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Diurnal timing of warmer air under climate change affects magnitude, timing and duration of stream temperature change

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Abstract:

Stream temperature will be subject to changes because of atmospheric warming in the future. We investigated the effects of the diurnal timing of air temperature changes – daytime warming versus nighttime warming – on stream temperature. Using the physically based model, Heat Source, we performed a sensitivity analysis of summer stream temperatures to three diurnal air temperature distributions of +4 °C mean air temperature: i) uniform increase over the whole day, ii) warmer daytime and iii) warmer nighttime. The stream temperature model was applied to a 37-km section of the Middle Fork John Day River in northeastern Oregon, USA. The three diurnal air temperature distributions generated 7-day average daily maximum stream temperatures increases of approximately +1.8 °C ± 0.1 °C at the downstream end of the study section. The three air temperature distributions, with the same daily mean, generated different ranges of stream temperatures, different 7-day average daily maximum temperatures, different durations of stream temperature changes and different average daily temperatures in most parts of the reach. The stream temperature changes were out of phase with air temperature changes, and therefore in many places, the greatest daytime increase in stream temperature was caused by nighttime warming of air temperatures. Stream temperature changes tended to be more extreme and of longer duration when driven by air temperatures concentrated in either daytime or nighttime instead of uniformly distributed across the diurnal cycle. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS stream temperature; climate change; diurnal distribution; air temperature; daytime warming; nighttime warming

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INTRODUCTION

Stream temperature has been recognized as an important environmental factor in freshwater ecosystems since the 1960s (Caissie, 2006; Webb *et al.*, 2008). Naturally, stream temperature fluctuates on seasonal as well as daily cycles (Sinokrot and Stefan, 1993), and these fluctuations are important to ecosystems. For example, the River Continuum Concept points to the variability in stream temperature (annual, daily and seasonal cycles) as important influences on aquatic species and habitats (Vannote *et al.*, 1980). Recent studies show that North American watersheds have witnessed noticeable increases in water temperature for the past few decades (Beschta and Taylor, 1988; Webb, 1996; Mohseni *et al.*, 1999; Bartholow, 2005). Efforts have been made to predict the influence of climate change on stream temperature and aquatic ecosystems to help restorations efforts and planning. However, the magnitude of increases in the future is poorly constrained, and the diurnal timing and durations of the increases have received little study.

Cold-water fish (such as salmonid species) are affected by increasing stream temperatures. Feldhaus *et al.* (2010) found that levels of heat shock protein 70 in redband rainbow trout (*Oncorhynchus mykiss gairdneri*) were positively correlated with stream temperature. Thermal stress in the short term leads to behavioural changes over the fish life cycle. Among fish populations in the Pacific Northwest of the USA, metabolism, food consumption, growth and reproduction ability have been found to be affected by stream temperatures (McCullough, 1999; Myrick and Cech, 2000; Selong *et al.*, 2001; Myrick and Cech, 2003; Myrick and Cech, 2004; Myrick and Cech, 2005).

Stream temperature is the product of heat exchange between water in the stream and its environment. Therefore, environmental changes may lead to changes in stream temperature. The stream exchanges heat with its environment via five major sources and sinks: shortwave (solar) radiation, longwave (thermal) radiation, streambed heat transfer (conduction), evaporation and convection (Stefan and Sinokrot, 1993; Khangaonkar and Yang, 2008). Further, stream temperature is influenced by boundary conditions (the temperature and discharge of upstream flow and incoming tributaries). The governing equation for heat budget and exchange in an open channel is the advection dispersion equation with aforementioned sources and sinks (Wright and Horrall, 1967; Brown, 1969).

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Diurnal fluctuations of air temperature vary in range, maxima and minima due to atmospheric conditions, elevation, topography and land cover. Maxima typically occur during the late afternoon to early evening, whereas minima occur during the late night to early morning. These diurnal fluctuations have a great impact on the stream's heat budget because air temperature affects the heat exchange between air and water. However, models of warming climate typically project an increase in the annual and monthly average air temperatures (IPCC, 2007) rather than the hourly changes important to stream temperature. Nevertheless, the prediction of future stream temperature requires the use of results from these climate models (Stefan and Sinokrot, 1993; Gooseff *et al*., 2005; Caissie *et al*., 2007; Mantua *et al*., 2009).

Stream temperature modeling studies can be divided into two approaches: statistical and deterministic. Statistical models correlate stream temperature with one or more variables such as air temperature and streamflow. Linear regression models are easier to use and require less input data compared with complex statistical models that involve correlating stream temperatures with more variables that can become mathematically complicated (Webb and Nobilis, 2007). Numerous studies have established statistical (linear and nonlinear) correlations between air and water temperatures. These correlations have been used to predict future stream temperatures under projected changes in climate. Stefan and Preudhomme (1993) and Pilgrim *et al*. (1998) found a linear correlation between air and water temperatures in the central USA. They detected that water temperature responses to air temperature changes were different according to the size of the river. Mohseni *et al*. (1998) developed a nonlinear regression function correlating the average weekly stream temperature with air temperature for different streams around USA. Studying a southwest English stream, Webb *et al*. (2003) found better correlation of air and water temperatures in rivers with below-average flow. Benyahya *et al*. (2007) used autoregression and periodic autoregression models to predict temperature in the Deschutes River, Oregon, USA. Statistical methods are commonly used to model past and future stream temperatures at annual, monthly and weekly time scales rather than at daily or diurnal time scales (Mohseni, *et al*., 1998; Webb *et al*., 2003; Caissie, 2006).

Deterministic models explicitly incorporate the heat budget, physics of flow and changes to these processes in streams. These models require detailed input data to calculate heat fluxes (Stefan and Sinokrot, 1993; Caissie *et al*., 2007), including meteorology, topography, stream geomorphology and hydrology. Stefan and Sinokrot (1993) studied five streams in the United States using a deterministic model and predicted that increasing air temperature could lead to a 2.4 °C to 4.7 °C increase in stream temperatures, while removing riparian vegetation could lead to a 6 °C increase. Cristea and Burges (2010) predicted that a 4 °C increase in air temperature in the Wenatchee River, Washington, USA, would increase stream's maximum temperatures by 2.5 °C–3.6 °C in the 2040s. Modellers who use deterministic models modify existing data sets of atmospheric and initial conditions to generate future scenarios to modify the impact on stream temperature.

There are several methods to modify an existing air temperature data set to model future scenarios of global warming. Chief among these is the uniform case where a single increase in air temperature is added uniformly to the entire data set. This is sometimes called the *delta case* or the *delta method*. The uniform case generates a uniform increase in air temperature over the diurnal cycle. It generates projected daily average, maxima and daily minima temperatures that are higher than the originals by the same value. However, we do not know if temperatures will change uniformly.

Alexander *et al*. (2006) and Morak *et al*. (2011) reported that during the second half of the 20th century, minima increased faster than maxima over most of the planet. In addition, the diurnal temperature range has been decreasing over the same period (Vose *et al*., 2005). Consequently, a diurnal uniform increase in air temperature is not the only method to modify air temperature data sets in the deterministic models that aim to simulate future scenarios. The expected increases in the monthly average air temperature might result more from the increased nighttime air temperatures than the increased daytime temperatures. Conversely, the expected increases in the monthly average air temperature might result from increased daytime air temperatures.

These findings increase the uncertainty in modeling future impact of air temperature warming on stream temperatures. Although numerous studies examined past diurnal air–water temperature correlation, the majority of future projection deals with weekly and daily correlations. We use sensitivity analysis to compare and contrast the two most extreme cases with the uniform case, examining the changes in stream temperature resulting from daytime versus nighttime warming.

To our knowledge, the only study that investigated nonuniform changes in air temperature over the diurnal cycle was Gooseff *et al*. (2005). Using a deterministic model of the Lower Madison River, Montana, USA, and an output from four general circulation models (GCMs), Gooseff *et al*. found that daytime warming of air temperature and changed shortwave radiation warmed streams beyond the upper zero net growth temperature for *Oncorhynchus mykiss* (rainbow trout) by more time than nighttime warming of air and changed shortwave radiation. However, Gooseff et al. found that nighttime warming of air and changed shortwave radiation warmed stream beyond the maximum temperature for growth for rainbow trout by more time than daytime warming of air and changed shortwave radiation. Gooseff et al. did not isolate the effects of changed air temperatures from those of changed solar radiation.

The objective of this study is to understand the response in stream temperatures to the timing of diurnal changes in air temperature under climate change and to isolate those effects from changes in shortwave radiation. To meet this objective, a calibrated physics-based stream temperature model for the Middle Fork John Day River (MFJD), Oregon, USA, was changed to reflect possible timing scenarios for future air temperature warming.

METHODS

We based our study on an upper section of the MFJD in northeastern Oregon, USA (Figure 1). The study section extends for 37.0 km beginning immediately upstream of the confluence with Clear Creek (44°35′48″N, 118°29′36″W) and ending immediately downstream of Camp Creek. The drainage area of the study section is 827 km^2 (663 km^2 excluding the area of Camp Creek subbasin), and elevations range from 1000 to 1250 m with a total of 19 tributaries. The upper elevations of the study section's drainage basin receive an annual average of 1270 mm of precipitation, with less than 10% falling during the hottest months of July and August. Flow in the MFJD at Clear Creek drops from 2.5 m^3·s^{-1} at the beginning of May to 0.2 m^3·s^{-1} at the end of September, with slowly declining discharge through July and August. The study section is made up of unconstrained subreaches running through wide riparian meadows connected by confined subreaches with narrow valley floors (Crown and Butcher, 2010). Bedrock geology in the reach is predominantly Columbia River Basalt Group and felsic volcanic and volcaniclastics of the John Day Group (Hunt and Stepleton, 2004). Gold mining, dredging and railway constructions during the second half of the 19th century to early 20th century led to tree clear-cutting along the riparian zone and geomorphologic changes in the valley. Sinuosity was reduced, and banks were hardened. Furthermore, trees were removed for cattle grazing and firewood and could not be replanted due to the coarse texture of the mining spoils, leading to large-scale reduction in tree cover in some subreaches (Beschta and Ripple, 2005).

We used the model Heat Sources in our simulations. Heat Source (Boyd, 1996; Boyd and Kasper, 2003) is a physically based finite-difference model that simulates stream thermodynamics and hydrodynamics. It is distributed and maintained by the Oregon Department of Environmental Quality (http://www.deq.state.or.us/wq/tmdls/tools.htm) and has been used in several stream temperature studies and reports (e.g., Loheide and Gorelick, 2006). Heat Source simulates advection and dispersion of heat, and heat exchange processes including fluxes of shortwave and longwave radiation, air–water interface convection, evaporation rate and bed conduction. The current version (8.0) contains packages that calculate local channel hydraulics and the hourly solar radiation flux on the water surface based on sun angle, vegetation, topography and the water surface and the wetted channel dimensions.

Crown and Butcher (2010) parameterized and calibrated Heat Source to simulate MFJD stream temperature based on records and measurements from the years 2002 and 2004 as part of a total maximum daily load assessment for the John Day River. Original data sets for discharge and temperature were generated by a combination of in-stream measurements, thermal infrared surveys and a generic temperature profile (Crown and Butcher, 2010). We extracted the relevant model input elements for our study section in the MFJD from Crown and Butcher's model. Our stream section uses stream temperature records from seven data loggers located along the main stem MFJD [records from 2002 at 3.2, 13.2, 13.75, 17.45, 19.15, 20.55 and 28.3 river

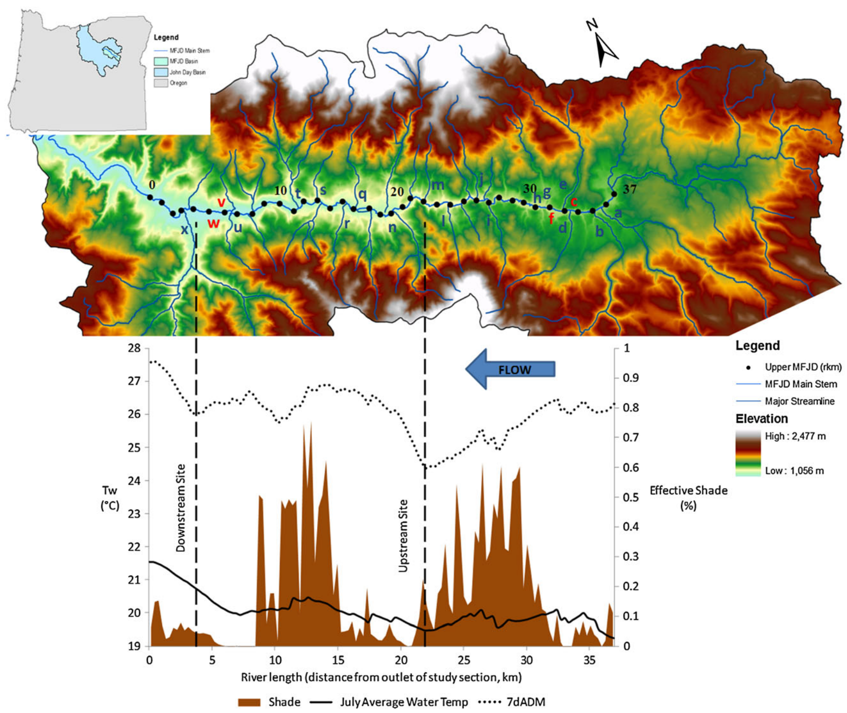

Figure 1. Map of the study section of the Middle Fork John Day (MFJD) and summary data of longitudinal effective shade, 7dADM stream temperature and average stream temperature during July 2002

kilometres (rkm)—numbering according to our study section] and five data loggers on major tributaries installed between May and October 2004. At each data logger location, values for cloudiness, humidity, wind speed and air temperature were adjusted from the Agrimet site in Prairie City, Oregon (22.0 km away from upstream end of reach at 44°27′42″N, 118°42′50″W, and elevation 1079 m). The accuracy/error of the model was confirmed for key days (hottest days) at locations where data loggers were installed (for further information, see Crown and Butcher, 2010).

Records showed that at the upper end of the study section, stream temperature ranged from 11.6 °C to 27.7 °C in July 2002, whereas at the lower part of the study section (data logger at 3.2 rkm), river temperature ranged from 12.4 °C to 28.7 °C in July 2002. The air temperature ranged between 4.8 °C and 39.9 °C in the same month.

Our sensitivity analysis did not include any changes in the boundary conditions. The flow regime and stream water temperature at the upstream boundary of the study section were kept at their 2002 values (see Table I). In addition, the discharge and temperature of tributaries entering the main stem MFJD were not changed in our study section. Crown and Butcher (2010) reported the flow and temperature of the major tributaries entering the MFJD. Their report also lays out the method for estimating the missing information for tributaries' temperature and discharge. Thus, tributary and upstream boundary temperatures fluctuated over time, both diurnally and over longer periods, following the temperatures observed during the 2002 base year. Discharge also varied over the simulation period to include the values over the year (e.g. snowmelt flow and summer flow). Although we expect the temperature and discharge of the upstream boundary and the tributaries to change with climate, our focus here is not a prediction of future temperature but an investigation of sensitivity to the diurnal timing of air warming.

Mantua *et al.* (2010) calculated spatially and temporally downscaled future air temperature from the A1B and the B1 emission scenarios based on results from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4), providing average monthly air temperatures for many watersheds throughout the Pacific Northwest (IPCC, 2007). Elsner *et al.* (2010) projected future air temperature on a monthly basis on a 1/16° grid for the A1 scenario. Both the A1B and B1 assume the same growth rate in the world's population, whereas the B1 scenario uses lower emissions and cleaner energy technologies. The results of the A1B July–August study of Mantua *et al.* (2010) have an average increase in air temperature of 3.43 °C by the 2040s and 5.88 °C by the 2080s. Their B1 July–August results have an average increase in air temperature of 2.64 °C by the 2040s and 4.24 °C by the 2080s. Given the range of these projections, this study uses a base case of +4 °C warming in July's monthly average air temperature relative to July 2002.

Air temperature averaged 21.0 °C for July 2002. We increased air temperature by 4 °C in our scenario, resulting in a monthly average air temperature of 25.0 °C for our

Table I. Summary of boundary conditions over the simulations period (stream discharge and temperature of tributaries and upper end)

No.	Name	rkm	River Bank	Discharge ($m^3 \cdot s^{-1}$)			Temperature (°C)		
				Max	Min	Average	Max	Min	Average
	Upper End Flow	36.95	—	0.58	0.17	0.30	27.69	11.57	19.23
a	Clear Creek	35.5	Left	0.16	0.06	0.09	28.0	12.0	20.5
b	Bridge Creek	34.7	Left	0.11	0.04	0.06	28.4	12.2	20.8
c	1st Cert. 82405 Divers	33.75	—	0.00	−0.06	0.00			
d	Davis Creek	33.35	Left	0.04	0.02	0.03	32.2	13.8	23.6
e	Vinegar Creek	32.65	Right	0.08	0.02	0.04	34.6	14.8	25.4
f	2nd Cert. 82405 Divers	32.3	—	0.00	−0.06	0.00			
g	Vincent Creek	31.55	Right	0.03	0.01	0.02	29.8	12.8	21.8
h	Dead Cow Creek	31.45	Right	0.01	0.00	0.00	17.1	9.9	12.7
i	Deerhorn Creek	26.6	Left	0.08	0.03	0.05	35.2	15.2	25.7
j	Little Boulder Creek	25.85	Right	0.04	0.02	0.02	35.4	15.2	25.9
l	Little Butte Creek	23.75	Left	0.01	0.00	0.01	32.4	13.9	23.8
m	Hunt Gulch	23.3	Right	0.00	0.00	0.00	32.7	14.1	24.0
n	Butte Ck	19.25	Left	0.07	0.03	0.04	23.3	9.2	15.9
o	Granite Boulder Ck	17.55	Right	0.09	0.01	0.06	21.9	8.3	15.0
p	Ruby Creek	16.2	Left	0.02	0.01	0.01	22.0	9.0	15.7
q	Beaver Creek	16.15	Right	0.01	0.01	0.01	22.5	9.4	16.5
r	Ragged Creek	15.88	Left	0.01	0.00	0.00	25.8	11.2	18.9
s	Dry Creek	12.9	Right	0.00	0.00	0.00	38.3	16.4	28.0
t	Big Boulder Ck	11.4	Right	0.17	0.01	0.11	22.8	9.8	16.7
u	Dunston Creek	7.6	Left	0.00	0.00	0.00	27.7	11.9	20.3
v	1st Permit 28039 Divers	6.35	—	−0.12	−0.12	−0.12			
w	2nd Permit 28039 Divers	5.2	—	−0.03	−0.03	−0.03			
x	Camp Creek	3.25	Left	0.06	0.02	0.05	32.0	11.2	21.0

Values were extracted from 2002 data sets—modified from Crown and Butcher (2010). The model's boundary conditions were not changed in any air warming scenarios.

sensitivity analysis. Air temperature was modified with three different algorithms by adding a specified value to the hourly 2002 air temperature but maintaining a +4 °C average for each day (midnight to midnight). The first algorithm was the uniform case whereby all hourly values were increased by +4 °C. The second and third algorithms used the 'rubber band method'. In the warmer nighttime case, the maximum daily temperature was held constant, and other temperatures were changed in proportion to their difference from the maximum daily temperature. The minimum daily temperature (nighttime) was increased the most so we refer to this as the 'warmer nighttime case'. In the warmer day case, the minimum daily temperature was held constant, and other temperatures were changed in proportion to their difference from the minimum daily temperature. The maximum daily temperature (daytime) was increased the most so we refer to this as the 'warmer daytime case'. We reemphasize that the change in each day's average temperature was +4 °C for all three cases.

The equations for the mean values are, for all cases,

$$\overline{T_{d\Delta}} = \frac{\sum(T_i + \Delta)}{24} \tag{1}$$

$$\overline{T_{m\Delta}} = \frac{\sum_{j=1}^{d_e} \frac{\sum(T_i+\Delta)}{24}}{d_e} \tag{2}$$

where $\overline{T_{d_\Delta}}$ is the new average daily value after the addition, T_i is the air temperature at i hour of the 2002 day, Δ is the change in mean air temperature on a monthly basis, $\overline{T_{m_\Delta}}$ is the new average monthly value after the addition and d_e is the number of days in the month.

The equation for the uniform case is simply

$$T_i^* = T_i + \Delta \tag{3}$$

The equation for warmer daytime temperatures is

$$T_i^* = T_i + \frac{\Delta(T_i - \text{Min}_\text{d})}{\overline{T_d} - \text{Min}_\text{d}} \tag{4}$$

where $\overline{T_d}$ is the old daily average temperature, T_i^* is the new air temperature at i hour and Min_d is the daily minimum temperature. Other variables are as previously defined.

The equation for warmer nighttime temperatures is

$$T_i^* = T_i + \frac{\Delta(\text{Max}_\text{d} - T_i)}{\text{Max}_\text{d} - \overline{T_d}} \tag{5}$$

where Max_d is the daily maximum temperature. A comparison of Equations 3–5 shows that their averages are the same. Water discharge and temperature inputs at the upper end of the study section and from the tributaries were not modified from the original data set because our objective is to study the influence of the diurnal timing of air temperature. The water balance and input stream temperatures were the same as the original 2002 validated Heat Source model (Crown and Butcher, 2010).

For a detailed analysis of the effects of diurnal timing of air temperature changes, we chose two locations along the study section and one typical day in July. We chose an upstream site, at 22 rkm, and a downstream site, at 4 rkm. The upstream site is located at the edge of a relatively shaded stretch of the stream, downstream of some tributaries and minor diversions and at the location of the lowest 7-day average daily maximum (7dADM) value (Figure 1). The downstream site is located some distance from a shaded section, downstream of one major tributary (Big Boulder Creek) and major diversions (at 6.3 and 5.2 rkm) and at the location of a higher 7dADM value than the upstream site. The upstream site is located at a section that is characterized with high effective shade (>50%), whereas the downstream site is at a section with low effective shade (<10%). In addition, we chose one typical day in July for the sub daily analysis. A typical day, as we characterize it, has an average temperature and diurnal temperature range that represents the month. We chose 26 July 2002 as a typical day—the stream temperature average was 20.35 C° and the stream temperature range was 6.57 C°.

The 7dADM is a major water quality standard used by policy makers and stakeholders in Oregon and several states in the United States (USEPA, 2003). It is determined by calculating the moving average for the daily maximum for every model segment simulated by the model run. In our simulations, this period is 1 May to 31 August.

RESULTS

Air temperature for the month of July averaged 25.0 °C at 3.2 rkm for all simulated cases (Figure 2). However, the range of air temperatures was different for each case. The uniform case maintained the diurnal temperature variation present in 2002. The warmer daytime case generated a wider range of air temperatures than the warmer nighttime case.

The 7dADM stream temperatures increased, relative to 2002, for all three cases (Figures 3a and 3b). The 7dADM increase was greatest in the upper part of the study section for the daytime warming case and was greatest in the lower part of the study section for the nighttime warming case. The increase in 7dADM temperatures differed between cases by more than 1 °C in some locations but was the same between cases in other locations. The largest differences among the cases occurred at 7–10 rkm (moderate shade) and at 16–20 rkm (low shade). At the upstream site (22 rkm), the 7dADM increased by 1.1 °C under the uniform case, 1.2 °C under the warmer daytime case and 1.3 °C under the warmer nighttime case. At the downstream site (4 rkm), the 7dADM increased by 1.8 °C under the uniform case and 1.9 °C under both the warmer daytime and nighttime cases.

Diurnal changes in stream temperature in response to the three different warming cases are shown in Figure 4. The uniform case generated an increase in stream temperature that was nearly constant throughout the

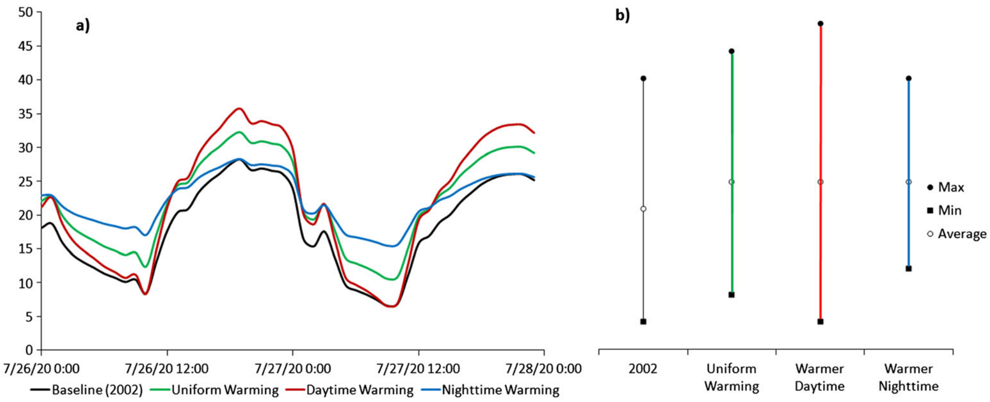

Figure 2. Air temperatures input at 3.2 rkm in July (close to the downstream site). (a) Diurnal temperature for 48 h for 2002 and for the warmer climate cases (all +4 °C): uniform, warmer daytime and warmer nighttime. (b) Air temperature ranges in July for 2002 and for warmer air cases

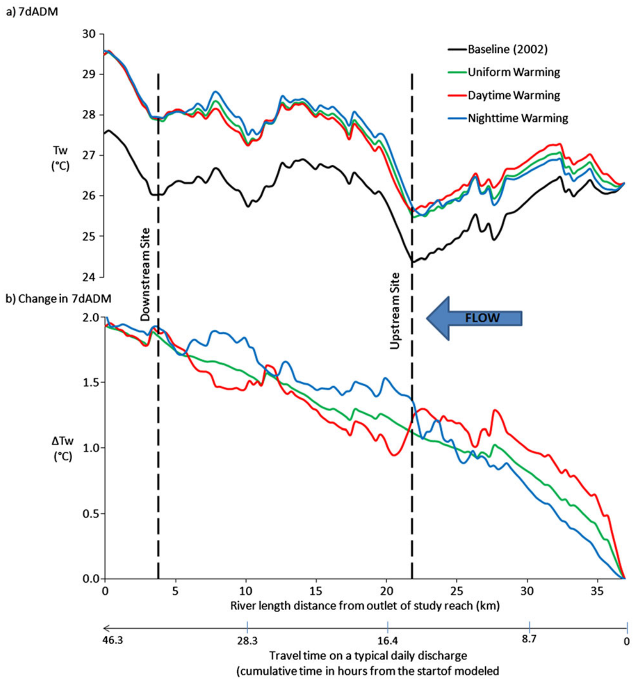

Figure 3. (a) 7dADM of stream temperatures responding to the three cases of warmer air (4 °C increase in average monthly air temperature), June–August. (b) Change in 7dADM stream temperatures responding to 4 °C increase in average monthly air temperature. The compared sites (indicated by dashed dark line) are at points where there is small different in 7dADM

day, 1.0 °C to 1.1 °C warmer at the upstream site and 1.8 °C to 2.1 °C warmer at the downstream site. The other two cases, however, generated an increase in stream temperature that varied throughout the day. Stream temperature increases ranged from as little as 0.4 °C warmer to as much as 2.2 °C warmer at the upstream site and from 1.1 °C to 2.7 °C warmer at the downstream site. For warmer daytimes, the stream temperature increases tended to be out of phase with stream temperature. For warmer nighttimes, the stream temperature increases tended to be in phase with stream temperature. Consequently, for the warmer daytime case, the largest stream temperature increases occurred around midnight, and these changes commonly decreased temperature swings from day to night. For the warmer nighttime case, the largest stream temperature increases occurred around midday, and these changes commonly increased temperature swings from day to night.

The temporal distribution of warmer air along the diurnal cycle influenced the magnitude and timing of change in stream temperatures (Figure 5). The uniform case resulted in smaller variability in changes in stream temperature relative to either the warmer daytime or the warmer nighttime. Both the warmer daytime and warmer nighttime cases generated many instances when stream temperatures were nearly 1.0 °C warmer or cooler than the uniform case.

The diurnal distribution of changes in air temperature influenced the duration (the number of hours per day) that stream temperatures increased (Figure 6). Warmer daytimes

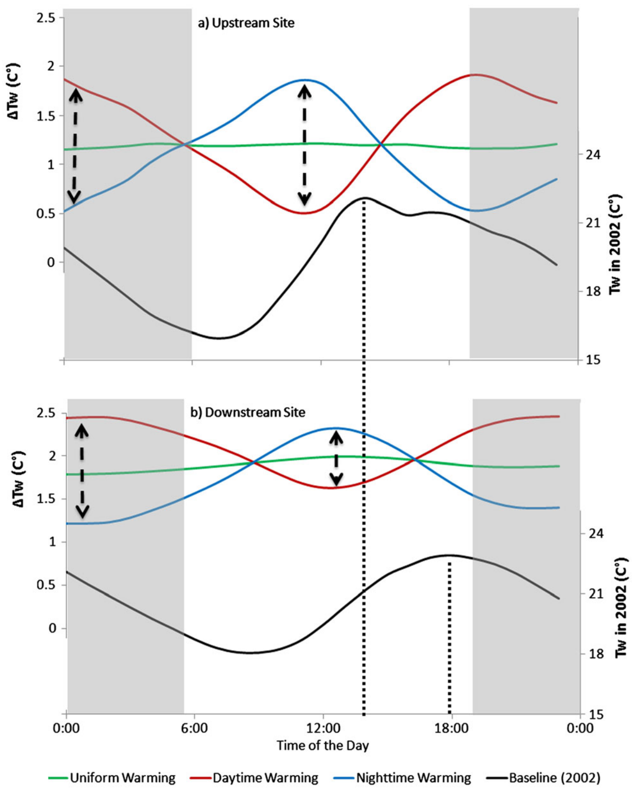

Figure 4. Diurnal fluctuation of stream temperature in 2002 (black line) and stream temperature changes responding to the three cases of warmer air. (a) Upstream site and (b) downstream site. The figure shows the results of a single day—26 July. The peak temperature in the 2002 case occurs earlier in the day at the upstream site than the downstream site, whereas the downstream site shows lower difference between warmer daytime and warmer nighttime change than the upstream site at the time of the peak temperature

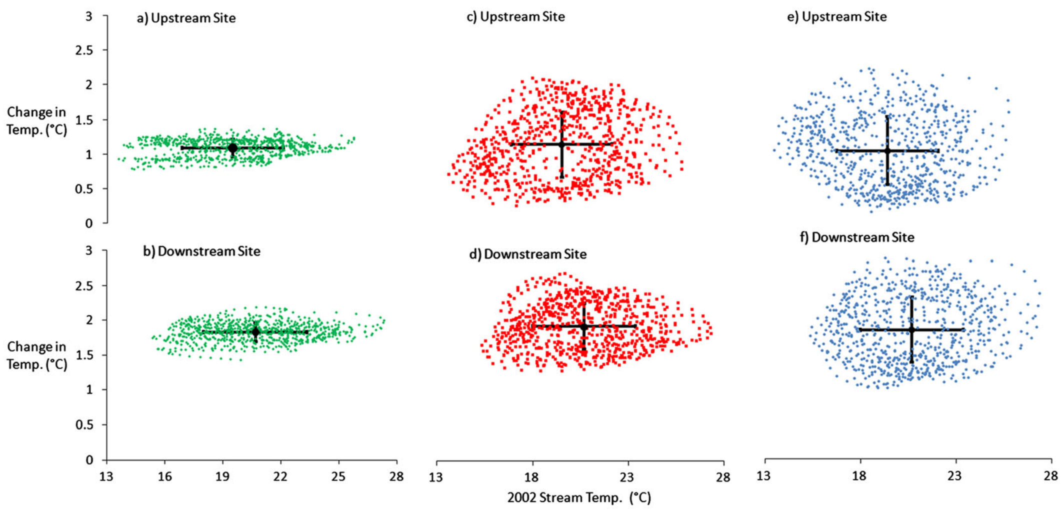

Figure 5. Range of changes in stream temperature relative to 2002 (simulation results) responding to the different warmer air cases at the upstream and the downstream sites. (a and b) Uniform case. (c and d) Warmer daytime case. (e and f) Warmer nighttime case

and nighttimes generated increases of stream temperature lasting for 1–2 h/day across a range of temperatures at the upstream site and 2–3 h/day across a range of temperatures at the downstream site. The uniform warming generated increases of approximately 8 h/day concentrated at approximately +1.1 °C at the upstream site and approximately 7 h/day concentrated at approximately +1.8 °C at the downstream site. Table II provides detailed duration information for two specific temperatures (18 °C and 22 °C). All warming scenarios show higher exceedance durations for both comparison temperatures at both sites. Yet, warmer daytime and nighttime differ than uniform warming. In particular, stream temperature increased for longer durations exceeding 22 °C under warmer daytime and nighttime. The downstream site shows the most differences between the different warming scenarios.

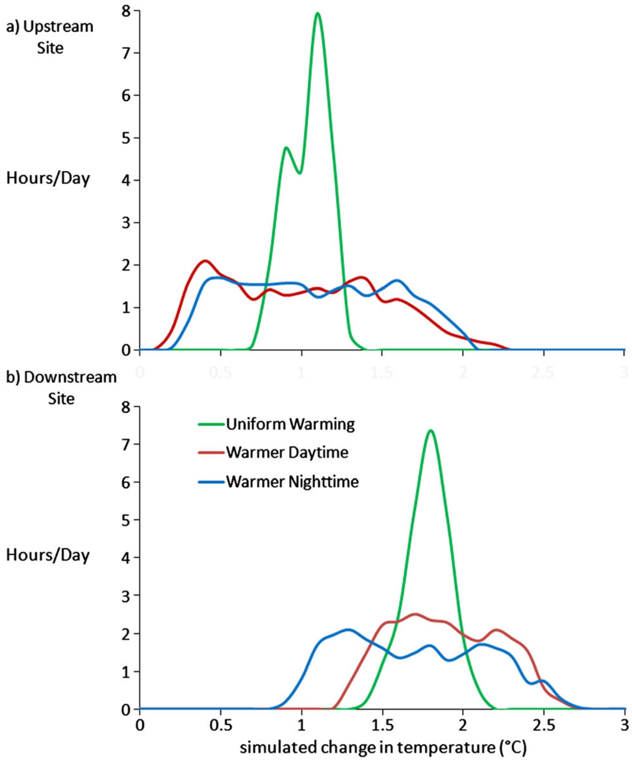

Figure 6. The daily average duration (h/day) of the change in stream temperature (summary for July simulation results). (a) Upstream site and (b) downstream site. The uniform case resulted in a moderate, narrow range of stream temperature increases for a longer duration than the warmer daytime and nighttime cases, which resulted in shorter durations for a wide range of change in stream temperature. Note that at 4 rkm, the warmer nighttime resulted in lower increases in stream temperatures than the warmer daytime

DISCUSSION

The effects of climate change on the heat budget

The stream's total heat flux for the 2002 base case (Figure 7) was positive (heat gain) during the daytime and negative (heat loss) during the nighttime. Solar radiation dominated the heat budget during the daytime; evaporation dominated the heat budget during the nighttime. Longwave radiation, air convection and bed conduction alternated between sources and sinks but were minor components of the heat budget.

The change in the total heat flux (Figure 8) was positive (heat gain) most of the time for all cases. In contrast to the total heat flux, longwave radiation and air convection were the largest contributors to the change. Solar radiation, the largest overall component of the total heat flux (Figure 7), was unchanged assuming cloud cover was unchanged.

For the uniform case (Figure 8a), the changes in the four major heat fluxes were approximately constant over the diurnal cycle. Relative to the 2002 base case, energy gains in air convection and longwave radiation added approximately 40 W/m^2 to the stream's total heat flux. Energy losses in evaporation and bed conduction removed approximately 10 W/m^2 from the stream's total heat flux. For the uniform case, the difference between air temperatures and stream temperatures increased everywhere and at all times. This difference was the primary driver of the nearly constant change in increased (net positive) air convection and longwave radiation heat fluxes and in decreased (net negative) evaporation heat flux. Total heat flux changes generated by diurnally uniform air temperature changes have been qualitatively similar in other studies (Stefan and Sinokrot, 1993; Mohseni and Stefan, 1999; Cristea and Burges, 2010).

For the warmer daytime and nighttime cases (Figures 8b and 8c), some of the heat fluxes varied significantly over the diurnal cycle. Relative to the 2002 base case, energy gains in air convection and longwave radiation added approximately 0 to approximately 70 W/m^2 to the stream's heat budget at different times of the day. Energy losses in evaporation and bed conduction removed approximately 5 to approximately 15 W/m^2 from the stream's heat budget. The change in the heat fluxes peaked between noon and midnight for warmer daytime case. The opposite was true for the warmer nighttime case, where the changes in the heat fluxes peaked between midnight and noon.

In general, the heat changes were in phase with air temperature changes, but stream temperature changes were out of phase with air temperature changes. Warmer daytime air temperatures generated positive daytime heat flux changes. In a simple, static system, temperature change is proportional to the integral of heat fluxes—that is, heat fluxes have a cumulative effect on temperature. Although the heat budget of a stream is not simple and the system is not static, heat fluxes still tend to have a cumulative effect on temperature. The simulation showed that the effect of changes in air temperature on stream temperature was lagged. Stream temperature changes

Table II. Exceedance duration under 2002 conditions simulation and lower than 4 °C increase in air temperature for the uniform warming, warmer daytime and warmer nighttime (summary for July)

		2002	Uniform warming		Warmer Day		Warmer Night	
Stream temperature	Site	(h/day)	(h/day)	Relative to 2002 (h/day)	(h/day)	Relative to uniform (h/day)	(h/day)	Relative to uniform (h/day)
>18 °C	Upstream	16.4	19.0	+2.6	18.7	−0.3	18.9	−0.1
	Downstream	19.7	23.4	+3.7	23.4	0.0	23.4	0.0
>22 °C	Upstream	4.5	7.6	+2.9	8.5	+0.9	7.9	+0.3
	Downstream	7.8	13.4	+5.6	13.7	+0.3	13.0	−0.4

Simulation results for all warming scenarios show longer durations of exceedance at both sites for both selected temperatures (18 °C and 22 °C). Results of warmer daytime and nighttime simulations show various durations compared with the uniform warming.

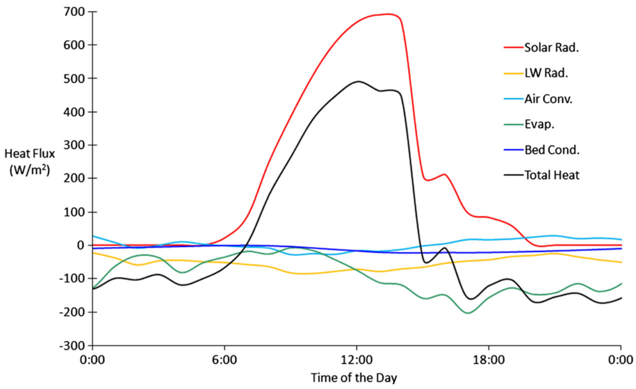

Figure 7. Components of the heat budget in 2002 at the downstream site. Solar radiation is the main driver of stream heat budget followed by longwave and evaporation. Air convection and bed conduction are the lowest

tended to be greatest after several hours of changed heat flux, so that warmer daytime air temperatures generated the greatest changes in water temperature at night. Similarly, warmer nighttime air temperatures were also out of phase with stream temperature changes, which were largest during the daytime. All three cases vary in influencing 7dADM calculations, among other stream temperature standards.

The 7dADM is calculated from the daily maximum stream temperatures. In the John Day River, those temperatures generally occur during the daytime (afternoon to evening). Daily maximum temperatures are lower at the upstream site than the downstream site. In addition, these peak temperatures occur during the early afternoon at the upstream site and towards the end of the day at the downstream site (Figure 4 shows a typical daily temperature cycle in July). Our simulations showed that the timing of air warming and its magnitude influence both the timing and the magnitude of stream warming. The results (Figure 4) indicated that nighttime air warming had the greatest influence on the daytime stream temperatures. At the upstream site for 26 July, the maximum difference in 7dADM between warmer daytime and nighttime scenarios was 1.6 °C at 11:00, whereas the difference at the maximum daily temperature was 0.7 °C at 15:00. At the downstream site, the maximum difference in the 7dADM between warmer daytime and nighttime scenarios was 0.9 °C at 14:00, whereas the difference at the maximum daily temperature was 0.6 °C at 17:00. Because the difference between stream temperatures under the warming scenarios is lower at the downstream site, the 7dADM values at this site tend to be similar.

The similarities in 7dADM values at the downstream site are partly due to cold-water inflow immediately upstream of this site. Tributaries entering the stream along the study section have influence on the stream heat budget. Although the warmer nighttime scenario has the potential to cause higher 7dADM values, cold tributaries entering the stream can offset the effect of a warmer nighttime. Two cold tributaries entering the stream upstream of the site: Dunston creek and Big Boulder Creek. Both streams have lower temperatures than the main stem Middle Fork John Day. In addition, Big Boulder Creek’s discharge is relatively high compared with other tributaries. Under these circumstances, warmer nighttime will yield smaller increases in daytime stream temperature and so the 7dADM is not increased as much, and warmer daytime will not have as large effect on daytime stream temperatures.

The increase in stream temperature averaged for 14 July was only 1.2 °C at the upstream site where heat fluxes were higher, as opposed to a 1.9 °C at the downstream site where heat fluxes were lower. This counterintuitive result is partly an artifact of the way we

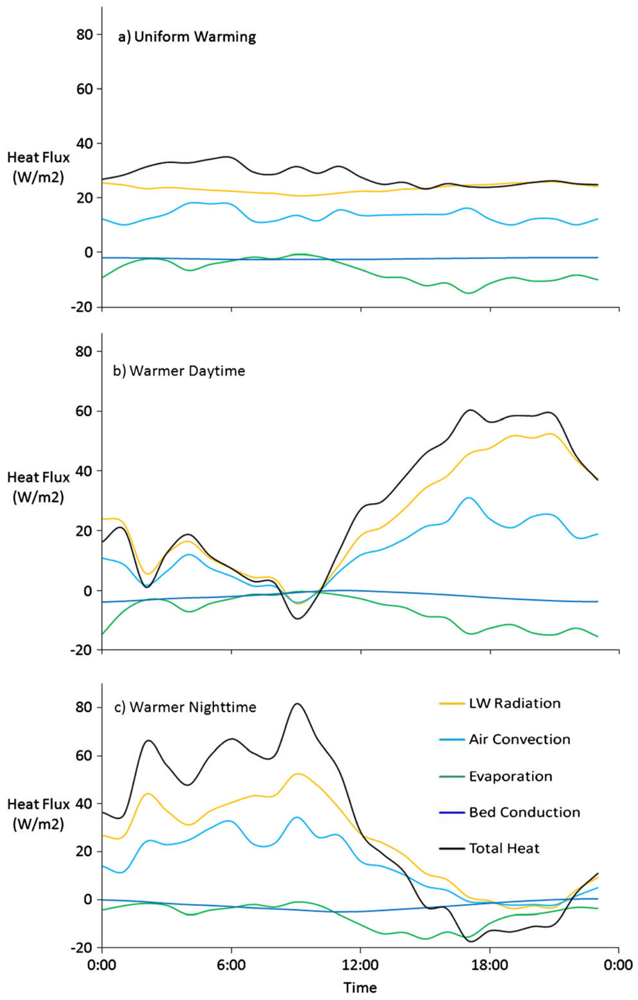

Figure 8. Changes to the heat fluxes under a warmer climate. The uniform warming case resulted a semi-uniform changes to all heat fluxes (other than solar radiation, whereas the model assumes no change to solar radiation). a counterintuitive results were shown under warmer daytime and nighttime cases: most of the change in heat fluxes occurred during the nighttime under daytime warming and during the daytime under nighttime warming. Changes to heat fluxes at the downstream site (not shown) were almost identical to those at the upstream site

set up our model runs. We held the upstream boundary condition for discharge and water temperature constant at its 2002 values for all simulations. Stream water heated as it flowed downstream because it was exposed to much warmer air temperatures. This heating was cumulative, so that downstream locations warmed more than upstream locations, regardless the heat fluxes at a particular point. This highlights the fact that stream temperature is a function of both cumulative upstream effects and heat fluxes at a given point throughout the diurnal cycle.

Model limitations

As is the case for any modeling study, the scope of our results is limited by our assumptions. Our simulations disregarded changes in boundary conditions for discharge and temperature at both the headwaters and the incoming tributaries. The longitudinal increase in stream temperature in our model simulations is, at least in part, an artifact of our modeling approach in which we kept upstream and tributaries discharge and temperature the same as the 2002 base case. We expect that the boundary conditions have significant impact on the stream's temperatures. These impacts are possibly critical to a prediction of stream temperature in a changing climate. However, the goal of this study was not the prediction influence of future condition on stream temperatures but to understand the sensitivity of stream temperatures to the timing of changes in air temperatures.

In our study, we used the 'one-at-a-time' sensitivity analyses approach to simulate the influence of changing one factor on stream temperature; that is, air temperature (for further information, see Saltelli *et al.*, 2006). We added one level of complexity when we simulated the time-related change in air temperature. In real stream conditions, many other factors are expected to change because of warmer climate. The influence of these changes on stream temperature was not studied in this article. Yet, modeling the influence of all changes in the system as a whole would yield better representation of future conditions.

Implications of different diurnal patterns of air temperature increases

We examined what is perhaps the simplest alternative way to distribute an average air temperature increase over time. Data currently available to us included downscaled projections of future air temperature changes resulting from ensemble means of many GCM runs (Mantua *et al.*, 2009 and 2010). These data provided an estimate of the future change in mean monthly air temperatures. However, modeling the sensitivity of stream temperatures to air temperature timing required hourly inputs of a variety of micrometeorological data, including solar radiation, air temperature, relative humidity and wind speed. This disparity between the data source and the data needed to run the model makes it difficult to use GCM outputs to project future changes in stream temperature.

Most previous attempts to model changes in stream temperature resulting from climate change have used the delta method, or uniform case, by taking a time series of weather data and adding a constant value to the air temperature (e.g. Caissie *et al.*, 2007; Cristea and Burges, 2010). However, climate-induced changes in air temperature are unlikely to be uniform (Alexander *et al.*, 2006; Morak *et al.*, 2011). Unfortunately, there are an unlimited number of ways that increased air temperatures could be manifest. They could result from short periods (days to a week) of each month with historically unprecedented and extremely hot weather, with air temperatures over much of the intervening time running near current long-term means. Alternatively, long periods could be slightly warmer than the historical mean. Clearly, an infinite number of potential time series could be produced for a sensitivity analysis using mechanistic models to examine possible effects on stream temperature. We chose to examine the potential effects of differential nighttime versus daytime warming because some studies have found that warm nights have become more frequent with time (Alexander *et al*., 2006). Also, the daytime and nighttime scenarios could be considered end members of possible distributions of warmer air, at least during a 24-h period.

Gooseff *et al*. (2005) found that warmer daytime air and increases in solar radiation led to larger maximum increases in stream temperature than warmer nighttime air, but that warmer nighttime air leads to more hours of moderate increase in stream temperature than warmer daytime air. The study of Gooseff et al. differed from ours in that their model's solar radiation changed. This difference, in addition to a different location, makes direct comparison difficult. However, the differences in results suggest that some conditions may generate in-phase changes of air temperature and stream temperature, whereas other conditions may generate out-of-phase changes. The reasons for the differences should be clarified by future research. Therefore, our results are in agreement with Gooseff et al. that nighttime warming of air is likely to lead to longer times of moderately warmer stream temperatures than daytime warming of air. Climate change with predominantly warmer nighttimes or predominantly warmer daytimes is likely to generate more extreme stream temperatures ranges.

Our results show that air temperatures of equal daily average but of different diurnal range led to different distributions of stream temperature changes. The warmer day/night cases generated periods of several hours duration that were warmer than would occur for the uniform case. Whether this difference is important will depend on the details of a stream's ecology and on the associated thresholds for ecological damage. Where streams are already close to temperature thresholds, the details of daytime or nighttime warming may be critical.

The 7dADM and the duration curves are similar for nighttime warming and daytime warming of the air. However, details on the timing are different—for example, nighttime versus daytime warming of stream temperature. The impact of these timing details is unknown. Much research for cold-water fish species has examined upper lethal temperature thresholds. Stream temperature regulates several environmental variables, from the concentration of dissolved oxygen to the rates of biogeochemical processes via Arrhenius' equation. Consequently, ecosystems may be sensitive in different ways to changes in the nighttime and daytime stream temperature regimes.

CONCLUSIONS

In the MFJD of Oregon, USA, simulations of a +4 °C increase in average July air temperature generated approximately +1.8 °C warmer 7dADM stream temperatures at the downstream end of a 37-km study section. Temperature changes concentrated in one part of the day (e.g., warmer daytime or warmer nighttime) led to a wider range of stream temperatures and more extreme temperatures than a uniform increase in air temperature. Changes in air temperature over the diurnal cycle had different timing than the changes in stream temperature. The changes in air temperature were generally out of phase with changes in stream temperature because of the cumulative nature of changes in heat fluxes on stream temperature. Warmer daytimes and nighttimes generated longer durations of the warmest stream temperatures. Together, the results suggest that stream temperatures in a warming climate are sensitive not only to the average temperature increase but also to the timing of the increase. We emphasize, however, that the upstream and tributary temperatures were not changed in our simulations. To make predictions of true changes to stream temperature, upstream and tributary temperatures matter, as well as any changes in shade and geomorphology.

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