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 #2

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This paper describes a coupled hydrologic and stream temperature model driven by historical and future climate for the Columbia River Basin. Stream temperatures are correlated with air temperatures and hydrologic pathways to determine drivers of stream temperature change with climate warming/climate change.

Overall, this paper is well written, of an appropriate length, and is well-presented. However, a few major shortcomings exist that should be addressed prior to publication:

1. The contribution of this paper is not adequately described. The authors imply that they are the first to use a physically-explicit stream temperature model to assess atmospheric and climatic drivers of stream temperature change. However, this is not the case (see papers by Isaak and Null for other examples). The introduction acknowledges that deterministic numerical models and analytical approaches have been utilized, but then focuses on regression approaches. Better describing how this paper contributes to the existing literature would improve it immensely. Systematically describing hydroclimate effects on stream temperatures is a new and needed contribution, but this contribution is currently over-sold.

We certainly don't mean to imply that we are the first to use a physically-explicit stream temperature model. Instead, we wish to recognize these contributions in our literature review. To clarify this, we have provided new information and reorganized the introduction as shown below:

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.

Potential impacts of climate change on stream temperatures have been widely estimated using field investigations and modeling studies (Webb and Nobilis, 1994;Mohseni et al., 2003;Caissie, 2006;Hari et al., 2006;Nelson and Palmer, 2007;Webb et al., 2008;Isaak et al., 2010;van Vliet et al., 2011;Null et al., 2013;Ficklin et al., 2013). At larger spatial scales, regional regression models have been used to predict the impacts of climate change on stream temperatures (Mohseni et al., 1998;Mohseni and Stefan, 1999;Mohseni et al., 1999;Erickson and Stefan, 2000;Bogan et al., 2003;Webb et al., 2003;Stefan and Preud'homme, 1993). However, regression methods are not sufficient predictors of stream temperature because they do not account for hydrologic component inputs to the stream such as snowmelt, groundwater, and surface runoff (Constantz et al., 1994;Constantz, 1998;Pekarova et al., 2008;Ficklin et al., 2012;MacDonald et al., 2014). Neglecting these components severely limits the ability of regression-based models to accurately predict spatial variability in stream temperature changes, since the contributions of different sources to streamflow will be modified in a changing climate. Ignoring the distinct characteristics of different sources to streamflow therefore negatively impacts the assessment of the effects of climate change on aquatic biodiversity at landscape (and larger) scales.

To adequately capture the role of changing hydrology from a changing climate on stream temperature, numerical (Isaak et al., 2010; Kim and Chapra, 1997;Sinokrot and Stefan, 1994) and analytical (Null et al., 2013;Tang and Keen, 2009;Edinger et al., 1974) stream temperature models, in conjuction with hydrologic models, have been applied with success. These models allow stream temperature assessments at the local or regional level. For example, our prevous work in the Sierra Nevada mountain range in California found subbasin-scale stream temperature differences from region-to-region largely from localized changes in hydrology from changes in climate. Additionally, Null et al. (2013) found increasing stream tempreatures with increasing elevation due to the transition from snow- to rain-dominated, an effect opposite what would be predicted by a model based solely on air temperature

The primary objectives of this work are to [1] predict changes in stream temperature over the coming century across the Columbia River Basin at the ecological province level, [2] identify the contribution of specific hydrological components (such as snowmelt, surface water runoff, etc.) to the overall heat and water budget across the watershed, and [3] add to the literature regarding the role of changing hydrology on changes in stream temperature. Specifically, we aim to demonstrate the extent to which future changes in hydrology—streamflow, surface runoff, snowmelt, groundwater inflow, and lateral soil flow as simulated using global climate projections at the subbasin scale— could critically affect changes in localized stream temperatures, which are of high importance for aquatic species. The Columbia River Basin is a snowmelt-dominated region, where projected increases in global air temperatures are expected to result in early snowmelt runoff. These changes lead to reduced late spring and summer water discharges that change the thermal content of stream flow. Moreover, previous stream temperature assessments indicate that the Columbia River Basin is sensitive to changes in climate (Mantua et al., 2010;Chang and Psaris, 2013; Luce et al., 2014); these sensitivities vary spatially and are governed in part by the land use, hydroclimate and topographic variables of the local region (Chang and Psaris, 2013).

We use a landscape-scale hydrological model—the Soil and Water Assessment Tool (SWAT; Arnold et al. (1998))— combined with a stream temperature model that simulates stream temperature based on the effects of subbasin air temperature and hydrology.(Ficklin et al., 2012). The SWAT model efficiently represents snowmelt and runoff processes, and also incorporates a full range of water quality processes (Gassman et al., 2007). SWAT has been found to accurately simulate streamflow in regions where snowmelt dominates the hydrology (Wang and Melesse, 2005; Watson and Putz, 2012; Zang et al., 2012). Downscaled output from seven General Circulation Models (or Global Climate Models, GCMs) using one representative concentration pathway (RCP) associated with a trajectory of future greenhouse gas accumulation in the atmosphere for the late-21st century was used to drive the calibrated SWAT model at the subbasin-scale. For all Columbia River Basin ecological provinces, we spatially and temporally explore the changes in stream temperature, and interpret these changes with respect to changes in the hydrologic system.

2. The stream temperature model is inadequately described. It is simply described as a model that ‘reflects the combined influence of meteorological conditions and hydrological inputs on water temperature within a stream reach’ (pg 5799, 1st paragraph) and model that ‘includes the effects of hydrologic component inputs on stream temperature’(pg 5801, 1st full paragraph). Is it a physically-based, regression, or equilibrium temperature approach? There is a reference for Ficklin et al. 2012, but since the model is fundamental to this study, it must be described much more fully. The calibration optimization technique is described in more detail than the stream temperature model itself.

Reviewer #1 also commented on this. Please see the new detailed model description added in 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:

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

[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:

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

[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).

3. Similarly, what is the spatial resolution of the modeling? It may be at the ecological province scale and if so average size with ranges of ecological provinces should be provided; although pg 5799, 1st paragraph discusses water temperature within stream reaches.

The modeling was performed at the subbasin scale, as shown in Figures 5 and 6. We now include the average spatial resolution of these subbasins in the study area section:

We used the SWAT model coupled with a stream temperature model to predict streamflow and stream temperature throughout the Columbia River Basin at an average spatial resolution of 250 km^2.

4. Model fit is not great with ~8 points with RMSE in the 13-20 C range from June – November (out of about 50 calibration/validation sites total). It is unclear if these locations are used when reporting results. If so, are results meaningful and representative of stream temperatures? Particularly, one of the main findings from this paper is that stream temperature increases the most during summer – but these outliers would considerably skew results. If not, how are locations with poor fit removed from results analysis?

The points with extremely high RMSE values during the summer months are due to the flow-dependent calculation of streamflow when flows are extremely low. This creates sporadic nonphysical fluctuations in stream temperature calculations and therefore greatly increases the RMSE with observed values. We chose not to remove these sites in order to not misrepresent the accuracy of the model for all time durations, because the other seasons were adequately simulated. However, if these calibration sites (and all sites) become dry or iced-up during the future projections they were removed from the analysis.

We discuss the drying or icing of streams in the last paragraph of the Methods section:

Additionally, with changes in climate, it can be expected that drying of streams will occur. 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.

And also in the Stream temperature projections section:

It is important to note that a large number of subbasins were removed from this analysis due to no-flow conditions (i.e., running completely dry or icing-up) from changes in climate (hatched areas in Figures 5 and 6). Of these, winter had the largest number of subbasins removed from the analysis (31%), followed by fall (18%), summer (16%), and spring (15%). The average period of subbasins with no-flow conditions is projected to 34%, or 81 months out of the 240 months for the 2080s time period. We consider these subbasins to not be reliable refugia for aquatic species.

Lastly, we have added a section to the third paragraph of the Discussion/Conclusions section discussing the stream temperature modeling errors:

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.

Similarly, the text (pg 5803 ln 17-19) says the majority of simulated stream temperatures were in the 2-3C RMSE range, but figure 2 shows ~7/50 sites in the 2-3C RMSE range, with the large majority > 3C. Text is misleading and oversells model fit. Finally, what parameters are adjusted with calibration? It is hard for the reader to make sense of calibration without know what parameters are changed.

Thanks for this comment. We completely agree and have changed that sentence to:
"RMSE values between observed and simulated daily stream temperatures range from 2-5 °C for the majority of observation sites."

The calibration algorithm changes 4 parameters in the calculation of stream temperature. To make this clear, we have explicitly mentioned them in the Model description section as noted above. Also, we have included a table of the final obtained parameters in the Supplementary Information.

5. The authors do a nice job of describing stream temperature changes by ecological province, but I would like to know what drove changes (e.g., runoff, snowmelt, air temperature. . .). Pg. 5804 ln 14-16, pg 5807 ln 7-10, and pg 5807 ln 14-17 are examples that could use explanation.

We treat the results section simply as a place to present the results and not explain why stream temperatures are change. We further describe why stream temperatures are changing in the Discussion/Conclusions section, as well as in Section 3.6, Table 5, and Figure 7. In these sections we go into detail why stream temperatures are changing.

6. Pg 5811 1st full paragraph: The authors explain why snowmelt contributes water during summer. But why is snowmelt positively correlated with stream temperatures? This contradicts current understanding of thermal characteristics of rivers. It must be explained more thoroughly.

This result was interesting for us. First, this relationship was not significant, suggesting that the correlation was not robust. Secondly, we attribute this finding to the fact that snowmelt did not change for a large portion of these basins with changes in climate. To us, this indicates that snowmelt (albeit a small amount) is still feeding streams during the summer. An increase in stream temperature during the summer (which is normally found) and steady flow of snowmelt (or small increases) will likely lead to a positive correlation (or a small positive correlation), which is exactly what we found. This is fully discussed in the 6th paragraph of the Discussion/Conclusions:

> Snowmelt changes were negatively correlated during the spring, fall, and winter seasons, and positively correlated during the summer season. A decrease in snowmelt will lead to an increase in stream temperature because the cooling effect that snowmelt has on stream temperature is no longer present. In summer, snowmelt and stream temperature were positively correlated (albeit not significant), suggesting the counterintuitive notion that an increase in snowmelt led to an increase in stream temperature. This can be explained largely because snowmelt changes did not occur at all in 975 (60% of the subbasins with streamflow) of the CRB subbasins, while for spring, fall, and winter, these values were 89 (5%), 50 (3%) and 48 (3%), respectively. These observations suggest that snowmelt is still a component of the hydrologic cycle during the summer season.

7. Some of the Pearson correlations are barely significant. Please discuss why you're confident that you're not overfitting hydrologic parameters.

We agree that overfitting could be the case, but this is a problem with any modeling study with limited observational data. For watershed hydrology, we calibrated the Columbia River Basin to over 100 streamflow gauges throughout the watershed. Based on the results presented in the streamflow calibration section we are fairly confident that the hydrology is being adequately simulated. However, for observational stream temperature data, the data is much more spatially and temporally limited. Additionally, the validation of each site's calibration with independent data is essentially a check against overfitting.

Even so, we feel that generalizations can be still made on our model results, even if the correlations are small, but significant. We include all tables and figures so that readers can make informed decisions about whether correlations exist or if there is another factor happening. This also sounds like a great opportunity for future research.

Minor Revisions:

Title – consider switching 'biological implications' to 'habitat implications' as this paper has no explicit biological criteria, but uses thermal habitat of fish species.

Great idea and we agree. The title has been changed to:
Climate change and stream temperature projections in the Columbia River basin: habitat implications of spatial variation in hydrologic drivers

Abstract ln 9-11: the temperature changes without an extent of time or description of climate change are not meaningful.

We have added "late 21st century" to this sentence:
"We use a hydrologic model coupled with a stream temperature model and downscaled General Circulation Model outputs to explore the spatially and temporally varying changes in stream temperature for the late 21st century at the subbasin and ecological province scale for the Columbia River Basin."

Pg 5798: How big are ecological provinces? Give average and range.

We have added this sentence in the Study Area section:
The ecoprovince areas (Figure 1) for this study average 68,000 km^2 and range from 300 km^2 (Columbia Gorge) to 145,000 km^2 (Mountain Columbia).

Pg 5801 last line: Justify why the model was calibrated using trimesters, but results presented using quarters.

This was done for two reasons:
[1] The stream temperature curve is often a rising limb, peak, and then falling limb. The goal of the calibration was to adequate capture the three sections of the stream temperature curve.
[2] We aimed to limit the calibration time by using only three time periods. We could have used 4 seasons or 12 months to maximize the objective function, but this would have been increasingly computationally expensive and the time spent on calibration would have been much longer.

We have now included this information:
"Four calibration parameters for each subbasin were adjusted using the algorithm, and three objectives were specified including the RMSE values for the January-April, May-August, and September-December time periods to match the stream temperature rising limb, peak, and falling limb."

Additionally, we present the results as seasons because that is most useful for readers and water resource managers. While there is a discrepancy between the calibration time periods and the time periods of the results, this will have no effect on the results.

Section 3.3 – This may fit better with methods – as climate projections are not your results, but rather your input data.

While this study does not solely concentrate on the climate projections, we feel that this section is better suited juxtaposed to the stream temperature projections so that readers can quickly reference the changes in air temperature and precipitation.

Pg. 5804, ln 20ish: Could you separate dry reaches from iced reaches? Where streams ice over, there is likely to be deep pool habitat for fish. But where streams dry, there will be mortality and barriers to migration – so these should be described and analyzed separately.

This sounds like a good idea and a valid reason to go back and update the stream temperature model. Right now the stream temperature model simulates NaN when the streamflow is below a particular small streamflow, whether it be due to drying or icing. We could potentially 'flag' streams that are dry or iced up based on the local air temperature to determine if they are dry or iced. However, just based on this results of this paper, it might be misleading to be reliant solely on air temperature.

Table 4: Are data for only the 2080 period? Clarify time period of data.

This has been fixed. Please see the new Table 4 caption:
Table 4. Sensitivities of stream temperature changes to changes in maximum and minimum air temperatures for the Columbia River Basin during the 2080s