Interactive comment on "Climate change and stream temperature projections in the Columbia River Basin: biological implications of spatial variation in hydrologic drivers" by D. L. Ficklin et al.

Anonymous Referee #1

******Please note that a copy of this document is uploaded as a supplement because the equations will not show up in plain text*****

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General Comments

This paper is generally well written and the findings are interesting. The modeling approach is useful and results are timely given that the Columbia River is an important international basin. Some of the key findings of the paper seem to contradict our current understanding of process drivers of stream temperature. Therefore, more clarification is needed on how the model was applied (e.g. calibration parameters) so that the results can be interpreted by the reader. Although this is a discussion paper it would also be useful to include a better model description for those readers who do not have access to the Ficklin et. al. (2012) paper.

Thank you very much for the detailed and thoughtful comments. We believe we have addressed all of these concerns. Please see below.

Specific Comments

The introduction is well written; however, more context in terms of impacts of stream temperature change on aquatic organisms would be useful.

Thanks for the comment. Given the wealth of information regarding stream temperature and aquatic organisms, we have only included some of the most relevant publications for this paper. We have added a few sentences to the first paragraph of the paper:

"The temporal and spatial variability of stream temperature is a primary regulator of the life-history, behavior, ecological interactions, and distribution of most aquatic species (Peterson and Kwak, 1999). For example, metabolic processes in ectothermic freshwater organisms (e.g., fishes, amphibians, invertebrates) are directly regulated by water temperature (Angilletta, 2009), and thus the persistence of populations and the rate of energy flow through aquatic ecosystems is dependent on the thermal characteristics of a local habitat (Woodward et al., 2010). Moreover, much like terrestrial species, the timing of important life-history traits such as reproduction and migration is heavily dependent on seasonal thermal regimes (Johnson et al., 2009; Woodward et al., 2010). Additionally, stream temperature plays a large role in chemical kinetic rates and is important for governing stream management for recreation as well as urban and industrial water supplies. Therefore, to better understand hydrologic systems and to better manage water resources in a changing environment, it is critical to predict the potential effects of climate variability and change on stream temperature, and to characterize how these changes affect the distribution and diversity of freshwater taxa."

Angilletta, M. J.: Thermal adaptation: a theoretical and empirical synthesis. Oxford University Press, Oxford, 2009.

Johnson, A. C.,Acreman, M. C, Dunbar, M. J., Feist, S. W., Giacomello, A. M., Gozlan, R. E., Hinsley, S. A., Ibbotson, A. T., Jarvie, H. P., Jones, J. I., Longshawb, M., Maberly, S. C., Marsh, T. J., Neal, C., Newman, J. R., Nunn, M. A., Pickup, R. W., Reynard, N. S.,

Sullivan, C. A., Sumpter, J. P., and Williams, R. J.: The British river of the future: how climate change and human activity might affect
two contrasting river ecosystems in England, Science of the Total Environment, 407 4787–4798, 2009.
Woodward, G., Perkins, D. M., and Brown, L. E.: Climate change and freshwater ecosystems: impacts across multiple levels of organization, Philosophical Transactions: Biological Sciences, 365, 2093-2106, 2010.

Section 2.2 - page 5799: The stream temperature model should be presented better here. A simple description that includes specific stream temperature equations, spatial and temporal scales of modelling, and better descriptions of important variables would be useful, particularly since some of the results seem counter-intuitive. This would help the reader understand what the model is not representing.

Please see the new detailed model description added to Section 2.2:

We used the SWAT model coupled with a stream temperature model to predict streamflow and stream temperature throughout the Columbia River Basin. SWAT is an integrative, mechanistic model that utilizes inputs of daily weather, topography, land use, and soil type to simulate the spatial and temporal dynamics of climate, hydrology, plant growth, and erosion (Arnold et al., 1998). Within SWAT, surface runoff and soil water infiltration were simulated using the modified Curve Number method (Neitsch et al., 2005). The Penman-Monteith method was used to estimate potential evapotranspiration. Stream temperature was simulated using the Ficklin et al. (2012) SWAT stream temperature model that uses local air temperature and hydrology for stream temperature estimation:

$$T_{w,local} = \frac{(0.1 \cdot sub\_snow) + (T_{gw} \cdot sub\_gw) + \lambda(T_{air,lag} \cdot (sub\_surq + sub\_latq))}{sub\_wyld} \quad [1]$$

where *sub_snow* is the snowmelt contribution to streamflow within the subbasin (m^3), *sub_gw* is the groundwater contribution to streamflow within the subbasin (m^3), *sub_surq* is the surface water runoff contribution to streamflow within the subbasin (m^3), *sub_latq* is the soil water lateral flow contribution to streamflow within the subbasin (m^3), *sub_wyld* is the total water yield (all contributing hydrologic components) contribution to streamflow within in the subbasin (m^3), T_{gw} is the groundwater temperature (°C; annual average input by user), and $T_{air,lag}$ is the average daily air temperature with a lag (°C), and λ is a calibration coefficient relating to the relative contribution of the surface water runoff and later soil water flow to the local water temperature and is included to aid in calibration in case of improper hydrologic model calibration. The lag (days) is incorporated to allow the effects of delayed surface runoff and soil water flow into the stream. The 0.1 in Equation [1] represents the assumed temperature of snowmelt (0.1 °C).

After stream temperature of the local contributing water is determined, the stream temperature before the effects of air temperature is determined by:

$$Twater_{intial} = \frac{T_{w,upstream} * (Q_{outlet} - sub\_wyld) + (T_{w,local} * sub\_wyld)}{Q_{outlet}} \quad [2]$$

where $T_{w,upstream}$ is the temperature of the streamflow entering the subbasin (°C) and Q_{outlet} is the streamflow discharge at the outlet of the subbasin.

The final stream temperature is calculated by adding a change to the initial stream temperature in the subbasin from differences between stream and air temperature and travel time of water through the subbasin. Depending on T_{air}, the final stream temperature is estimated as:

$$T_{water} = Twater_{intial} + (T_{air} - Twater_{intial}) * K * (TT) \quad if\ T_{air} > 0 \qquad [3]$$
$$T_{water} = Twater_{intial} + ((T_{air} + \varepsilon) - Twater_{intial}) * K * (TT) \quad if\ T_{air} < 0 \qquad [4]$$

where T_{air} is the average daily air temperature (°C), K is a calibration conductivity parameter, TT is the travel time of water through the subbasin (hour) and is calculated from the SWAT simulations, and ε is an air temperature addition coefficient (°C), which was included to account for water temperature pulses when T_{air} is below 0°C. For the case when the effects of Tair and the hydrologic contributions are such that the final is T_{water} < 0°C, the stream temperature model sets T_{water} to 0.1 °C. T_{water} is also assumed to be the temperature of water discharge to downstream subbasin, and is further routed along the stream network. The calibration parameter, K, acts as a proxy for reach-specific adjustment of the radiative forcing, such as shading due to a vegetation canopy or geomorphic changes resulting in differing geometry. Additional details regarding the stream temperature model can be found in Ficklin et al. (2012).

Section 2.5 - page 5801: What are the calibration parameters? It is not possible to determine what the model is doing without presenting these parameters.

The calibration parameters are discussed in the new stream temperature model section (see above).

Also, please present the final set of calibration parameters.

We have included the final set of stream temperature calibration parameters for each subbasin in the supplemental information.

In addition, the manuscript does not present any uncertainty analysis. Uncertainty analysis can be conducted using the optimization algorithm and should be included in this manuscript.

For this model setup and this study, there are a large number of potential uncertainties. These include, as noted by Wilby and Harris [2006] (see comment after next), differences in GCM output, downscaling methods, hydrological model structure, hydrological model parameters, and greenhouse gas emission scenarios. As you mention, the genetic algorithm seeks the optimal calibration parameter set to minimize the error between the simulated and observed values for all objective functions. Therefore, it results in equally optimal, but different, parameter sets that exhibit trade-offs between the objective functions. However, we believe that a simple analysis of uncertainty (e.g., choosing equal optimal parameter sets and viewing the changes in model output) is misleading. This exercise reveals small uncertainty values that do not characterize the overall model performance and will believe it will mislead readers. See comment after next for further discussion.

Section 3.2 - page 5803: The high RMSE during summer months suggests that the model is not properly accounting for some factor (likely groundwater contribution, the effect of hyporheic exchange flow, shading, and/or bed heat flux). Therefore, results during the summer are also likely not representative. Please describe how model results are useful within the context of these very large errors.

This problem is likely due to the fact that each of the hydrologic components affect stream temperature differently throughout the year, yet we only characterize the influence of the different hydrologic components on stream temperature using four calibration parameters for each subbasin for each year. Specifically these include influences from snowmelt, groundwater, surface water and radiative transfer effects from flow transit time. Instead, we specified 3 objective functions relating to the errors produced in 3 seasonal time periods. Therefore, the yearround calibration parameters exhibited trade-offs between the objective functions. A different approach would be to allow for seasonally varying calibration parameters that allow the influence of the different hydrologic components to vary seasonally. This may allow for components (e.g., groundwater) to become more influential in particular seasons. We did not pursue this methodology because it greatly increased the number of parameters to be calibrated (approximately 25,000 parameters; 4 parameters for each season for ~2100 subbasins). This will be left for a future study to characterize the dynamic influence of hydrological components on stream temperature. However, for this study we have added a portion in the paper describing that the calibration parameters attempt to characterize hydrologic influences on stream temperature year-round, and so are essentially juggling trade-offs between the seasonal variations of influence. The high RMSE from summer months are due to the near-zero and highly fluctuating discharge values amongst the many tributaries. These low discharge values, coupled with calibration parameters that are attempting to capture hydrologic component influences occurring yearround, present the observed errors.

We addressed these points in the paper in the third paragraph of the Discussion/Conclusions section:

However, we do note that our simulations for stream temperature demonstrated higher errors during the summer months. This is due to low and fluctuating discharge values that ultimately affect stream temperature. Also, it is likely due to the fact that hydrologic components may influence stream temperature differently during different seasons. For this study, we used annual calibration parameters and allowed them to vary for each subbasin. An alternative approach would be to utilize seasonally varying calibration parameters, and to analyze the dynamic (i.e., seasonal) influence of hydrologic components on stream temperature. This may better capture the stream temperature fluctuations in the summer months. Nonetheless, our spatially resolved methodology using a mechanistic model, SWAT, better characterizes the complex processes of stream temperature throughout the CRB by accounting for the hydrologic components contributing to stream temperature and its variation.

Section 3.4 - page 5804: Lines 16 and 17 suggest that many of the projections fall within the range of modelling error. How is one to know if the projections are a function of expected changes or simply a modelling artifact? Further description of model parameters may help clarify this issue.

This has been added to the manuscript in the second paragraph of the Discussion/Conclusions section:

As with any modeling study, modeling errors originate from multiple sources. Wilby and Harris (2006) discuss these aforementioned uncertainties in detail and ranked their importance in decreasing order as follows: differences in GCM output, downscaling methods, hydrological model structure, hydrological model parameters, and then greenhouse gas emission scenario. While their work was performed for a hydrological model, the results still hold true for our stream temperature model. Particular to this study, in order to quantify the differences between errors due to parameter uncertainty and GCM (or projection) uncertainty, much more work needs to be done and is well beyond the scope of this work.

Wilby, R. L., and Harris, I.: A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the River Thames, UK, Water Resources Research, 42, W02419, 2006.

Additionally model parameter discussion was included (see above).

Section 3.4 - page 5804: Lines 17 to 20 indicate that a large number of sites were removed. This fundamentally changes the outcome of the manuscript and deserves much more attention. What might be expected if streams are dry during the winter? This argues that the trends presented may not be realistic. This may also present a substantial limitation in the modelling technique. Therefore, it would be useful to discuss these findings in terms of expected changes in stream temperature even though the model may not represent the important processes during this period.

I believe there might be confusion with what was removed from the analysis. The sentence:

"In this study, streams that have no flow for an extended time period of the year (and thus have no stream temperature) are removed from the stream temperature analyses, but since drying streams are an important barrier for aquatic species migration, they will be discussed."

refers to streams that dry naturally (every summer) or from changes in climate (increase in air temperature, changes in precipitation). The stream temperatures from these streams were removed from the analysis, and the streams that contained water throughout the year were kept in the analysis.

This was done for two reasons:
[1] we do not consider these streams to be reliable refugia for fish
[2] because we are doing seasonal and annual analyses, including the streams might "skew" the stream temperature for this particular stream for when water is within the reach. Therefore the results from including streams that dry would not be indicative of the actual stream temperature.

Lastly, because stream drying is extremely important for water resources and aquatic species, we include the number of subbasins that were removed from the analysis for each season for the entire Columbia River Basin. This at least gives an idea of how many subbasins were removed from the analysis.

Section 3.6.1 - page 5806: The findings in lines 20 to 23 differ substantially from our current understanding of stream temperature drivers in mountain streams. A better description of the causal relationship between groundwater and stream temperature is required given that groundwater has been shown by many previous studies to play a large role in governing thermal regimes. Why would groundwater not be correlated with stream temperature during the periods (summer, winter) where it plays the largest role?

This is correct. We attribute this result to groundwater being an already major component in the streamflow during this time period. If groundwater is already the major source of streamflow then any changes to groundwater will not likely change the stream temperature. For example, if 85% of the streamflow comes from groundwater, and is then decreased to 75%, the change in stream temperature isn't likely to significantly change. We discuss this aspect in the second-to-last paragraph in the Discussions and Conclusions section:

"However, no significant correlation was found during the summer, when groundwater is a large source of stream flow. This is likely because groundwater is the main source of water for this season, any climate-induced changes in groundwater will not have a major effect on stream temperature because the main water source for streamflow is still groundwater. For example, if 85% of the streamflow comes from groundwater, and is then decreased to 75%, the change in stream temperature isn't likely to significantly change. Additionally, no groundwater inflow change correlations were found for the winter season."

Discussion - line 29 on page 5810: This finding does not make physical sense. Many studies have shown stream temperature to be inversely correlated with streamflow due to a streams' increased ability to store heat with higher volume. Please explain this finding and describe the physical mechanisms.

While it is true that stream temperature is inversely correlated to streamflow, we are not sure this is always the case. For example, what if streamflow volume decreases due to a decrease in surface runoff and soil lateral flow, but the snowmelt and groundwater components remain the same? Will stream temperature still decrease even thought a larger contribution of cooler water influx? We are essentially stating that the mix of hydrologic components might matter more than the volume of streamflow in determining stream temperatures, which is why we include the sentence:
"Since streamflow is a mix of incoming hydrologic components, it is difficult to determine correlations."
in the Discussion and Conclusions section.

Discussion - lines 20 to 23 on page 5811: This sentence is not clear. If groundwater is a major proportion of the flow then shouldn't changes in groundwater result in changes in stream temperature? The subsequent sentence suggests there were no changes in the winter; however, many of the sites were removed from the analysis due to substantial changes. How can this finding be supported? Please clarify.

Subbasins were only removed from the analysis if they were dry or frozen for a substantial period of time. For this paper we only discuss subbasins that are still projected to hold water in the future. Additionally, we believe we have addressed the groundwater question in one of the above comments:

"We attribute this result to groundwater being an already major component in the streamflow during this time period. If groundwater is already the major source of streamflow then any changes to groundwater will not likely change the stream temperature. For example, if 85% of the streamflow comes from groundwater, and is then decreased to 75%, the change in stream temperature isn't likely to significantly change."

A figure with projected trends shown on a map similar to Figure 1 (with ecological provinces) would be useful.

We originally had all of the projected trends figures with ecological provinces, but the amount of data shown in addition to the ecological provinces became too cumbersome for viewing. We therefore use Figure 1 as a reference figure for the ecological provinces.

Technical Corrections
Abstract - line 2: Should read "air" temperature, not just temperature.

Fixed within the manuscript.

Introduction - page 5797, line 26: "7" should be spelled out (this applies throughout the manuscript).

Fixed throughout the manuscript.

Please ensure to differentiate between air temperature and water temperature (e.g. page 5808).

Fixed throughout the manuscript.