Air-Stream Temperature Correlation In Forested And Urban Headwater Streams In The Southern Appalachians

By: **Chuanhui Gu**,1* **William P. Anderson Jr**,1 **Jeffrey D. Colby**2 and **Christopher L. Coffey**2

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Air-stream temperature correlation in forested and urban headwater streams in the Southern Appalachians

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Abstract:

Air temperature can be an effective predictor of stream temperature. However, little work has been done in studying urban impacts on air-stream relationships in groundwater-fed headwater streams in mountainous watersheds. We applied wavelet coherence analysis to two 13-month continuous (1 hr interval) stream and air temperature datasets collected at Boone Creek, an urban stream, and Winkler Creek, a forest stream, in northwestern North Carolina. The main advantage of a wavelet coherence analysis approach is the ability to analyse non-stationary dynamics for the temporal covariance between air and stream temperature over time and at multiple temporal scales (e.g. hours, days, weeks and months). The coherence is both time and scale-dependent. Our research indicated that air temperature generally co-varied with stream temperature at time scales greater than 0.5 day. The correlation was poor during the winter at the scales of 1 to 64 days and summer at the scales of 1.5 to 4 days, respectively. The empirical models that relate air temperature to stream temperature failed at these scales and during these periods. Finally, urbanization altered the air-stream temperature correlation at intermediate time scales ranging from 2 to 12 days. The correlation at the urban creek increased at the 12-day scale, whereas it decreased at scales of 2 to 7 days as compared with the forested stream, which is probably due to heated surface runoff during summer thunderstorms or leaking stormwater or wastewater collection systems. Our results provide insights into air-stream temperature relationships over both time and scale domains. Identifying controls over time and scales are needed to predict water temperature to understand the future impacts that interacting climate and land use changes will have on aquatic ecosystem in river networks. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS stream temperature; urban; multi-scale; time series; Southern Appalachians

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INTRODUCTION

Stream temperature is one of the most important measures of water quality and of considerable significance to aquatic ecology and water resources (Caissie 2006; Webb *et al*. 2003). Water temperature is especially vital to aquatic ecosystems in cold-water streams that support trout and other cold-water fish species. Trout populations prefer colder climates and cold-water streams in high-altitude regions such as the Southern Appalachians. In this region, urban development can adversely affect the temperature of cold-water streams. Elevated stream temperatures due to urbanization have been recognized as the key contributor to stream habitat loss for cold-water species (Wang *et al*. 2003); however, understanding urban impacts on the stream temperature regime, especially in mountainous headwaters, is still quite limited.

Urbanization increases stream baseflow temperature through modification of the flow regime (Anderson *et al*. 2011; Webb *et al*. 2008), increased solar heating due to decreased riparian canopy shading(Krause *et al*. 2004) and direct inputs of heated wastewater (Kinouchi 2007), which may cause deterioration of cold-water stream habitat (Somers *et al*. 2013). Urbanized streams generally have lower groundwater input but higher stormwater inflows than non-urbanized streams. Recent studies have found larger thermal heterogeneity in urban streams than in forested streams (Somers *et al*. 2013). Summer storm runoff over hot impervious surfaces can cause acute thermal pollution in urban streams (Herb *et al*. 2008). Heated storm runoff accounted for temperature surges of more than 7 °C associated with summer thunderstorms at urbanized headwater streams in the Piedmont region of Maryland, USA (Nelson and Palmer 2007), and greater than 6 °C in the Blue Ridge Province (Anderson *et al*. 2010).

Climate and land use changes are likely causes of alterations in stream temperature, which, in turn will affect stream ecological health (Kaushal *et al*. 2010). It is critical to understand the mechanisms with which stream

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temperature responds to climate change. Small headwater streams are especially sensitive to transient thermal disturbances such as thermal pollution due to their limited thermal capacity. Headwater streams are also more vulnerable with respect to hydrologic disturbance from urban land use because they typically have higher relief, small drainage areas and thin soil layers compared with higher order streams (Wohl 2010). The problem is especially serious in the Southern Appalachians, where native fish species are already facing an increasing threat from rising stream temperatures (Flebbe *et al.* 2006). Cold stream environments may be in danger from a combination of global warming, urban sprawl and decreasing riparian vegetation, where stream temperatures may rise above the maximum tolerance level of fish species. The study of small-order headwater streams, the primary habitat for trout species, is extremely lacking, which makes it challenging to understand the impact of potential global climate changes on these streams.

Previous attention has been given to the relationships between air and stream temperatures (Mohseni and Stefan 1999). Air temperature is a widely used independent variable in regression models to predict stream temperatures because it is a surrogate for the net energy balance that may affect the water surface (Mohseni and Stefan 1999), and air temperature data are usually readily available. A weekly time scale is often used in regression models because diurnal and other transient factors are averaged away at this scale. Short-term water temperature variation (e.g. daily), however, may be crucial to aquatic organisms adaptation capability and tolerance level. Few research efforts have studied stream temperature fluctuations at shorter time scales. Steel and Lange (2007) found that dams significantly attenuated temperature variation at short time scales less than 8 days in the Willamette River Basin, Oregon. Zolezzi *et al.* (2011) also found that thermopeaking by reservoir release can induce short-term alterations in water temperature and highlighted its importance in better understanding complex drivers of the river thermal regime.

Air-stream temperature correlation is not constant over time and frequency (or time scale, and they will be used interchangeably hereafter) domains. Previous studies have found that the correlation increases from 2 h, through daily to weekly scales (Stefan and Preudhomme 1993), but weaker sensitivity at annual scales (Webb and Nobilis 1997). Some studies have found that the air-stream temperature relationship changes with stream flow (Webb *et al.* 2003), groundwater contribution (O'Driscoll and DeWalle 2006) or urban development (Erickson and Stefan 2000). However, none of these studies have investigated the temporal pattern of air-stream temperature correlation. Also missing from previous studies is the identification of the temporal scale at which correlation reaches a maximum or minimum.

Our approach is unique in that we address the aforementioned knowledge gaps by exploring the temporal dynamics of air-stream temperature relationships at multiple scales from sub-daily to monthly. The main goal of this study is to explore the temporal scales and the time of year at which air temperature controls stream temperature using wavelet analysis of high-resolution continuous stream and air temperature data collected for two headwater streams in the Southern Appalachians. This paper presents the first application of the continuous wavelet transform to the analysis of air-stream temperature relationships. We address three questions: (1) at which time scales (e.g. hours, days or weeks) are the correlations (if any) between air and stream temperatures most pronounced?, (2) do the correlations change over time or are they influenced by some transient disturbance? and (3) how does urbanization affect the relationships described in the aforementioned questions? By identifying the time scales, timing and urbanization impacts of air-stream temperature correlation, the answers to these three questions will inform how streams respond to interacting land use and climate change in the Southern Appalachians.

METHODS

Study site

The study sites are located in the Upper South Fork of the New River (USFNR) watershed, which includes the Town of Boone in the Blue Ridge Physiographic Province in northwestern North Carolina (Figure 1). Rainfall distribution is even with an annual average ranging between 1000–1400 mm/year. Normal mean annual air temperature is 9.4 °C with the daily average temperature in July of 20.3 °C and daily average temperature in January of −0.4 °C (North Carolina State Climate Office). The streams we studied are third and fourth order perennial streams, Boone Creek and Winkler Creek, respectively, nested in the headwaters of the USFNR. The streams can be classified as mountain streams with high topographic relief, thin soils and the close proximity of hillslopes (Turner *et al.* 2013). Previous studies have found that urban infrastructure has caused thermal pollution in Boone Creek (Anderson *et al.* 2010; Rice *et al.* 2011). In addition, long-term stream temperature data reveal that 71 temperature surges occurred over four summers of data collection with a mean temperature increase of 2.39 °C and a maximum increase of 6.36 °C (Anderson *et al.* 2011). In contrast, Winkler Creek flows through primarily forested areas. The sub-basins share similarities in drainage area, relief and bedrock geology, which make them highly comparable paired sub-basins with which to screen out land use impacts. The USFNR watershed has a wide range of fish species including cold-water fish species (e.g. trout) that require cool temperatures and abundant dissolved oxygen.

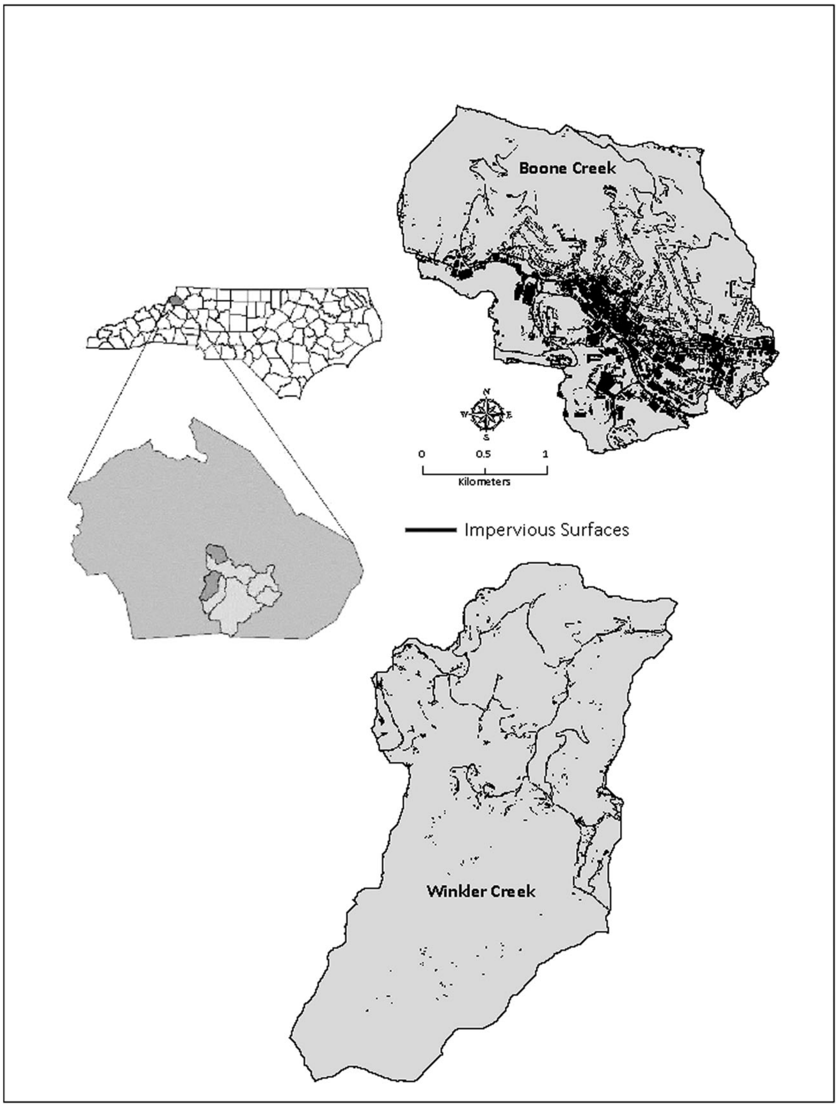

Figure 1. Map of Winkler Creek and Boone Creek watersheds in Upper South Fork of the New River watershed located in Boone, NC. Boone Creek with a drainage area of 5.3 km^2 (upper right) is an urban stream with approximately 23.5% impervious cover, whereas Winkler Creek with a drainage area of 6.99 km^2 (bottom right) is a forested stream with approximately 3.76% impervious cover

The area of the Boone Creek sub-basin is approximately 5.3 km^2. The elevation ranges from 960 to 1426 m, with a mean elevation of 1071 m. The mean slope of the sub-basin is 16°, with an orientation generally trending from the northwest to southeast (Figure 1). The main channel of Boone Creek has a reach length of 2877 m with a mean annual discharge of 0.1 m^3/s and flows through the urban area of the Town of Boone and the Appalachian State University campus. The percentage of impervious area within the entire sub-basin is approximately 23.5%, and the percentage of impervious area within a 12.2 m buffer of all the streams in the drainage area is 32.2%. The percentage of forested area within the entire sub-basin is approximately 60.2%, and the percentage of forested area within a 12.2 m buffer of the streams in the drainage area is 48%. The percentage land cover values were calculated on the basis of impervious and forested layers classified from 1-m spatial resolution aerial photography (aggregated from 15.2-cm resolution aerial photography), acquired in 2010, using the software programme Feature Analyst (Overwatch Textron Systems, Sterling VA) implemented as an extension in the geographic information system ArcMap (ESRI, Redlands, CA). Overall accuracy for each of the land cover classifications was 96%, with a Kappa statistic of 0.84 for the impervious classification layer and 0.91 for the forested layer (Coffey 2011). Fish species commonly found in Boone Creek include Blacknose Dace (*Rhinichthys atratulus*), Creek Chub (*Semotilus atromaculatus*), Stone Roller (*Campostoma anomalum*) and Rosyside Dace (*Clinostomus funduloides*).

The area of the Winker Creek sub-basin is approximately 7 km^2.The elevation of Winkler Creek ranges from 990 to 1332 m, with a mean elevation of 1124 m. The mean slope of the sub-basin is 17°, with an orientation generally trending from the southwest to northeast (Figure 1). The main channel of Winkler Creek has a reach length of 5210 m with a mean annual discharge of 0.2 m^3/s and flows through forested areas. The percentage of impervious area within the entire sub-basin is approximately 3.8%, and the percentage of impervious area within a 12.2 m buffer of all the streams in the drainage area is 5.3%. The percentage of forested area within the entire sub-basin is approximately 86.6%, and the percentage of forested area within a 12.2 m buffer of all the streams in the drainage area is 81%. Fish species commonly found in Winkler Creek include Blacknose Dace (*R. atratulus*), Brown Trout (*Salmo trutta*) and Green sunfish (*Lepomis cyanellus*).

Water temperature data were collected as a part of a long-term water quality monitoring programme. We used Troll 9500 multi-parameter sonde (In-Situ Inc., Ft.Collins, CO, USA) to record temperature every 15 min from June 2010 to present. Hourly, 2-m air temperature data were obtained from NC State Climate Office. The air temperature station is located about 3 km away from the two stream temperature measurement sites. Data gaps exist in the stream temperature data because of sporadic failure of the instruments; thus, only data records from June 2010 to September 2011 that are free of large gaps have been included in the analyses. Some short-term missing data (i.e. <2 days) caused by the instrument calibration were interpolated from neighbouring days to obtain an adequate sample size of long-term temperature time series.

Wavelet analysis

We used wavelet analyses to examine air-stream temperature relationships at multiple time scales simultaneously by decomposing a complicated signal into the time-frequency domain (Torrence and Compo 1998).

The continuous wavelet transform of a time series (x_n, $n = 1,\ldots, N$) with uniform time steps δt is defined as the convolution of x_n with the scaled and normalized wavelet:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n' - n)\delta t}{s} \right] \quad (1)$$

where N is the number of points in the time series, ψ^* is the normalized wavelet function at scale s and translated in time by n, and the (*) indicates the complex conjugate.

In this study, we used the Morlet wavelet because of its suitability to detect oscillating patterns (*Torrence and Compo* 1998):

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \quad (2)$$

where ω_0 is the non-dimensional frequency and η is dimensionless time.

Following Torrence and Webster (1999), we define wavelet coherence as the absolute value squared of the smoothed cross-wavelet spectrum, normalized by the smoothed wavelet power spectra,

$$R_n^2(s) = \frac{|s^{-1} W_n^{XY}(s)|^2}{s^{-1}|W_n^X(s)|^2 \; s^{-1}|W_n^Y(s)|^2} \quad (3)$$

where the angular brackets indicate a smoothing in time and scale, n is the time index and s is the scale, $W_n^X(s)$ and $W_n^Y(s)$ are wavelet transforms of time series X and Y, respectively. $W_n^{XY}(s)$ is the cross-wavelet spectrum defined as $W_n^{XY}(s) = W_n^X(s) W_n^{Y^*}(s)$, where (*) indicates the complex conjugate. Note that this definition is similar to a traditional correlation coefficient. As a result, $R_n^2(s)$ values range from 0 to 1. Wavelet coherence is superior to the cross-wavelet transform because it can find covariation between two time series in the time-frequency domain even without high common power (Grinsted *et al.* 2004).

Because there is a large amount of information presented in a wavelet coherence plot, it is often necessary to extract this abundant information by averaging the results over scales or times. One technique is to average the correlation coefficients at every scale over the whole time series to compare them across scales, which leads to a plot of R^2 *versus* scale. The time-averaged wavelet coherence is defined as

$$R_n^2(s) = \frac{1}{N} \sum_{0}^{N-1} \left| R_n^2(s) \right| \quad (4)$$

where N is the length of the time series. It is also desirable to condense the results for a single scale. The result is a graph of R^2 at a given time scale *versus* time. The temporal dynamics of wavelet coherence at a given time scale can thus be obtained (Grinsted *et al.* 2004).

RESULTS

The wavelet coherence analysis indicated that a strong correlation between air and stream temperature generally existed when the time scale was longer than 0.5 day (Figure 2). The red areas (showing significant correlations) were not continuous throughout the analysed period, because data gaps existed in the winter and summer seasons of 2011. There was an extensive correlation disappearance from December 2010 to March 2011, while the correlation disappearance was more sporadic from May to September 2011. The results indicated that variables other than air temperature may explain stream temperature variation during those periods. In addition, the time scales over which the correlation decreased were different in the summer and winter of 2011. Specifically, the correlation disappearance in the summer occurred over the periods between 1.5 and 4 days, whereas missing correlations in the winter were

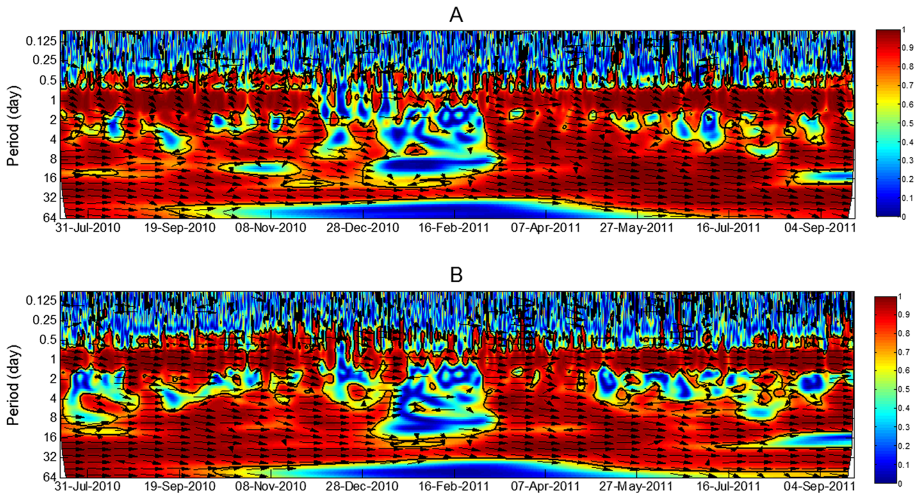

Figure 2. Wavelet coherence analysis and phase difference between air temperature and stream temperature of (A) Winkler and (B) Boone Creek from 15 July 2010 to 6 September 2011. The phase difference is shown by arrows: in-phase pointing right (no lags between time series). The colour codes for power values are from dark blue (low values) to dark red (high values). Black contour lines represent the 5% significance level, and the thick black line indicates the cone of influence that delimits the region not influenced by edge effects. The red to blue colour gradient represents the decreasing correlation coefficient

associated with a wide range of time scales from 1 day to 64 days. Finally, there were fewer low-correlation moments in the summer of 2011 in Winkler Creek than in Boone Creek.

Noteworthy, the regions where the correlation is lacking are associated with periods of stress characterized by winter freezing days (i.e. below-zero degrees Celsius air temperature) and summer groundwater-dominant baseflow conditions (i.e. stream fed by groundwater) as shown in the corresponding temperature time series in Figure 3. In the summer of 2011, there was a much lower variation in stream temperatures than air temperature, probably because of stronger thermal inertia caused by cold groundwater inputs. In the winter of 2011, the correlation between in air-stream temperatures disappeared when air temperatures dropped below the freezing point while stream water temperatures stayed above zero degrees (Figure 3(B)).

To better illustrate the changes of air-stream temperature correlation at different time scales, we constructed global wavelet coherence spectra, which is the time-averaged correlation coefficient R^2 across time scales (Figure 4). Sub-daily air-stream temperature correlation was generally low (<0.7). Daily and monthly scales are two time scales at which R^2 reached a maximum (0.95), whereas at bi-daily and bi-monthly scales R^2 reached local minima of 0.57 and 0.47, respectively.

The spectra also indicate the time scales most affected by urbanization with respect to air-stream temperature correlation. The strongest alteration in the correlation is

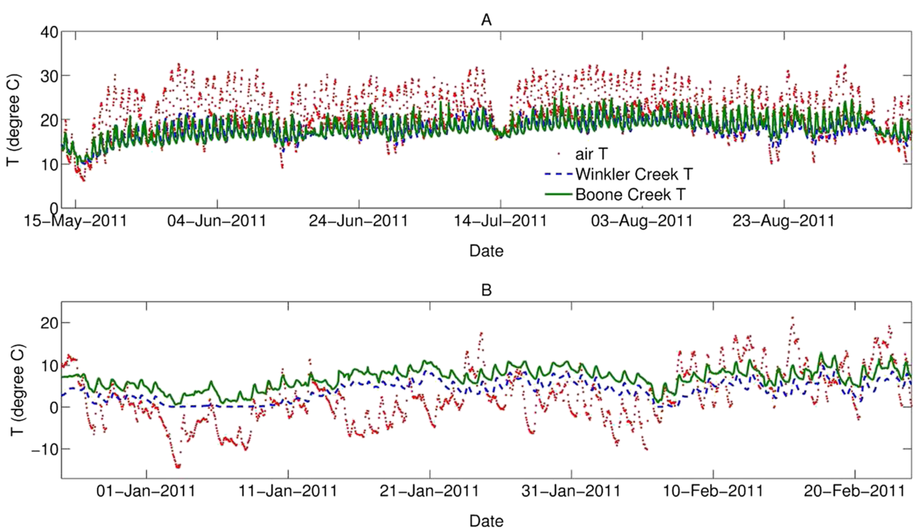

Figure 3. The time series of air temperature and stream temperature for Boone Creek and Winkler Creek during (A) Summer 2011 and (B) Winter 2011

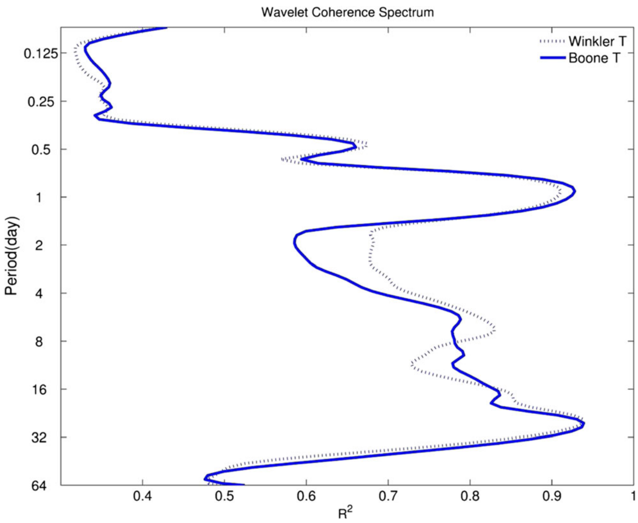

Figure 4. Global wavelet coherence spectra of air-stream temperature relationships for Boone Creek and Winkler Creek

associated with short time scales of around 2 days, where the correlation coefficient of Boone Creek is 15% lower than that of Winkler Creek. Intermediate time scales ranging from 2 to 15 days also showed significant differences in R^2 values between the two streams. Specifically, time-averaged R^2 values of Boone Creek were lower than that of Winkler Creek at the weekly scale, while the converse was true around time scales of 12 days.

The single-scale wavelet coherence is useful to examine how the air-stream temperature correlation at a certain time scale changes over time. We focus on the strongly altered bi-daily scale by urbanization (Figure 5). Figure 5(A) shows the wavelet coherence (i.e. R^2) computed at the bi-daily scale for both streams. The overall R^2 values were relatively low at this scale and decreased over the winter and summer seasons. Differences in R^2 between Boone Creek and Winkler Creek can be used to examine alterations of correlation at a given time scale of interest. Figure 5(B) illustrates quantified R^2 differences (Boone Creek–Winkler Creek) at the bi-daily scale. Zero values of R^2 differences indicate the absence of alteration. Correlations were lower in Boone Creek than Winkler Creek, as represented by negative ΔR^2 values for the majority of period, especially in the summer 2011. In contrast to bi-daily scale, the weekly wavelet coherence plot shows consistently high R^2 values (i.e. >0.8) through the study period except for the winter of 2011 and early August in 2011 (Figure 6). In general, correlation coefficients R^2 were lower in Boone Creek than Winkler Creek.

DISCUSSION

Previous studies have used regression analysis to investigate air-stream temperature relationships (Krider *et al.* 2013; Webb *et al.* 2003). However, these analyses failed to capture both scale-dependent and time-dependent features of stream-temperature-controlling processes. The advantage of wavelet analysis is its ability to quantify the time series in both time and frequency domains.

Water and air temperature were strongly correlated (i.e. $R^2 > 0.5$) in both streams at most times of year and across a majority of temporal scales. Even stream temperature variations at the 0.5-day scale were well explained by variations in air temperature, with R^2 of almost 65%. However, there is little variation in stream temperature at the scales less than 0.5 day that can be explained by air temperature. This is consistent with previous studies that reported the weakest correlation at sub-daily time scales (Caissie 2006) because other factors such as riparian shading and time lag are important at these short time scales. Erickson and Stefan (2000) suggest that small

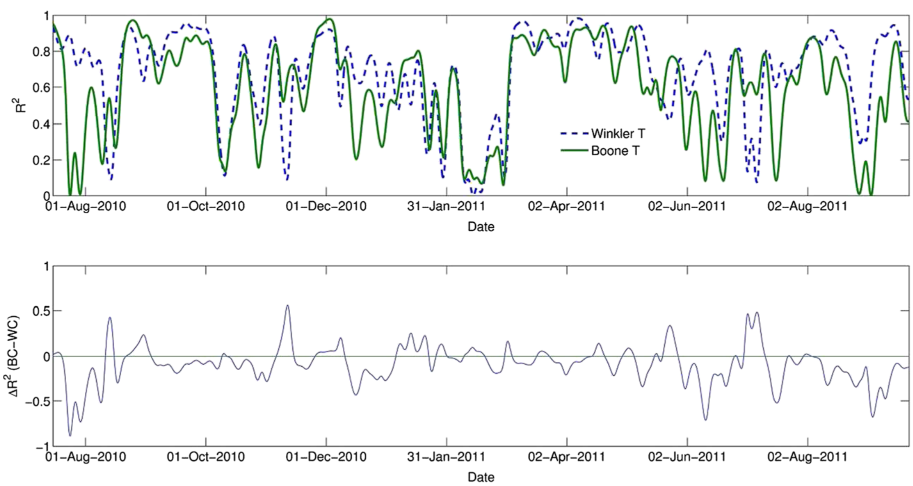

Figure 5. Bi-daily wavelet coherence of air-stream temperature for Boone Creek (solid line) and Winkler Creek (dash line) (A); and the difference of Bi-daily wavelet coherence ΔR^2 (Boone Creek–Winkler Creek) (B)

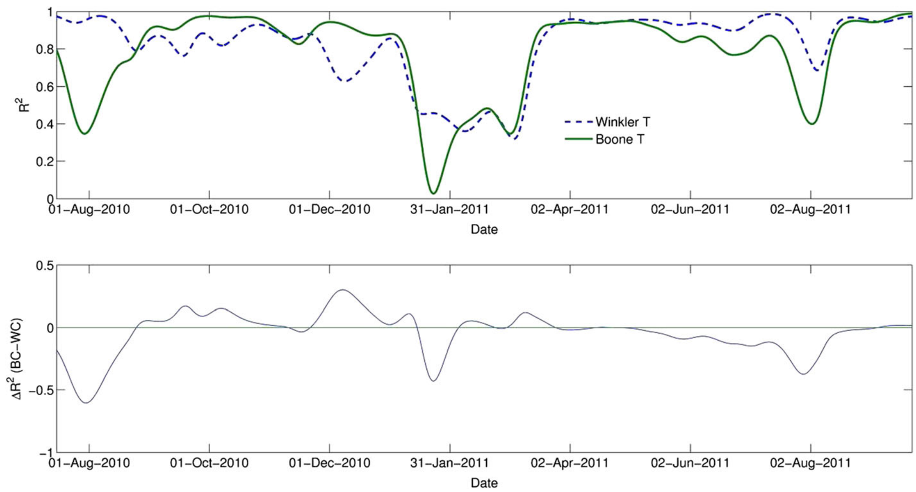

Figure 6. Weekly wavelet coherence of air-stream temperature for Boone Creek (solid line) and Winkler Creek (dash line) (A); and the difference of weekly wavelet coherence ΔR^2 (Boone Creek–Winkler Creek) (B)

watersheds and high groundwater input might lead to low correlations between air and water temperature; however, we find that the mean R^2 values at the weekly scale are 0.78 and 0.8 for Boone Creek and Winkler Creek, respectively, which fall within the range of R^2 values from 0.59 to 0.98 found on 40 streams in Minnesota (Krider *et al.* 2013). The two sub-basins in the current study have small drainage areas; therefore, the thermal capacity of the streams is low, which facilitates air-water temperature equilibrium.

Our results do not support previous findings in that the correlations of air-stream temperature increase as the time scale increased from hourly, through daily, to weekly (Erickson and Stefan 2000). The weekly scale, which is most often used for air-stream temperature relationship analysis, was not the best-correlated time scale for these mountainous headwater streams. Rather, the correlation of air-stream temperature peaked at daily and monthly time scales in our study. This implies that, at least in this mountainous headwater region, the accuracy of regression models based on air temperatures may be the highest at daily and monthly scales rather than a weekly scale, whereas the regression models at sub-daily, bi-daily or bi-monthly scales may not be reliable because of the low correlation of air-stream temperature.

The link between air and stream temperature was not constant throughout the period studied, and other drivers of stream temperature may exist. We were able to detect two period windows when air-stream temperature correlation was poor: (1) short time scales (i.e. approximately 1.5 to 4 days) during the summer 2011, when evaporative cooling might limit stream temperature rise and (2) time scales from 1 day to 64 days during the freezing events in winter 2011, when stream temperatures often reached 0 °C as an asymptote (Figure 2). This is consistent to a classic S-shaped curve of air-stream temperature relationship (Mohseni and Stefan 1999). Mohseni and Stefan (1999) suggested that evaporative cooling contributes to breakage of air-stream temperature correlation when air temperature rises beyond 25 °C. Groundwater input and riparian shading in addition to evaporative cooling at our sites might further reduce the air-stream temperature correlation because canopy shade and percentage of total flow as groundwater are both at their greatest levels in the summer. Shading and baseflow reduce the high stream temperatures encountered in summer, essentially removing the temperature extremes. The small drainage areas at our sites may contribute further to low air-stream temperature correlation because the short residence time of the stream water does not allow equilibration with the atmosphere (Erickson and Stefan 2000). Kelleher *et al.* (2012) found that small streams (stream order ≤3) with high groundwater contributions have low thermal sensitivities, defined as the slope of the air-stream temperature relationship, as streams are kept cool during summer by groundwater influx. Our study suggested that the strength of air-stream correlation in addition to the slope might also be influenced by environmental factors such as groundwater input and riparian shading.

The summer and winter anomaly of air-stream temperature correlation varied with respect to time scales. The correlation discontinuity in the winter was associated with the time scales ranging from 1 to 64 days, which was due to the cold climate in this mountainous region, where weekly averaged air temperatures in winter can drop well below the freezing temperature. On the other hand, the correlation disappearance in the summer was associated with shorter time scales from 1.5 to 4 days. The summer air-stream temperatures were still strongly correlated at the weekly scale. This was probably due to sporadically high temperatures in such a high-elevation region so that weekly averaged air temperatures did not rise sufficiently to affect water temperature at this time scale. Levelling off of stream temperatures at high air temperatures did not necessarily exist for weekly air-stream temperature relationships in these cold-climate headwaters. Erickson and Stefan (2000) also found that groundwater inflow, stream shading and wind sheltering do not typically affect the strength of correlation at the weekly scale. These findings imply that predicting stream temperature at high (>25 °C) air temperature from regression models is still reliable as long as a weekly time scale is used. Thus, it may not be necessary to include evaporative cooling effects in constraining the impact of higher air temperatures under scenarios of global warming for this high-altitude region and probably many parts of the Southern Appalachians.

Urbanization has some minor impacts on the strength of air-stream temperature relationships. The annually averaged correlation coefficients of air-stream temperatures in Boone Creek were lower than those at Winkler Creek at a scale of 2 to 7 days (Figure 4). Previous studies have shown that urbanization increases stream thermal sensitivity because of lower baseflow and riparian shading (Kelleher *et al.*, 2012). The present study indicates that the strength of air-stream temperature relationships can be further reduced by urbanization. In urban settings, artificial heat inputs such as effluent from large underground stormwater collection systems can significantly disrupt the air-stream temperature relationship. In addition, summer heated runoff over impervious surfaces may further weaken air-stream temperature relationships by introducing more scatter (i.e. temperature spikes). The reduction of R^2 at weekly scales by urbanization (Figure 4) questions the robustness of weekly air-stream temperature regression models. Conversely, the increased correlation coefficient at 12-day scales in the urban stream might be attributed to reduced baseflow and limited riparian shading in urban settings.

The characteristics of stream temperature at short time scales might have been completely neglected if time-averaged data were used, despite the fact that short time scale stream temperature dynamics and its control strongly affect cold-water fisheries. For instance, it is critical to predict both maximum and minimum temperatures in order to assess the stress and subsequent recovery periods of aquatic species during periods of high stream temperature (Breau *et al.* 2007). This confirms the need for high temporal resolution datasets to characterize the stream temperature regime. Furthermore, the present study indicates that processes controlling stream temperatures might dominate at different time scales and different times of the year, which might have potential ecological consequences.

CONCLUSIONS

Stream temperature response to future potential climate and land use changes can be understood through air-stream temperature correlation, which indicates how much variance of stream water temperatures are explained by air temperature. Both scale-dependent and time-dependent features of air-stream temperature relationships are largely missing in previous studies. This paper presents the first analysis of air-stream temperature relationships across both time and frequency domains using wavelet analysis. Through a comparative study of stream temperatures in forested and urban headwater streams, air-stream temperature correlations in both streams were found to be dynamic in our study. Poor correlations were found between stream and air temperatures in the winter and summer seasons. However, weekly air-stream temperature relationships were still strong in these cold-climate headwaters. Thus, it may not be necessary to include evaporative cooling effects in restraining the impact of higher air temperatures under scenarios of global warming for this high-altitude region and probably many parts of the Southern Appalachians. The annually averaged correlations were also found to be scale-dependent. The maximum correlations occurred at daily and monthly time scales, whereas the minimums were associated with sub-daily, bi-daily and bi-monthly time scales. This implies that daily and monthly scales are the best for regression models of air-stream temperature for this mountainous region. The correlation of the urban stream was higher at the 12-day scale and lower at the 2- to 7-day scale, when compared with the forested stream, which challenges the predictive validity of regression models of air-stream temperature relationships. Identifying controls over different time scales is needed to predict water temperature to better understand the potential future impacts of the interacting effects of climate and land use changes on aquatic ecosystem in river networks.

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