Characteristics of annual water temperature profiles in snowmelt-influenced and rain-dominated watersheds

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Abstract

We describe a low-parameter model that characterizes the effect of snowmelt and the seasonal temperature cycle on stream temperature. A sinusoidal function describes a base seasonal cycle and a second sinusoidal function describes the snowmelt effect. The model was applied to 151 USGS gaging station data sets from east and west sides of the Cascade mountains. The model parameters are related to indices of summer, winter and annual temperatures, as well as watershed snow accumulation and the relative intensity of spring runoff. Because daily temperatures can be estimated from the parameters, the model is useful for predicting day-to-day temperatures on the scale needed to represent the effects of temperature on fish bioenergetics and stream ecology. The model should have utility for extrapolating coarse climate model predictions to within-season temperature patterns needed for modeling bioenergetic impacts of climate change.
Introduction

Because of the importance of temperature on stream ecology, and fish metabolism in particular [Brett 1979], significant efforts have been made to understand and predict water temperatures across various scales [Caissie 2006]. Seasonal index methods are common in many studies. For example, Petersen and Kitchell [2001] studied the implications of climate regimes on the bioenergetics of juvenile salmon predators of using bimonthly indices: April/May, June-Aug15, and Aug16-Oct. Connor et al. [2002] related the timing of life-history stages of Chinook salmon to a winter-spring average and a spring average temperature. Railsback and Rose [1999] used a July-Sept average water temperature for modeling inter-annual stream trout growth. However, seasonal average temperatures are poor at characterizing the important effects of temperature in regulating the timing of fish hatching and emergence and the extension of growth-favorable temperatures into the summer [Beer and Anderson 2001]. Models that do predict daily stream temperatures have been related to daily air temperatures through statistical regressions [Mohseni et al. 1998; Mohseni and Stefan 1999] or through stochastic methods that seek to remove the seasonal trend in temperatures and model the residuals.
over short time intervals [Ahmadi-Nedushan et al. 2007, Caissie et al. 1998]. See Caissie [2006] for a review. Higher resolution models that may capture these important deviations from pure sinusoidal patterns tend to be data intensive [Bogan et al. 2003, Sinokrot and Stefan 1993] and are therefore of limited use in evaluating systems where detailed information is sparse.

In general no low parameter model is available to project the combined effect of factors on the seasonal river temperature pattern at a scale relevant to stream ecology, but there is growing evidence for the relationship. For example, in a 30 km² Scottish watershed, indices for annual average, summer, winter and autumn temperatures over 30 years were steady while springtime temperatures had increased [Langan et al. 2001] with variability in the snowpack being the most likely explanation. Furthermore the available models do not generally address the combined effect of rain and snowmelt contributions to the seasonal patterns of flow and temperature, which is important to stream ecology and in particular to early life history of fish [Beer and Anderson 2001].

We present a six parameter model of daily stream temperatures that is driven by an annual temperature cycle modified by seasonal snowmelt. Using temperature information from USGS gaging stations in the Northwestern United States we illustrate that the stream temperature cycle provides valuable information on watershed hydrologic functions. Because the model characterizes basic seasonal patterns, we illustrate how the model parameters and therefore daily temperatures can be inferred from seasonal indices.
We model daily stream temperature, \( \theta_x \), as the sum of two factors: a continuous sine function, \( T_x \), principally characterizing the effect of the annual air temperature and a short-period sine function characterizing the effect of snowmelt \( S_x \) such that

\[
\theta_x = T_x - S_x
\]  

(1)

where \( x \) is the day. The annual factor is similar to one Ahmadi-Nedushan et al. [2007] used to portray seasonal air and water temperatures:

\[
T_x = A + B \sin \left( \frac{2 \pi x}{365} + C \right)
\]  

(2)

where \( A \) is the grand mean across a water year, \( B \) is the temperature range and \( C \) is a phase adjustment to capture the dates of the annual minimum and maximum temperatures. The cooling effect of colder snowmelt water that enters streams in the spring and is characterized as:

\[
S_x = \begin{cases} 
\frac{1}{2} D \left[ 1 - \sin \left( \frac{2 \pi x}{F} \right) \right] & \text{for } x \geq E + F \leq x \leq E + F \\
0 & \text{for } x < E \text{ and } E + F < x
\end{cases}
\]  

(3)

where \( D \) is the snowmelt magnitude, \( E \) is the snowmelt beginning date, and \( F \) is the snowmelt duration. \( S_x \) ensures that the contribution of snowmelt to temperature only occurs between days \( E \) and \( E + F \). To decouple the effects of snowmelt from the annual
air temperature cycle we also impose that the snowmelt end date occur at or before the fitted maximum temperature, \( \max \hat{\theta}_x \):

\[
E + F \leq x_{\max \hat{\theta}_x}
\]  (4)

This condition helps to decorrelate parameter D from A and B and improves the relation of model parameters to environmental properties.

The model is fit to data with the Gauss-Newton algorithm that minimizes the sum of squares. Data is divided according to the water year, which begins on October 1 and ends September 30.

To characterize the fit we computed the root-mean-squared error (RMSE) between the observed and model-predicted temperatures using the formula:

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\theta_{x_i} - \theta_{\text{Obs,}i})^2}{n - 6}}
\]  (5)

Data

We obtained water temperature data from a USGS web site for gaging stations across Oregon, Washington and Idaho [USGS 2007] after completion of the NWISWeb Refresh of Water Quality announced on January 25, 2007. All temperature records included in the analysis could be obtained from one of these methods (in preferred order): 1) daily mean temperature, 2) average of daily minimum and maximum, 3) AM or PM temperature.
Sites or individual years were eliminated if January temperatures were absent or the fitted parameters were out of reasonable bounds defined: $2 \leq A \leq 20$, $-25 \leq B \leq 25$, $0 \leq D \leq 20$, $100 < E < 250$, $F \geq 30$.

We obtained information on snowpack depth and density in terms of a Snow Water Equivalent (SWE), which is measured at 750 Snow Telemetry (SNOTEL) sites throughout the Northwest by the Natural Resources Conservation Service [NRCS 2007].

For the Idaho sites chosen for detailed analysis, we used April indices from “Kootenai basin”, “North Fork Clearwater”, and “Salmon River”. In Oregon, we used two or three SNOTEL sites in each of the watersheds that had concurrent records in April and averaged the earliest April record to obtain a single index for the SWE. The Oregon SNOTEL sites were: Marion Forks Pillow, Santiam Jct. SNOTEL, Ski Bowl Road, Mount Ashland Switchback, and Big Red Mtn Pillow. In the Skagit watershed in Washington, we used Meadows Cabins, Freezeout Creek Trail, New Lake Hozomeen, Thunder Basin Pillow, and Devils Park SNOTEL sites.

Air temperature data was obtained from the National Climatic Data Center web site [NCDC 2007] with air temperature records from Dworshak Dam, ID; Spokane Airport, WA; Medford Airport, OR; Salem Airport, OR; and Bellingham Airport, WA.

Results

We fit the temperature model defined by equations (1), (2) and (3) to data from USGS gaging station sites in Washington, Oregon and Idaho with all years combined for each site. A total of 151 sites (Figure 1) met our criteria for the water temperature data and a
subset of 75 had data from five or more years. A total of 76 sites were fit using records
from < 5 water years, 46 sites were fit using records from 5-10 water years, 16 sites were
fit using records from 11-20 water years and 13 sites used records from >20 water years.
The distribution of the RMSE of the model fit to data was close to normal with a mean of
1.43°C and a standard deviation of 0.34°C.

Figure 2 illustrates the model fit to the 2005 temperature data for the Anatone, WA
gaging station on the Snake River and Figure 3 illustrates the corresponding flows with
the beginning and end of the model-determined snowmelt season delineated. At this site
snowmelt had a significant impact on spring stream temperature.

The six model coefficients have identifiable relationships with the seasonal distribution
of temperature and snowmelt. We denote parameter A as a mean temperature index in the
absence of snow effects on water temperatures. Across the sites the mean temperature
index had a linear relationship (p < 0.0001, $R^2=0.81$) with the observed average
temperature over the water year (Figure 4a). A Melt Index (MI), A – D, expresses the
difference between the mean temperature index and the maximum temperature deviation
attributable to snowmelt. Across rain-dominated and snow-dominated watersheds, this
Melt Index exhibits a linear relationship (p < 0.0001, $R^2=0.72$) with the average river
temperature in April and May (Figure 4b). A winter index, defined A – B, has a strong
linear relationship (p < 0.0001, $R^2=0.97$) with average January stream temperatures
(Figure 4c). Correspondingly a summer index, defined A + B, is significantly related (p <
0.0001, $R^2=0.92$) to the observed August/September average stream temperatures
(Figure 4d).
Parameter D characterizes the effect of snowmelt on spring temperatures and is related to
the fraction of the yearly runoff that occurs in the spring. To characterize this
relationship we define the flood-to-base flow ratio (FBR) as the ratio of the average flow
during the snowmelt period to the average flow during the remainder of the water year.
The parameter E characterizes the beginning of the snowmelt influence and F the
duration of the influence, which corresponds with the interval of increased runoff from
snowmelt (Figure 3). (FBR) is calculated as

\[
FBR = \left( \frac{365 - F}{F} \right) \left( \frac{\sum_{i=E}^{E+F} flow_i}{\sum_{i=1}^{365} flow_i - \sum_{i=E}^{E+F} flow_i} \right)
\]  

where i has a one day increment. For the Anatone, WA gage site in Figure 3, FBR = 2.38.
The ratio varies according to the degree of rain and snowmelt contributions to the flow.
Across the streams depicted in Figure 1, FBR has an exponential relationship with the
snowmelt parameter (D). This is expressed in a linear form as:

\[
\log FBR = a + bD
\]

where a = 0.392 and b = 0.204, with \( R^2 = 0.46 \) (Figure 5).

In addition, we explored how the model characterized site-specific temperature and
snowmelt patterns from six watersheds (Table 2); three east of the Cascade Range crest
and three west of the crest (Figure 1). The six individual sites are depicted in Figure 6
showing river temperature and flow over the entire year, as well as the modeled
temperature and the model-determined boundaries of the flood period. Each year was fit separately for comparison of yearly parameters within the watershed to corresponding yearly environmental variables. Since air temperature accounts for snow level fluctuations, variability in snowmelt rates [Kane et al. 1997; McCabe and Clark 2005], and is the most important controlling factor in water temperatures [Caissie et al. 1998, 2001; Ozake, et al. 2003; Ahmadi-Nedushan 2007], we examined the relationship of air temperature to parameter A as well as the relationship of the SWE to the April/May water temperatures and MI.

The streams east and west of the Cascade mountain crest are distinct. East of the crest, there is no significant relationship (p > 0.2) between the air temperature mean and parameter A, but there are notable effects of SWE on spring temperatures and flows (p < 0.0001 to p = 0.08). West of the Cascade crest, conditions appear to be reversed. The air temperature and parameter A are correlated, while SWE is not a significant predictor of April/May water temperatures or the Melt Index (p > 0.2), except for the Rogue River (gage #14372300) watershed where SWE is a significant predictor of April/May water temperatures (p = 0.0002).

In the six rivers for all years, the relationship between D and FBR expressed by equation (7) has an $R^2 = 0.4$ (not shown). The transformed relationship gives

$\log R = 0.151D - 0.158$, which follows the pattern obtained using all rivers in the regression (Figure 5).
The parameters exhibited little correlation across the 151 sites (Table 1), but within sites, correlations between parameters were quite variable(). For example,

Discussion

A six parameter model was fit to USGS gaging station water temperature data from the states of Washington, Oregon, and Idaho, USA. It characterizes seasonal temperature patterns and explicitly accounts for a snowmelt season. The model concisely describes day-to-day temperatures across an entire year and is thus useful for bioenergetic and growth models which require this level of detail. In addition, the parameters can be used to infer a number of properties of water temperatures and the complete seasonal profile can be used to de-trend seasonal temperature patterns with applications to stochastic modeling. The reduced residuals of detrended time-series should be easier to model with other mechanisms. The parameters and the indices derived from model fit have intuitive meanings: A is essentially the annual mean, B is one half of the range, C is the phase of the cycle, D is the magnitude of the snowmelt influence, E is the beginning of the snowmelt season and F is its duration. The model accounts for a spring snowmelt period explicitly and collapses to the simpler three parameter sinusoidal model when the snowmelt parameter (D) and/or the duration of the snowmelt season (F) diminishes.

The model parameters across the 151 sites are poorly correlated (Table 1), and by inference, the seasonal processes they describe are as well. However, this does not hold up within sites where strong positive and negative correlations between parameters do exist but are inconsistent across different types of watersheds (Table 3). This also
supports the idea that local characteristics of the watershed play an important role in creating the watershed’s temperature patterns.

Seasonal temperature conditions appear to be well modeled as is shown by the high correlations of the parameters to the winter, spring (Melt Index) and summer indices (0.97, 0.72, and 0.92 respectively) and good year-round modeling of temperatures (average RMSE = 1.43°C with a standard deviation of 0.34). The relationship of FBR to D (Figure 5) is non-linear because FBR is open ended whereas D, in practice, is constrained to fall between 0 and A.

In addition, emergent properties such as the strong correlation of MI to SWE for individual watersheds indicate the relative importance of the snowpack for controlling river temperatures and highlights the differences between the eastside and westside watersheds. In general, if the model-defined flood period brackets the observed spring flood interval, then SWE is an important predictor of spring water temperatures and MI.

The Salmon and Clearwater rivers in Idaho are heavily influenced by snowmelt and have large D parameters (Figure 7b and Figure 7c). They also have large FBR and SWE values, making April/May water temperatures more predictable (Table 2).

West of the crest, air temperatures have a stronger influence on the annual mean water temperature. While snowmelt is important, it is generally overshadowed by rain that otherwise dominates as the source of stream flow. The Skagit River temperature profiles are noted for a very small value for parameters B and D (Figure 7f). Although the headwaters are glacier fed, the river is regulated by a storage reservoir upstream which
also makes FBR insignificant. While air temperature is generally a good, first-order predictor of water temperature for one-week time scales [Mohseni et al. 1998], the relationship between annual average air temperature and annual average water temperature is not as strong. Further, as Mohseni et al. [1999] demonstrated, air temperatures do not have a simple blanket effect on water temperatures because many local aspects of the watershed contribute to the water temperatures: drainage area, weather patterns, local geomorphology, etc.

Still, in a rain-dominated watershed, air and rain temperatures are correlated because the lag time between rain-fall and stream flow is minimal. In the snow-dominated watershed, the water (in the form of snow) is stored for months and only when it reaches the melt-point does it contribute to the stream’s thermal regime. This does not deny the role that annual air temperature plays in determining water temperatures in a snow-dominated watershed, but rather that additional mechanisms are vital to understanding the relationship.

The role of snowmelt on temperatures (Parameter D, MI) and flow patterns (FBR) has important implications for stream ecology. For example, Beer and Anderson [2001] found that flow and temperature patterns in the Methow River, WA explained the spatial-temporal separation of two life-history strategies of Chinook salmon. Therefore, if snow-related patterns of melt and runoff change, the temperature and flow patterns will also change and therefore we surmise that the distributions of the life history strategies would be affected.
Finally, we suggest that this model, which generates realistic seasonal stream temperature profiles from seasonally average thermal and snow indices, has value for projecting the impacts of coarse scale predictions of global climate models to the finer scale impacts needed to assess consequences of climate change on river ecology.

Notation

$\theta_x$ stream temperature on day x, °C.

$\hat{\theta}_x$ estimated temperature on day x, °C.

A mean annual temperature parameter, °C.

B half of the annual range temperature parameter, °C.

C phase of the annual temperature model, days.

D maximum magnitude of the snowmelt contribution to water temperature, °C.

E beginning of the snowmelt (flood) period, day of year.

F duration of the snowmelt (flood) period, days.

MI melt index, °C.

$p$ statistical probability of obtaining the relationship observed if it did not in fact exist, dimensionless.

FBR flood-to-base flow ratio, dimensionless.

RMSE root mean squared error, °C.

$R^2$ correlation coefficient, dimensionless.

$S_x$ snowmelt contribution to stream temperature on day x, °C.
SWE  snow water equivalent, (field units) inches

$T_x$  sinusoidal model stream temperature on day $x$, °C.

$x$  day of year

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Figure 1. Locations of 151 USGS sites analyzed for temperature profiles. The light line demarks the crest of the Cascades. The six sites at which the effects of snowmelt and air temperature on water temperature were characterized in detail (Table 2) are identified A-F and their watersheds are shaded. Anatone site denoted by ▲.

Figure 2. Gaging station #13334300, Anatone, WA, temperature data for water year 2005 (October 2004 to September 2005) with the six parameter model fit and a three parameter fit. The thermal significance of each of the parameters is shown as well. Mean (A) = 12.8, Range (B) = 9.9, Phase (C) = 157, Snowmelt (D) = 5.0, Begin (E) = 179, and Duration (F) = 133.

Figure 3. Gaging station #13334300, Anatone, WA, flow data (m$^3$·s$^{-1}$) for water year 2005 (October 2004 to September 2005) The vertical lines are the beginning and end of the “flood” season defined with E and E+F. The Flood-to-Base Flow Ratio (FBR) is 2.38.

Figure 4. Relationships of model indices from the 151 sites that had sufficient environmental data. Each point is a single site. Regression line are significant at p < 0.0001. (a) Mean (A) and True Mean of Data in each year. (b) Melt Index A-D vs. April/May average temperatures. (c) Winter index A-B vs. January average temperatures. (d) Summer index A+B vs. August/Sept. average temperatures.
Figure 5. Non-linear relationship of Flood:Base Flow Ratio ($R$) to Parameter D ($R^2 = 0.46$) for 151 sites.

Figure 6. Temperatures (°C) and flows ($m^3/s$) from six watersheds. The solid lines are the model fits. Vertical lines in the flow plots identify the beginning and end of the “Flood” period identified from the model fit to the temperature data.

Figure 7. Histograms of Snow Parameter (Parameter $D$) for six watersheds, depicting their unique characteristics.
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Figure 7 Histograms of Snow Parameter (Parameter $D$) for six watersheds, depicting their unique characteristics.
Table 1. Correlations of temperature model parameters to each other across 151 sites.

<table>
<thead>
<tr>
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<th>C</th>
<th>D</th>
<th>E</th>
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<td>E</td>
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Table 2. Yearly analysis for six sites with SWE and average annual air temperatures (over the water year). “NS” indicates that the relationship is not significant (p > 0.2). Three large watersheds east of the Cascades and three small watersheds west of the Cascades are shown in Figure 1.

<table>
<thead>
<tr>
<th>Map Location</th>
<th>A</th>
<th>B</th>
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<tbody>
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<td>MI vs. SWE</td>
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Table 3 Correlation of model parameters across years within the six sites. The sign on the correlation depicts positive or negative correlations.

<table>
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