of the summer river temperatures recorded at these locations, the highest was 21.2 °C occurring on Aug. 3, 1998, and the lowest was 11.0 °C recorded on July 1, 1955. Restricting the analysis to the time span when records are almost contiguous (i.e. 1953-1998), it was found that the summer mean temperature, which ranges from 15 °C –19 °C, was increasing at a rate of 0.022 °C per year with a significance of 98%. Fig. 3 shows the latest available summer mean temperatures with their linear trend line. This line has a slope of 0.018 °C per year with a significance of 95%.

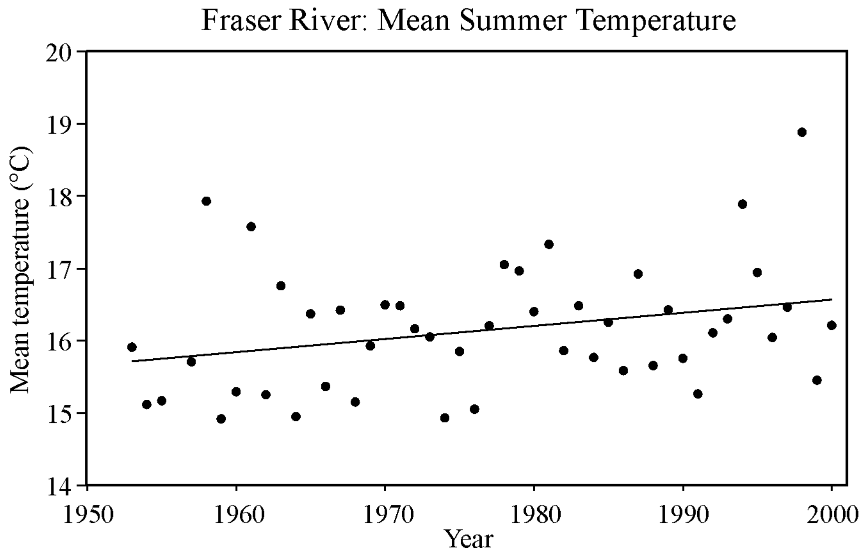

Fig. 3. Mean summer temperatures and their trend for the period 1953-2000.

The purpose of this paper is to extend the preceding analyses of historical data, and those described in Foreman et al. (2001), into the future through the use of global climate change models. These models, which predict possible climate changes under various scenarios of increasing greenhouse gases and aerosols, will allow us to assess the possible impact of changing climate conditions on river flow and temperature. Because of the sensitivity of salmon to water temperature it is critical to determine if the historical trends are likely to continue to the point where the survival of the Fraser River salmon stocks are threatened.

This manuscript is organised as follows. In section 2 we describe the methods used in this study with an emphasis on downscaling global climate data and our flow and temperature models. The Climate experiment is described in section 3. The statistical methodology, model validation, and projected changes in river flows and temperatures are presented in section 4. Implications of some of these changes are discussed in section 5 and the paper concludes with recommendations for future work in section 6.

2 Method

As an extension of the analysis of historic river conditions, this study was designed to determine the types of changes that could be expected under a changing climate. To do this, the same models that were used to hindcast river conditions from historical weather data were run using weather data derived from climate change models.

Model output from Coupled Global Circulation Models was downscaled to sites in the Fraser River watershed that had reliable historic weather records. The downscaled predicted changes were added to the historic data and then used to drive the flow and temperature models. Using the IPCC guidelines (IPCC-TGCIA, 1999), a baseline was established using the years 1961-1990. The modelled flow and temperatures were compared with the historical record in order to establish the validity of the models. The climate change impacts were then assessed by comparing the baseline values to future 30-year periods. Throughout this document, these periods are referred to in the short form as:

- 2020 – years 2010 through 2039

- 2050 – years 2040 through 2069
- 2080 – years 2070 through 2099.

2.1 General Circulation Models

A General Circulation Model (GCM) is a large-scale numerical model that simulates the physical processes that affect climate. They solve physical equations that describe the complex interactions among the atmosphere, ocean, cryosphere and land surface. GCMs are three-dimensional with horizontal grid resolutions typically between 250 – 600 km, 10 to 20 vertical layers in the atmosphere, and up to 30 layers in the oceans. While there is still a great deal of uncertainty about the accuracy of GCM output, especially at the regional level, there is a scientific consensus that they are a suitable tool to project future climate change (Grassle 2000, IPCC –Working Group I, 2001).

In this study output from two models were used. They are the Canadian Centre for Climate Modelling and Analysis model CGCM1 (Flato et al 2000) and the Hadley Centre for Climate Prediction and Research model HadCM2 (Johns et al 1997).

2.2 Downscaling

GCM model output is available on large grid scales (3.75° x 3.75° for CCGM1 and 2. 5° x 3.75° for HadCM2) that do not lend themselves to assessing the impact of climate change at local levels. Regional Climate Models are being developed that will have scales more suitable to local impact assessment, but the output from theses models is not yet generally available. Various techniques for mapping the large GCM grids to local levels have been developed (Wilby and Wigley 1997, Giorgi and Mearns 1991) and this process is referred to as downscaling. The hydrologic flow and temperature models used in this study were developed to use actual weather data from multiple sites located throughout the Fraser watershed. To produce accurate results, these models need data that are both internally consistent at each location (e.g. no heavy snowfall on days with no cloud cover), as well as systematically consistent among stations (i.e. the pattern of data at all stations must represent feasible weather patterns). These criteria can be achieved by using statistical climate inversion (Giorgi and Mearns 1991) where historical weather data values are adjusted by the amount of change predicted by the GCM. By using 30 years of historical data, we are reasonably well assured of capturing normal ranges of inter annual variability, as well as longer time scale phenomenon such as El Niño Southern Oscillation (ENSO) events and Pacific Decadal Oscillations (PDO) (Mantua et al 1997).

Statistical climate inversion results in a change in the mean value of a local weather variable by the amount of the change predicted by the GCM. The variance is unchanged for the variables where the GCM changes are expressed as absolute numbers (temperature, solar radiation and vapour pressure); however the variance will change for the other variables (wind speed, cloud cover and precipitation) that are adjusted by relative amounts. Statistical climate inversion will not change other weather characteristics such as rainfall persistence or frequencies. Predicting changes in local variance, persistence, frequencies, etc. of weather variables from GCMs is difficult since these models, with their large grid sizes, do not express local phenomenon accurately.

The flow and temperature models used in this study both require weather data from a number of stations through out the Fraser Watershed. The flow model requires daily precipitation and temperature data over an entire year to accurately represent the annual spring freshet that arises from snow pack build-up and its subsequent melting. The temperature model is used to provide river temperature forecasts throughout the salmon migration season and is only calibrated to operate in the summer months. The heat flux calculations in this model require hourly air temperature, dew point temperature, solar radiation, cloud cover and wind speed. For this study, the model was only run from July 1 to September 15, as historical data suggests that river temperatures outside of this range will not adversely affect migrating salmon. Historical daily weather data at 10 stations over the period of Oct. 1960[1] through to Dec. 1990 were used as the basis for predicting river flows. Daily weather data at 2 stations from 1961 through 1990 were used for the river temperature predictions.

The four grid cells nearest to each weather station were linearly weighted based on the relative distances from the grid centres to the station. Mean monthly changes for each of the required GCM weather variables were scaled by their weights and summed to produce the station change. These monthly station changes were then mapped to a 365-day year and smoothed with a heuristic process that minimised daily changes while preserving the monthly mean change calculated by the GCMs. This smoothing process was necessary to avoid problems caused by the introduction of large month end steps in the hourly weather variables used by the temperature model. Future weather was modelled by adding the smoothed changes to the historical observations at the stations, reintroducing leap days as required.

2.3 The UBC Watershed and Flow Models

The Fraser River Basin, with an area of 217,000 km^2, was modelled as 12 sub-watersheds using the UBC Watershed Model. (Quick and Pipes, 1976; Quick, 1995.) This model requires continuous precipitation and temperature data for each sub-watershed, and then generates continuous estimates of watershed outflow, based on the estimated snowpack accumulation and melting, together with rainfall. The daily outputs of streamflow from each of the 12 sub-watersheds were then linearly interpolated into hourly values as inputs to the UBC Flow Model, (Quick and Pipes, 1976).

The UBC Flow Model was used to represent the network of lakes and river channels that make up the Fraser River system. Because the temperature modelling requires flow and velocity information at hourly intervals, the Flow Model requires a 10-kilometre reach length to approximate the flow propagation rate.

For this study, the models were calibrated for a ten-year period (1970-79), and then verified for 50 years of continuous simulation. Comparison with the measured streamflow showed a close agreement over the whole of this 50-year period, which included the 30-year period used for the present work. This reliable and accurate flow simulation over an extended period of historical flows, from 1948 to 1997 inclusive, is a

[1] This two month extension prior to the normal baseline period is necessary to include all of the seasonal snowpack build up for the model runs that correspond to the 1961 model year.

vital step in establishing that the models will operate satisfactorily, before they are used to generate flows for the various climate change scenarios.

A selected sample of some of these simulated and measured flows is plotted in Fig. 4. This period was selected because it includes two of the larger flood years, 1972 and 1974. Only a five-year period, 1972 –1977, is plotted, so that some of the detail of the calculated and measured flows can be seen.

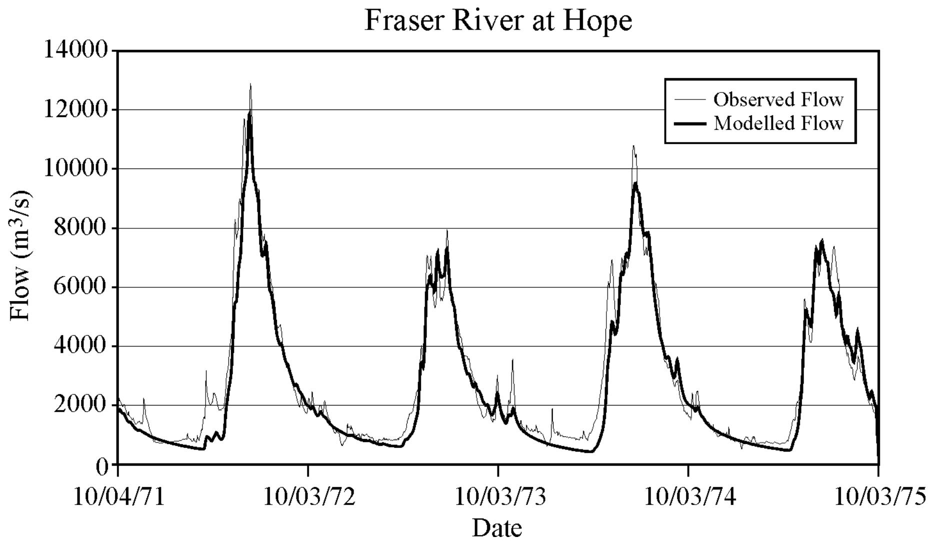

Fig. 4. Modeled and observed flow at Hope

2.4 The Temperature Model

The same one-dimensional temperature model described in Foreman et al (2001) was used for this study. This energy balance model has the form

$$E_{\Delta} = E_{flowin} + E_{trib} + E_{atm} - E_{flowout} \qquad (1)$$

E_{Δ} is the change in energy within the reach.
E_{flowin} is the energy of the water entering the reach from the reach upstream.
E_{trib} is a product of the tributary flow calculated by the flow model and the tributary temperature that was calculated, in this study, by the 1998 regression models described in Foreman et al (2001).
E_{atm} is the product of the heat flux across the surface of the river and it is calculated by a set of empirical equations that account for solar radiation, atmospheric long wave radiation, long wave back radiation, evaporation/condensation, conduction, solar reflection and atmospheric reflection.
$E_{flowout}$ is the energy of the water flowing downstream out of the reach.

2.5 Uncertainty[2]

It is not possible to quantify the uncertainties involved in climate change impact assessments. Climate Change modellers start by forcing their global circulation models

[2] For a comprehensive summary of uncertainty and downscaling the reader is referred to the IPCC Third Assessment Report (IPCC TAR WG1 2001) Chapter 10.

with hypothetical greenhouse gas and aerosol levels. . This forcing causes the models to operate outside the historic range of conditions where model error can be measured and uncertainty inferred. Impact modellers use this uncertain GCM output to force their impact models which are now, also likely to operate outside their normal operating range.

Nonetheless, while it is not possible to quantify uncertainty it has been possible to minimize the modelling errors through the impact assessment design.

- The downscaling method, using multiple grids, mitigates problems with GCM wave resolution at the individual grid level.
- The method of adding GCM changes to observed weather eliminates the absolute portion of any systematic GCM modelling bias. It does not, however, address the problems associated with changes in bias as the model moves outside its validated operating range.
- Running the model to cover a long time span (30 years) ensures that a reasonable level of climate variability is incorporated into the assessment.
- The use of the regression models for the tributary temperatures is problematic when the regression parameters lie outside of the domain used to determine the regression coefficients. Regression models are, however, less uncertain at extrapolation than the Neural Network models which are used in our operational river temperature forecast system.

3 Experiments

GCM data was downloaded from the Canadian Climate Impacts Scenarios (CCIS) web site (CICS 2001) (This site provides GCM data using the IPCC Distribution Centre guidelines). Though the CCIS site limits its database coverage to the geographical area that encompasses Canada, it conveniently contains data from several GCMs. Precipitation, minimum and maximum air temperature were downscaled for each of the 10 stations (Agassiz, Barkerville, Blue River, Fort St. James, Hope, Kamloops, Prince George, Salmon Arm, Smithers, and Williams Lake) that are needed to model the watershed flows. (See Fig. 1 for locations of these sites.) Mean air temperature, vapour pressure, solar radiation, cloud cover and wind were down scaled at Kamloops and Prince George and used in the temperature model. At the time of this study, the only model that provided all of these variables at either the IPCC Distribution Centre or the CICS site was the Canadian Centre for Climate Modelling and Analysis model CGCM1. The scenario selected for the study was the "greenhouse gas with aerosols" run based on the IPCC scenario 92a. The CGCM1 results from three model runs with differing initial conditions, plus an ensemble of those three runs, were used for this study (Boer et al[1] 2001, Boer et al[2] 2001). The flow and temperature models were first run using observed weather data over the baseline period 1961-1990. The models were then run with simulated weather for each CGCM1 experiment and each standard period, i.e., 2010-2039, 2040-2069 and 2070-2099. While incomplete weather data meant that we were unable to use multiple GCMs to test the robustness of our river temperature predictions, we were able to use ensemble data from the Hadley Centre for Climate Prediction and Research model HadCM2 as input to our flow model.

Fig. 5 demonstrates some of the complexities in predicted climate change. The variables used to predict river temperature can be seen to change throughout the year, however they do not all follow the same seasonal pattern. For example, the 2080 mean temperature change (the most commonly quoted climate change variable) is highest in the spring and lowest in the fall. Precipitation, on the other hand, shows a decrease in the late spring and an increase in fall. Furthermore, the precipitation change is published as a percentage so that it cannot be evaluated without knowledge of the baseline precipitation values.

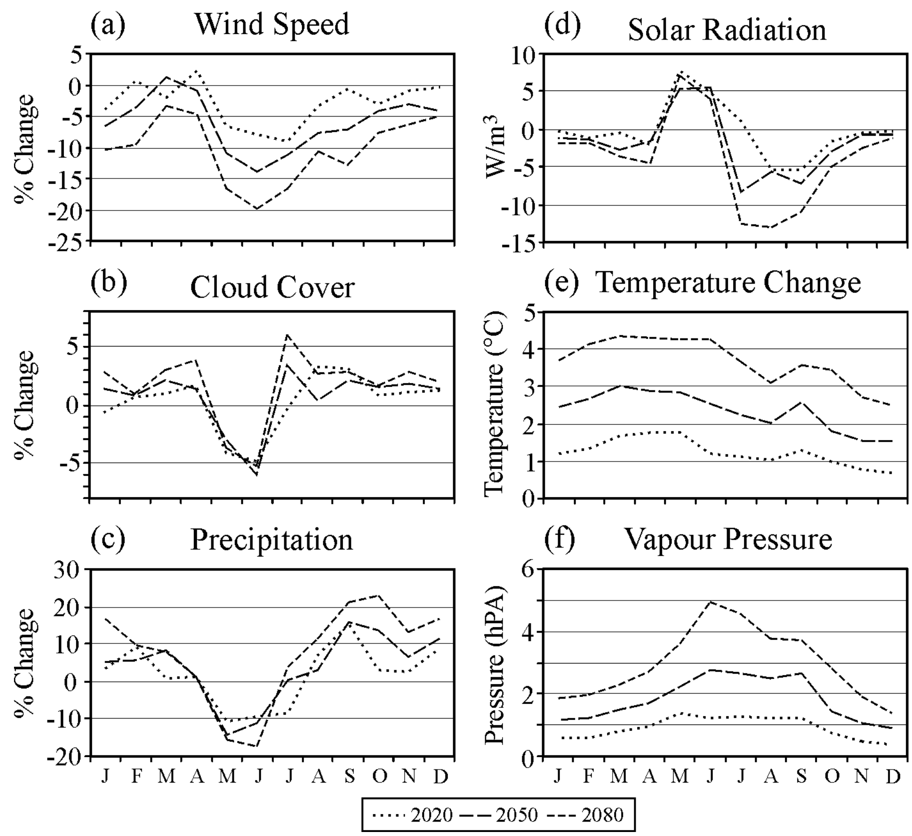

Fig. 5. CGCM1 Weather variables downscaled to Kamloops

4 Results

4.1 Statistical Analysis

The downscaling methodology of modifying historical weather observations by changes predicted by the GCM meant that the modelled flows and temperatures are paired with historical observations and subsequent statistical analysis must reflect this. Differences between baseline values and those from other periods, as well as the difference between the modelled and observed values over the baseline period, were calculated. Comparisons between the baseline and the observations were used to establish the validity of the model, and comparisons between the baseline and the future periods provided a measure of the expected impact of climate change.

A Lilliefors test (Wall 1986, US EPA 2000) was conducted for each set of data to determine if it was normally distributed. A Von Neumann (Wall 1986, US EPA 2000) test was then conducted to validate the independence of the data. Data that were both normal and independent meant that a t-test could then used to determine if the difference in the means was statistically significant. In cases where the data failed either the Lilliefors or the Von Neumann test, a Wilcoxon's Rank Sum (Wall 1986, US EPA 2000) test was used to test the hypothesis that the means were different. If the results of the Wilcoxon's Rank Sum test were significant then the Hodges-Lehmann difference (Wall 1986) was calculated.

4.2 GCM forcing comparison

While we did not conduct a detailed comparison of GCM output we did conduct one simple comparison to evaluate if the choice of GCMs would be likely to have a large affect on the results output from the impact models. To do this we compared the flow model results forced with CGCM1 weather to flow output forced with HadCM2 weather. (See Murphy (1999) and Wilby and Wigley (2000) for an assessment of the credibility of HadCM2 scenarios for downscaling and impact analysis.)

The small differences that resulted from different GCM forcing can be seen in Table 1. For 2020 and 2080, paired t-tests showed no statistical differences. For 2050 the t-test could not be applied since the data failed the Lilliefors test. The Wilcoxon's Rank Sum Test could not differentiate the two sets of data. With such similarity in flow during the critical salmon migration season we surmise that the differences in temperature model output that would arise from using HadCM2 based weather would not be radically different from the CGCM1 based output. This is further borne out by an examination for the grid by grid comparisons of GCM output for temperature and precipitation posted on the CCIS web site (CCIS 2001). All of the GCM models are tightly clustered on the temperature – precipitation scattergrams for the grids covering the Fraser River watershed.

Table 1. Mean flow at Hope during migration season using different GCM forcing.

GCM	Period		
	2020	2050	2080
HadCM2 (m^3/s)	4064	3816	3435
CGCM1 (m^3/s)	4046	3634	3406
Difference (m^3/s)	18	182	29

4.3 Model Validation

Actual weather observations from the period of October 1960 to December 1990 were used to model the flow and temperature of the river system. The model output was then compared to the observed river conditions in order to establish the model accuracy.

Following this procedure, it was determined (see Table 2) that the baseline and observed mean flow, minimum flow, peak flow, and peak flow dates were not statistically different. There was a 3 to 4-day shift in the timing between the observed and the baseline cumulative flow.

Table 2 Flow model statistics at Hope.

	Observed	Base	2020	2050	2080
Mean Flow (m^3/s)	2803	2920	2973	2963	3071
Difference from Baseline (m^3/s)	-117^{NSD}		53^{NSD}	43^{T}	150^{T}
Mean Peak Flow (m^3/s)	8705	8860	8443	7845	7241
Difference from Baseline (m^3/s)	-155^{NSD}		-417^{NSD}	-1015(-989)	-1619(-1614)
Mean Minimum Flow (m^3/s)	687	675	768	843	974
Difference from Baseline (m^3/s)	12^{NSD}		93^{T}	168^{T}	299^{T}
Julian Peak Flow Day	165	163	153	146	138
Difference from Baseline (days)	2^{NSD}		-10(-11)	-17(-17)	-25(-24)
Day on which the accumulated flow reaches $^1/_3$ of the total for the year.	156	160	151	143	134
Difference from Baseline	-4(-3)		-10^{T}	-18^{T}	-27^{T}
Day on which the accumulated flow reaches ½ of the total for the year.	180	184	176	171	166
Difference from Baseline	-4(-4)		-8(-8)	-13(-13)	-18(-18)

^{T} Mean Difference validated by paired t-test with >. 99 probability
(nnn) Hodges-Lehmann Difference validated by Wilcoxon's Rank Sum test with >. 99 probability
^{NSD} No Statistically verifiable Difference

The difference between the mean baseline temperature and the mean observed temperature at Hells Gate (see Table 3) was found to be only 0.2 °C. The small or negligible differences between observed and modelled flows and temperatures over the baseline period demonstrate the reliability of the flow and temperature models. This means that changes measured between the modelled baseline and the future periods should have some credibility. That is to say, if the weather downscaled from the GCM is reasonably accurate then the watershed flows and temperatures will likewise be reasonably accurate. The critical question concerns the accuracy of the weather predicted by the CGM. Until this is answered, the realism of our watershed forecasts must be treated as conditional on the realism of the GCM forecasts.

Table 3. Temperature model statistics

	Observed	Base	2020	2050	2080
Fraser River at Hells Gate Mean Temperature (°C)	16.2	16.4	17.2	17.9	18.3
Difference (°C)	-0.2^{T}		0.8^{T}	1.5^{T}	1.9^{T}
Thompson at Spences Bridge Mean Temperature (°C)	not available	17.0	17.9	18.5	19.1
Difference (°C)	not available		0.9(0.8)	1.5(1.4)	2.1(2.0)

^{T} Mean Difference validated by paired t-test with >. 99 probability
(nnn) Hodges-Lehmann Difference validated by Wilcoxon's Rank Sum test with >. 99 probability

4.4 Changes in river flow and temperature due to climate change

To understand the impact of the flow and temperature changes it is necessary to take a more detailed look at the data. This can best be done graphically.

4.4.1 Flow

Fig. 6 shows average daily mean flows at Hope for each of the 30-year periods in the study. It can be seen that the peak flow decreases over time and that it occurs earlier in the spring. It should be noted that there are differences in both the timing and the volume of the peaks shown on the graph and the peaks reported in Table 2. This is due to different methods of analysing the data. The peaks used in the table were found by identifying the date and volume of peak flow for each year and then calculating the statistics related to the peaks. On the graphs, the flow for each day was averaged over the 30 year period. The peak on the graph is the day with the highest average flow.

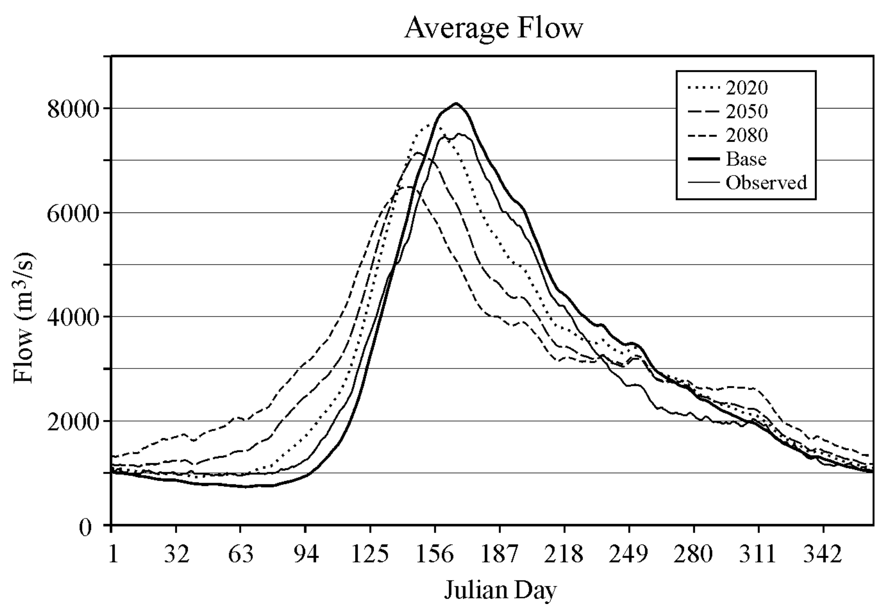

Fig. 6. Fraser River flows at Hope.

In addition to the changes in the peak flow characteristics, it is also clear that there is a significant change in the winter flow pattern. For the observed and the baseline period, the winter flow is virtually constant at approximately 1000 m^3/s. However, by 2080 the flow is continually increasing as winter progresses so that the April 1 flow rate is double the January 1 flow rate.

These seasonal changes are also evident in the flow change graphs in Fig. 7. The 2080 curve shows a significant increase in flow in April. However, the largest absolute change in flow is the decrease that occurs in June at the time of the freshet. When viewed as percentage changes, the 2080 flow pattern shows a 200% increase in March but only a 40% decrease in flow during the freshet.

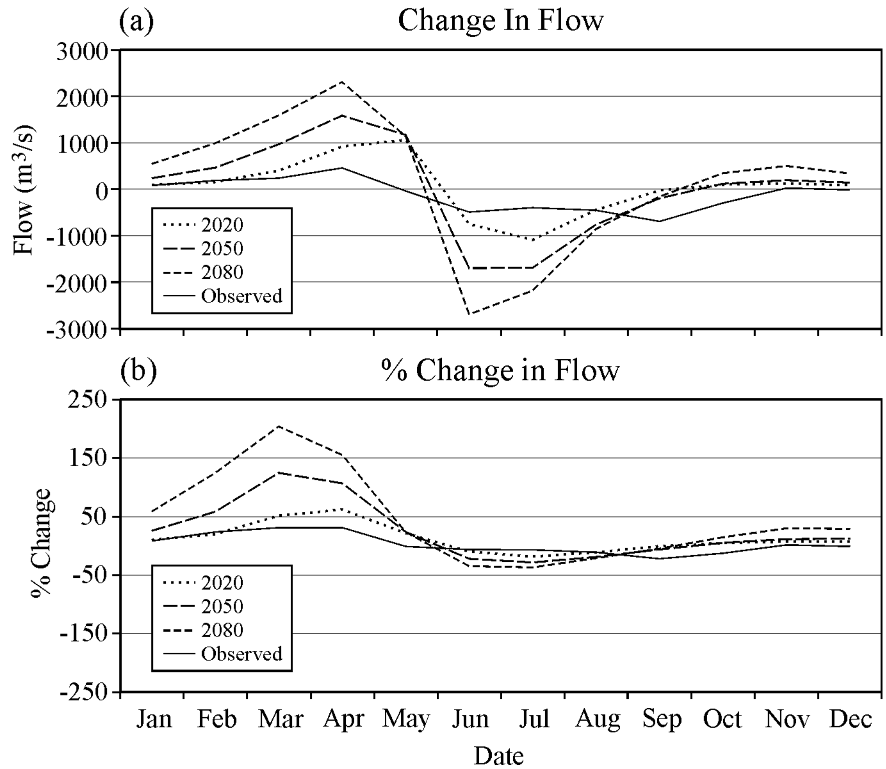

Fig. 7. Changes in flow at Hope.

Another way to view the change in the timing of the flow is to compare the dates by which cumulative flow milestones are reached. Fig. 8 shows the $^{1}/_{3}$ and $^{1}/_{2}$ cumulative flow milestones for the climate change study together with the regression lines calculated from historical records (Foreman et al., 2001). The apparent agreement between the historical projection and the predicted values is remarkable. Unfortunately the method of predicting future values means that the data does not meet the pre-requisite criteria for performing a regression test. Thus a statistical comparison of past and future trends cannot be made.

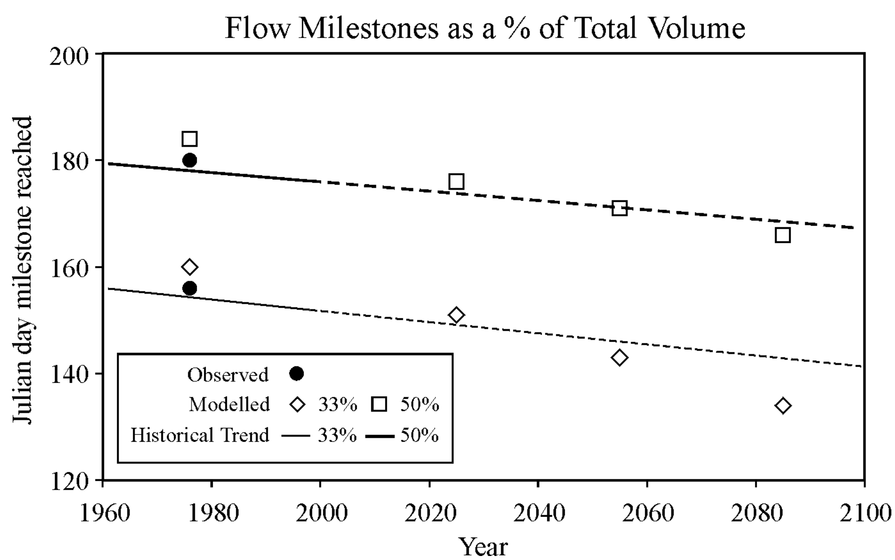

Fig. 8. Cumulative flow milestones for the Hope discharge.

Fig. 9 shows how the range of flow is expected to change. In 2080 there will be a modest (300 m^3/s) increase in the minimum flow with respect to baseline values, and a more significant (1600 m^3/s) decrease in peak flow. In spite of these range changes, the total volume of water flowing out of the watershed, represented by the mean flow, only increases by 150 m^3/s, or about 5%, by 2080.

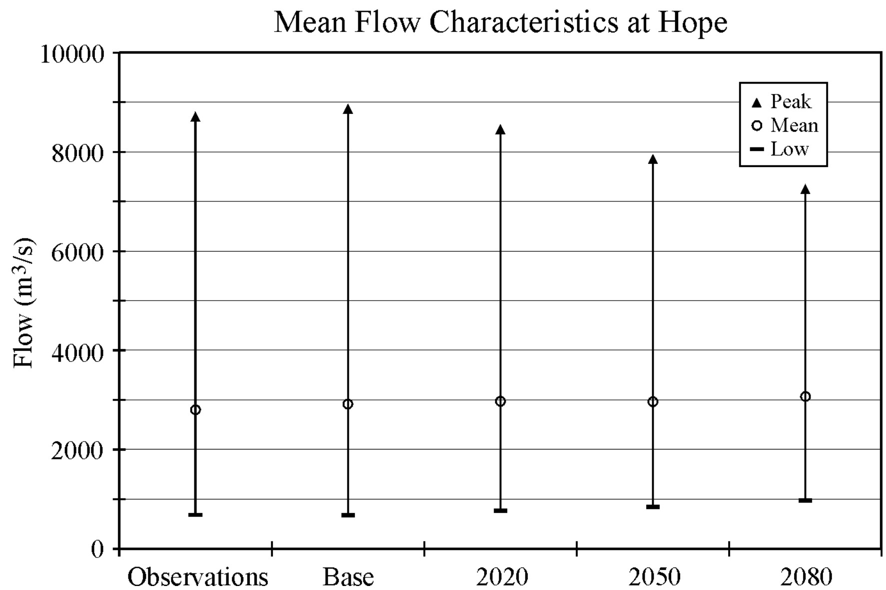

Fig. 9. Observed and predicted flow ranges at Hope.

Perhaps the most significant predicted change in future flow is shown in Fig. 10. Currently a freshet resulting from the melting of the snow pack that accumulated over the

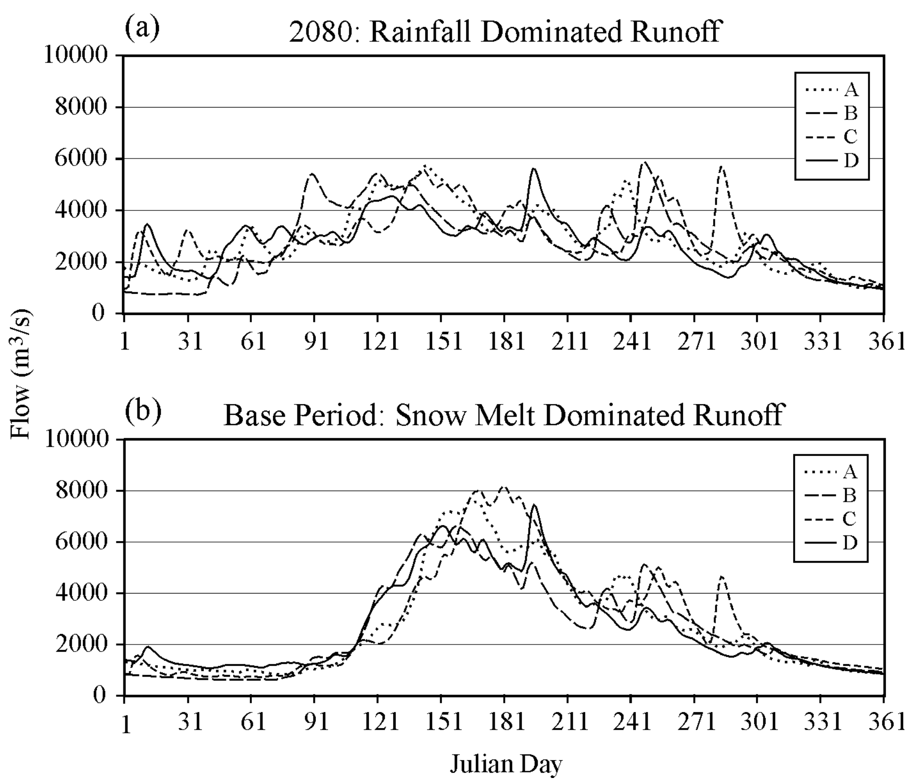

Fig. 10. Four annual discharges that demonstrate dramatic changes in the flow regime.

preceding winter dominates the Fraser discharge. Winter months are characterised by lower, more or less constant flows, in the 1000 m^3/s range. In the spring, as the snow melts, the flow increases rapidly until it typically, on average, reaches a peak in the 8000-10000 m^3/s range by about mid June. After the freshet, the flow generally declines until the early fall when it may be influenced by large rainfall events. However as seen in Fig. 10(a), by the end of the 21st century, our analysis shows that13% of the years are no longer snowmelt dominated. Peak flows are no longer clustered around June and may occur as early as the 1st week in April, or as late as the 2nd week in October. Fig. 10(b) shows that the corresponding four years in the baseline period were relatively normal.

4.4.2 Temperature

Fig. 11 shows average present and future water temperatures at Hells Gate on the Fraser River and Spences Bridge on the Thompson River. In both cases, the water temperature is seen to rise throughout July to a high in early August after which it cools slowly until the end of the study period in mid September. There are two important points to note in these figures. The first is that on the Fraser River, the mean 2080 temperatures at the start of the simulation period already exceed the mean high temperature for the baseline period and remain above that baseline high for approximately 7 weeks. On the Thompson River, the 2080 temperatures are not only above the baseline high for nearly 10 weeks, but they also exceed the 20°C temperature considered harmful to salmon spawning for approximately 4 weeks.

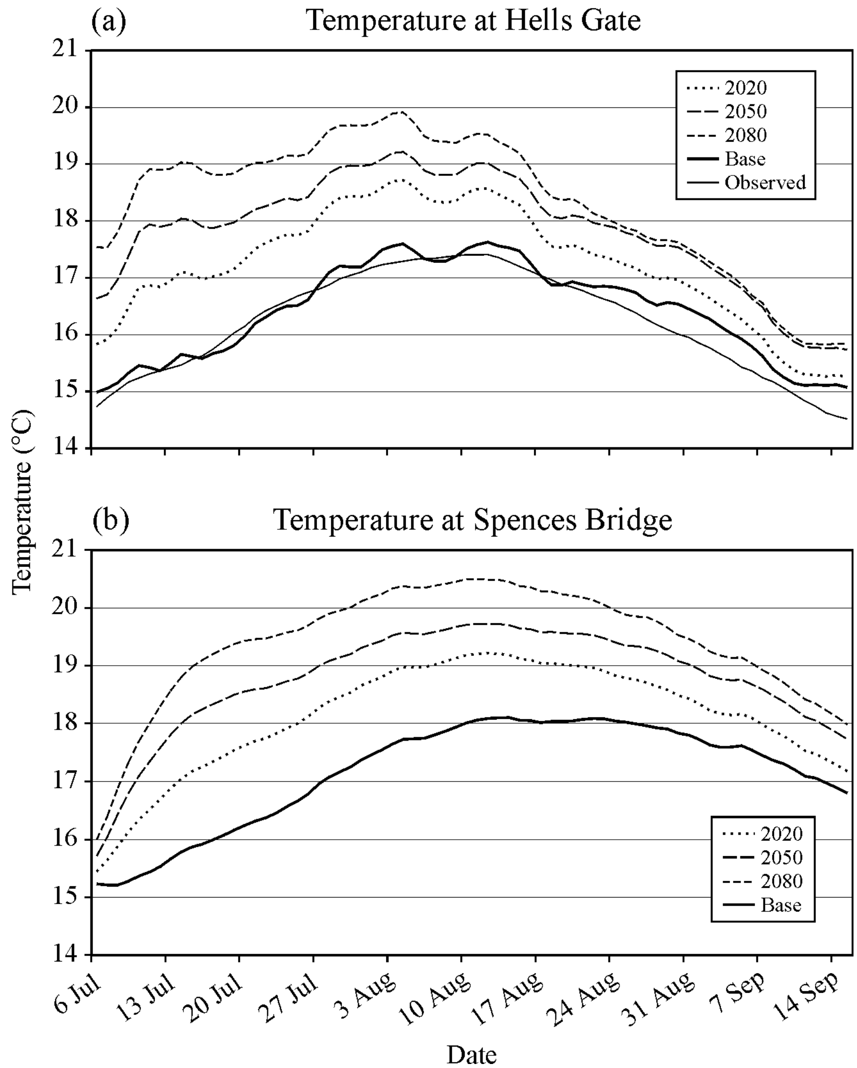

Fig. 11. Fraser and Thompson River temperatures

The expected mean temperature change at Hells Gate is shown in Fig. 12. The largest change, 3.5°C for the 2080 period, will occur in mid July and taper off thereafter to approximately 0.75°C by mid September.

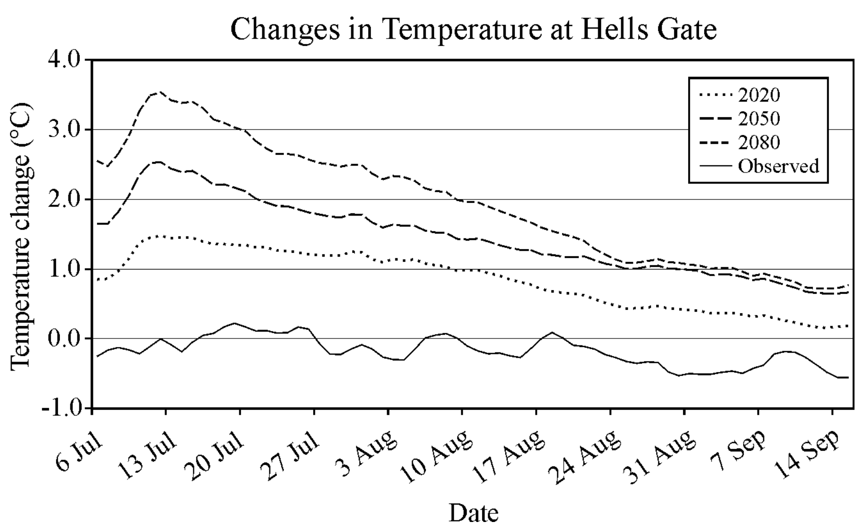

Fig. 12. Temperature change at Hells Gate with respect to baseline values.

Hells Gate summer mean temperatures are graphed in Fig. 13. Once again, a close, but statistically untestable, agreement between the historical trend and the climate change predictions can be seen. In fact, there is such close agreement between the 3 experiments ga1, ga2 and ga3 and the ensemble results, gax, that we felt justified in using the ensemble results for the detailed analysis of predicted river flows and temperatures.

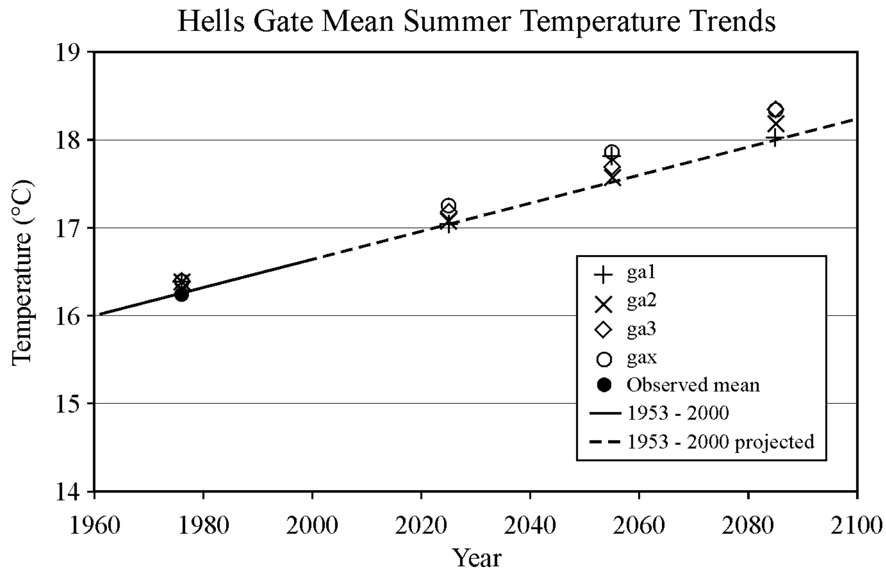

Fig. 13. Summer mean temperatures at Hells Gate.

5 Discussion

The flow model does not predict drastic changes in the mean or minimum flow characteristics of the Fraser River but the predicted decline in the peak flow may have serious implications. The impact of a reduced freshet on sediment transport, flood management, hydro-electric power generation, and riverine and estuarine ecosystems can only be addressed by experts in those fields. We note that the shift in timing of the flow is in accordance with predictions outlined in the report produced by working group II of the IPCC (IPCC –Working Group II, 2001).

While the flow changes are expected to be benign, the predicted river temperature changes could have serious implications for salmon. As it is known that exposure to excessively warm water degrades spawning success, a measure was developed to allow the comparison of current exposure levels to the levels projected under climate change. Cumulative exposure was determined by summing the number of 10-km reaches and hours where the temperature exceeds 20° C. The relative values of these exposure numbers, with the units Degree Reach Hours (DRH), give some measure of the threat to salmon spawning success. For the baseline period of 1961 to 1990, the highest exposure number was 238 DRH in 1961, but for the 2070 to 2099 period, the maximum had climbed to 2259 DRH. Taking the worst case year in the baseline period for each river as a critical threshold, Fig. 14 shows the percentage of years in each future 30-year period that exceed that threshold. Clearly these years should be considered a threat to salmon spawning success. On the Fraser, the highest temperatures occur in those sections of the river below its confluence with the Thompson. This means that fish migrating up the

Thompson will encounter debilitating temperatures in years when either river has temperatures that exceed the critical 20° C threshold. For the 2080 period, 57% of the thirty years will have Fraser River temperatures that exceed the worst year (1961) in the baseline period. The analogous number for the Thompson River is 67%. Consequently, unless the salmon can adapt by changing their time of migration, these increasing temperatures can be expected to have dramatic impacts on spawning success and viability of species. We note that the report produced by working group II of the IPCC (IPCC – Working Group II, 2001) also expects climate change to increase the stress on salmon.

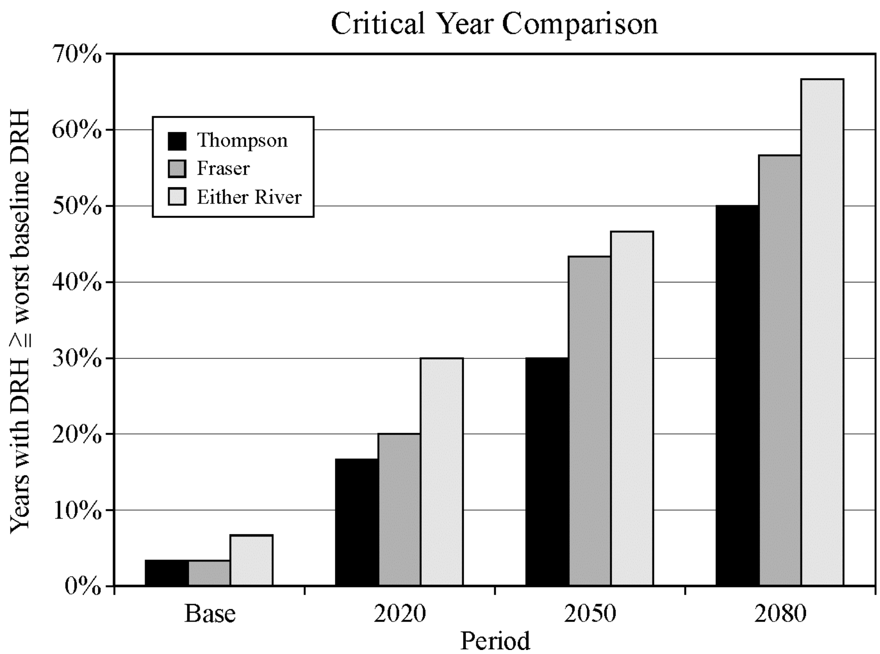

Fig. 14. Percentage of years with DRH above the baseline critical value.

The historical trends in flow and temperature that have been identified by Foreman et al (2001) are reproduced here with more current data (Figs. 2 and 3). The close agreement between the historic trends the flow and temperature predictions can be seen in Fig. 8 and Fig. 13. The smooth transition from historical trend to the climate change trend lends weight to the argument that the observed changes may be related to historic climate change that has already occurred.

6 Future work

Three areas of future work are suggested by this study. The first is the use of additional GCMs to produce our Fraser Watershed climate change data. Climate change models are continually being improved and we clearly want to use the most reliable climate change predictions that are available. As a corollary, the temperature model needs to be run with predictions from more than just the one GCM that distributes the required variables through the IPCC site.

The second task for the future is that the temperature model should be run for a longer period each year. This study limited the temperature simulations model to the July-mid September timeframe of the historical records. However the results of thise study indicate that by the end of the century, the temperatures deleterious to salmon spawning may occur prior to July 1. Running the model from May through September would give a better indication of the extent of the period when elevated river temperatures may threaten salmon spawning success. It may also indicate times when salmon spawning success might be mitigated if their arrival times in the river were to change.

The third future task is that other watersheds should be investigated. In particular, rivers that have not historically reached temperatures that are hazardous to salmon spawning may start to do so under climate change. Clearly it is important to consider all salmon populations that may be threatened by climate change.

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References

Boer G.J.; G. Flato, M.C. Reader, D. Ramsden. 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the twentieth century, Climate Dynamics 16, 405-425

Boer G.J.; G. Flato, D. Ramsden. 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: Projected climate to the twenty-first century, Climate Dynamics 16, 427-450

Bouke, G.R.; G.A.Chapman, P.W. Schneider, JR. and D.G. Stevens. 1975. Effects of holding temperature on reproductive development in adult sockeye salmon (Oncorhynchus nerka). *In:* Annual Northwest Fish Culture Conference, 3-5 December, 1975, Otter Rock, Oregon, 24-40

CICS. 2001, http://www.cics.uvic.ca/scenarios/

DFO, 1999, Fraser River Chinook Salmon, DFO Science Stock Status Report D6-11 1999 5 pp.

DFO, 1999, Skeena River Sockeye Salmon, DFO Science Stock Status Report D6-10 1999 7 pp.

Flato, G.M.: G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader, and A.J. Weaver. 2000. The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate, Climate Dynamics 16, 451-467

Foreman, M.G.G.: B. James, M.C. Quick, P. Hollemans and E. Wiebe. 1997. Flow and temperature models for the Fraser and Thompson Rivers, Atmosphere-Ocean, 35(1), 109-134.

Foreman, M.G.G.: D.K. Lee, J. Morrison, S. Macdonald, D. Barns and I.V. Williams 2001. Simulations and Retrospective Analysis of Fraser Watershed Flows and Temperatures, Atmosphere-Ocean, 39(2), 89-105

Gilhousen, P. 1990. Prespawning Mortalities of Sockeye Salmon in the Fraser River System and Possible Causal Factors. Bulletin XXVI, International Pacific Salmon Fisheries Commission. Vancouver, 53 pp.

Giorgi F. and L.O. Mearns. 1991. Approaches to the simulation of Regional Climate Change: A review. Reviews of Geophysics 29(2), 191-216

Grassl H. 2000. Status and Improvements of Coupled General Circulation Models, Science 16 pp 1991-2001

IPCC-Working Group I, 2001, Climate Change 2001: The Scientific Basis; Summary for Policymakers and Technical Summary, IPCC, Geneva pp98

IPCC-Working Group II, 2001, Climate Change 2001: Impacts, Adaptation and Vulnerability; Summary for Policymakers and Technical Summary, IPCC, Geneva pp89

IPCC-TGCIA, 1999: Guidelines on the use of Scenario Data for Climate Impact and Adaptation Assessment. Version 1. Prepared By Carter, T.R.: M.Hulme, and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69pp.

Johns T.C.: R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Michell, C.A. Senior, S.F.B. Teff, R.A. Wood. 1997. The second Hadley Centre coupled Ocean-atmosphere GCM: model description, spinup and validation, Climate Dynamics 13, 103-134

Mantua, N.J.: S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997 A Pacific decadal climate oscillation with impacts on salmon. Bulletin of the American Meteorological Society, Vol. 78, 1069-1079

Murphy, J., 1999 An evaluation of statistical and dynamical techniques for downscaling local climate. Journal of Climate, 12 , 2256-2284

Quick, M.C. and A. Pipes. 1976, A Combined Snowmelt and Rainfall Runoff Model, Can. J. Civil Eng., Vol. 3, No. 3, 449-460.

Quick, M.C. and A. Pipes. 1976, Non-linear Channel Routing by Computer, J. Hydr. Div., ASCE, Vol. 101, No. HY6, 651-664.

Quick M.C. 1995, The UBC Watershed Model. *In:* Computer Models of Watershed Hydrology Editor V.P. Singh. Published by Water Resource Publication 15 BN 0-918334-91-8.

Rand, P. and S. Hinch. 1998. Swim speeds and energy use of up-river migrating sockeye salmon: simulating metabolic power and assessing risk of energy depletion. Can. J. Fish. Aquatic Sci. 55(8), 1832-1841.

Servizi, J.A. and J.O.T. Jensen. 1977 Resistance of adult sockeye salmon to acute thermal shock. Int. Pacific Salmon Fisheries Comm. Progress Report No. 34., Vancouver, 11 pp.

Thompson, R.E. 1981. Oceanography of the British Columbia Coast. Can. Special Publication of Fisheries Aquatic Sci. 56, 291pp

U.S. Environmental Protection Agency, 2000, Guidance for Data Quality Assessment: Practical Methods for Data Analysis EPA QA/G-9 QA00 Update, Office of Environmental Information, Washington

Wall, F.J. 1986. Statistical Data Analysis Handbook. McGraw-Hill, New York

Wilby, R.L. and T.M.L Wigley. 1997. Downscaling General circulation model output: a review of methods and limitations. Progress in Physical Geography 21(4),530-548

Wilby, R.L. and T.M.L Wigley. 2000. Precipitation predictors for Downscaling : Observed and general circulation model relationships. Int. J. Climatol. 20,641-661

Williams, I.V.: M. McAllister, J.S. MacDonald and T.J. Brown, 2000. A spatially explicit cumulative effects model for estimating in-season impacts of temperature and discharge, migrating Fraser River sockeye. in: Proc 4th Int. Conf. Integrating GIS and Environmental Modelling (GISEM4): Problems, Prospects and Research Needs, 2-8 Sept 2000, Banff, Alberta. http//www.colorado.edu/research/cires/banff/upload/149