JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 43, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2007

STREAM TEMPERATURE SURGES UNDER URBANIZATION AND CLIMATE CHANGE: DATA, MODELS, AND RESPONSES[1]

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ABSTRACT: Multiple anthropogenic stressors, including increased watershed imperviousness, destruction of the riparian vegetation, increased siltation, and changes in climate, will impact streams over the coming century. These stressors will alter water temperature, thus influencing ecological processes and stream biota. Quantitative tools are needed to predict the magnitude and direction of altered thermal regimes. Here, empirical relationships were derived to complement a simple model of in-stream temperature [developed by Caissie *et al. Canadian Journal of Civil Engineering* **25** (1998) 250; *Journal of Hydrology* **251** (2001) 14], including seasonal temperature shifts linked to land use, and temperature surges linked to localized rainstorms; surges in temperature averaged about 3.5°C and dissipated over about 3 h. These temperature surges occurred frequently at the most urbanized sites (up to 10% of summer days) and could briefly increase maximum temperature by >7°C. The combination of empirical relationships and model show that headwater streams may be more pervasively impacted by urbanization than by climate change, although the two stressors reinforce each other. A profound community shift, from common cold and coolwater species to some of the many warmwater species currently present in smaller numbers, may be expected, as shown by a count of days on which temperature exceeds the "good growth" range for coldwater species.

(KEY TERMS: temperature; urbanization; climate variability/change; precipitation; flashiness; critical thermal maxima; impervious surface; temperature surge.)

Nelson, Kären C., and Margaret A. Palmer, 2007. Stream Temperature Surges Under Urbanization and Climate Change: Data, Models, and Responses. *Journal of the American Water Resources Association* (JAWRA) 43(2):440-452. DOI: 10.1111/j.1752-1688.2007.00034.x

INTRODUCTION

Water temperature is one of the primary underlying variables driving or constraining a range of biotic and abiotic processes in streams. Water temperature regimes will in turn be affected by a bewildering array of anthropogenic stresses over the coming century, including impacts associated with the widespread paving of watersheds, the destruction of riparian vegetation, and altered temperature and precipitation regimes due to climate change (Poff *et al.*, 2002; Gleick, 2003; Allan *et al.*, 2004; Van Sickle *et al.*, 2004). Many impacts associated with land use change have been well documented (Paul and Meyer, 2001; Walsh *et al.*, 2001). Deforestation has been shown to cause overall warming of stream water, increases in soil temperature, and

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[1] Paper No. J05088 of the *Journal of the American Water Resources Association* (JAWRA). Received June 30, 2005; accepted May 30, 2006.

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decreases in evapotranspiration (Hewlett and Forston, 1982; Bourque and Pomeroy, 2001; Krause *et al.*, 2004). Increased impervious surface exacerbates these effects by reducing infiltration and thus baseflow, which causes streams to be more "flashy" (Pluhowski, 1970; Rose and Peters, 2001; Brabec *et al.*, 2002). During extended low-flow and drought periods, shallow water becomes heated. Conversely, during heavy rains, runoff washes over hot pavement, producing temporary spikes in temperature (Galli and Dubose, 1990).

Land use change and climate change produce potentially interacting stresses at a range of temporal scales. With 3-5°C warming projected to occur nationally (National Assessment Synthesis Team, 2001), climate change will clearly cause some warming of streams, but the exact consequences depend on the seasonality of temperature shifts (Pilgrim *et al.*, 1998; Allan *et al.*, 2004). The global circulation models used to forecast climate change also predict more variability in precipitation and runoff in many parts of the world (Alcamo *et al.*, 2003). Fewer but more intense storms could produce drought- and storm-related heating in much the same way that urbanization does. Interactions between land use change and climate change could, for example, result in a situation where larger amounts of impervious surface are available to absorb heat, large storms are more likely, and their heated runoff is channeled more quickly into the stream.

Given the likelihood of significant changes in climate and of increased urbanization, there is a need for models which simulate their impacts and their interactive effects (Sarewitz *et al.*, 2000; Benda *et al.*, 2002). Models specifically focusing on urban streams have developed slowly compared to models for non-urban watersheds (Krause *et al.*, 2004). LeBlanc *et al.* (1997) modeled the physical processes associated with energy balance equations, focusing on riparian vegetation, groundwater impacts, and changes to the stream's hydraulic geometry. Krause *et al.* (2004) modified the Stream Network Temperature Model to assess changes in stream thermal habitat under altered streamflow, shade, and channel width. Both of these models require significant levels of parameterization and calibration, which may not be feasible at large numbers of sites. In addition, relatively few long-term, in-stream temperature series exist for low-order urban streams, where short-term warming effects (such as heated runoff during summer storms) would be expected to be the strongest. Collecting such data is not a simple matter; temperature loggers have become affordable, but maintaining them is difficult because loggers get washed away, silted in, or buried in these highly flashy systems. Thus in general, while stream temperature models are well-developed in many respects, understanding of urban stream temperature dynamics lags.

Climate and land use change models often cover large areas using a GIS framework; for this reason, a stream temperature model which minimizes the requirements for calibration would be ideal. Specifically, such a model would allow inputs that are available as geographic coverages to be used. Many regions around the world have extensive GIS data for characterizing land use, forest cover, and impervious surface. The national Land Use Land Cover Database (LULC, available at U.S. Geological Service, 2005) is one example; high resolution, smaller scale land use coverages are also available for many cities and counties in the U.S.

Overall stream health is of course dependent on a wide variety of factors in addition to temperature, including hydrology, geomorphology, habitat structure, and water quality (Fausch *et al.*, 1984; Karr, 1991). Nevertheless, water temperature is one critical element, because it regulates many processes, biotic and abiotic, in the stream. A temperature model that explicitly includes urban effects but has minimalist data requirements will benefit managers who need to make decisions about the development of watersheds. For example, temperature has long been seen as a "master" variable controlling survival, growth and recruitment of fish (Brett, 1956). Bio-energetic considerations suggest that above or below certain temperatures, fish cannot take in enough calories to offset their metabolic costs, regardless of the availability of food (Warren and Davis, 1971). "Good growth" temperature ranges have been measured for cold and coolwater species, respectively (Fang *et al.*, 2004a,b). Measurement of such sublethal stress is an important but often-overlooked component of ecosystem integrity (Rose, 2000). Thus, the maintenance of temperature within a range that allows good growth for fish provides one example of the way in which temperature affects overall stream health.

Here, empirical relationships linking urbanization and climate change to stream temperatures are presented for small urban streams. First, long-term temperature is correlated with land use, and then temperature surges due to summer thunderstorms are characterized. Finally, the empirical relationships are fit into a simple model (parameterized for an urbanizing watershed north of Washington DC) which uses future land use predictions and time-series from downscaled climate models to predict stream temperature. As an illustration of the magnitude of effects possible, the model is used to predict the probability of exceeding temperatures at which growth can occur for cold and coolwater fish (Fang *et al.*, 2004a,b), given realistic assumptions about climate change and land development.

METHODS

Temperature time-series were collected between summer 2002 and summer 2004 from 16 first to third order streams within five small watersheds just north of Washington DC, in the Piedmont region of Maryland (Figure 1; for full description see Moglen, 2000; Moore and Palmer, 2005). A century ago this landscape was dominated by agriculture; however, the sites now span a range of highly urbanized (closest to Washington DC) to mostly agricultural (farthest from Washington DC). In addition, one first order site (Little Bennett) is located in a state park and drains mostly forested land.

For each site, several indices of land cover/land use were recorded (Table 1): (1) % urban land in the subwatershed draining to the point, defined as the sum of high and medium density residential, commercial, and industrial land uses, (2) total impervious surface in the subwatershed, (3) total impervious surface in the buffer (defined here as the 50 m zone on either side of the stream), for the entire stream length above the measuring site, (4) deforestation in the subwatershed, defined as the sum of non-forested land use areas, and (5) deforestation in the 50 m buffer zone. Land use and impervious surface data were taken from a high-resolution space-time data series developed using aerial photographs, current county-level land use maps, property tax information, and property boundaries (described in Moglen *et al.*, 2004; summary land use data available at http://www.watersheds.umd.edu). Deforestation was available from the Regional Earth Science Applications Center (2004). Average baseflow discharge was also measured once each season for a year and averaged.

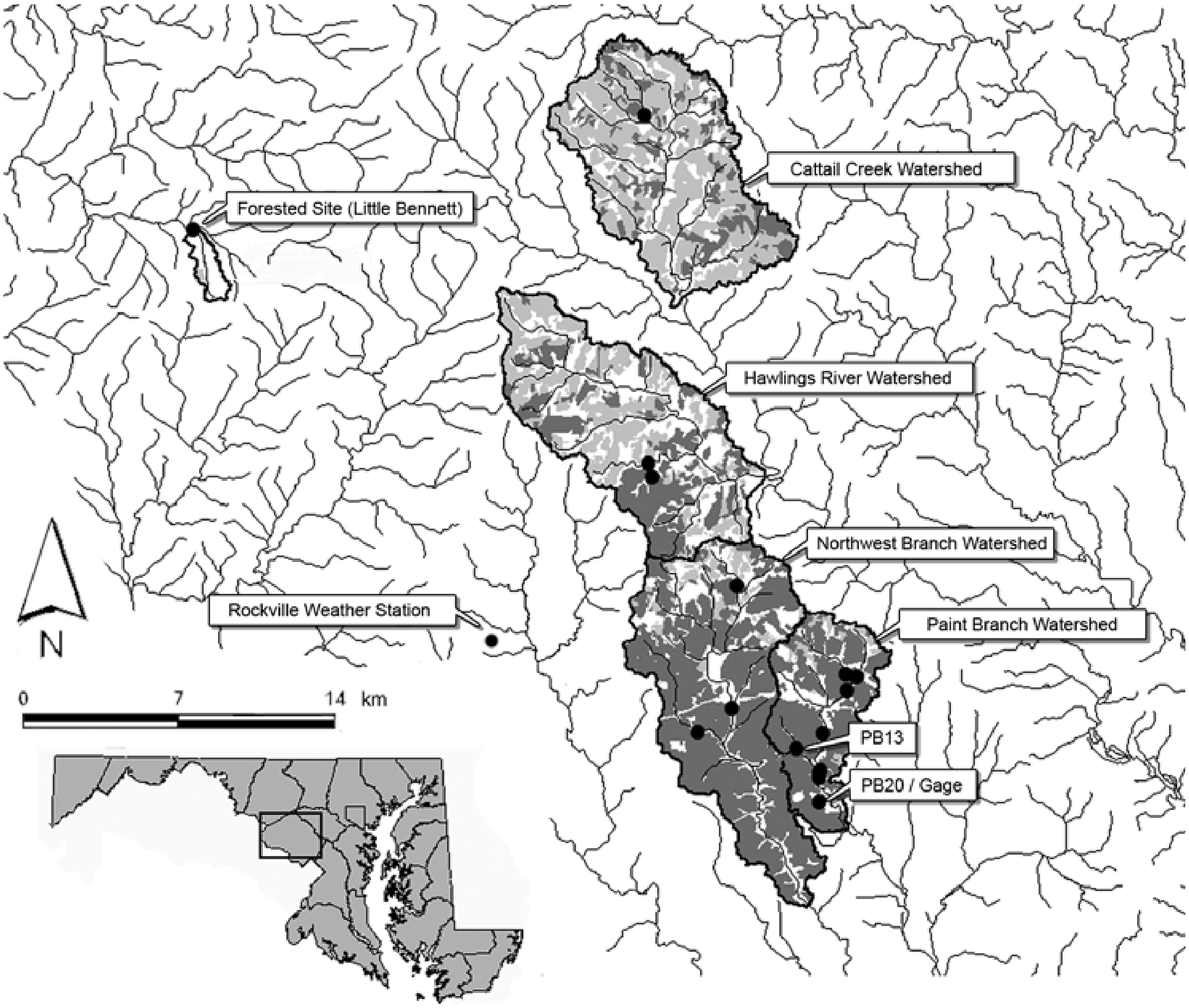

FIGURE 1. Five Watersheds in Which 16 Sampling Sites (Marked by Black Dots) Were Located. Within the outlined watersheds, dark gray represents urban land use, light gray represents agricultural land use, and white represents forested land. The gage and Rockville weather station are also indicated.

TABLE 1. Study Sites.

					Deforestation		**Impervious Surface**	
Site code	***n***	**Area**	***Q***	**Urban (%)**	**In Subshed (%)**	**In Buffer (%)**	**In Subshed (%)**	**In Buffer (%)**
LB01	115	3.2	0.027	2	14	5	1	1
CC02	25	3.4	0.023	24	n/a	n/a	8	4
PB06	62	19.7	0.061	59	51	28	19	12
NW05	117	3.1	0.011	18	51	27	10	4
PB07	61	23.8	0.098	60	53	30	20	13
PB09	61	28.2	0.127	64	55	32	22	15
PB01	61	5.3	0.057	60	56	36	18	13
PB03	61	9.9	0.034	59	59	36	18	13
NW13	117	3.4	0.007	82	60	39	25	18
PB08	61	4.2	0.014	83	64	42	30	23
HR18	117	5.6	0.026	9	64	40	3	1
PB13	174	2.7	0.012	90	64	44	32	23
PB02	217	3.3	0.017	54	65	36	16	12
HR19	117	2.7	0.010	92	70	50	29	21
NW18	20	9.2	0.020	71	71	59	35	29
PB20	99	0.8	0.007	80	89	84	58	65

Notes: Characteristics of the 16 stream sites used in the study. Sites are located in five watersheds: Northwest Branch (NW), Paint Branch (PB), Hawlings River (HR), Cattail Creek (CC), and Little Bennett (LB). n = number of summer (May through September) dates on which temperature was recorded; area = area of subshed in square kilometers; Q = average baseflow discharge (m^3/s, $n = 4$ measurements, one in each season); urban = sum of high and medium density residential, commercial, and industrial land uses; Deforestation = sum of all non-forested land use; Impervious Surface calculated as total impervious surface, see Moglen *et al.* (2004). "Subshed" refers to all points draining to the sampling point; "buffer" refers to 50 m strip on either side of the stream for entire upstream network.

Temperature was measured with Optic Stowaway Model WTA temperature loggers (Onset Computer Corp, Bourne, MA) placed approximately 10 cm below the water surface and set to record temperature every 30 min. Average daily temperature was calculated by averaging the minimum and maximum temperature recorded during the day. Daily minimum and maximum air temperature data were used for the calibration of the temperature model (see below). These data were obtained from the Rockville, Maryland weather gage (COOP-WBAN ID#:187705-99999, available at National Climatic Data Center, 2004; see Figure 1).

Temperature Shift due to Land Use

To evaluate the effect of land use on stream temperature, the temperature "shift" between each site and the largely forested reference site (Little Bennett) was calculated. For each site, the daily difference between average temperatures at that site and at the forested site was computed. The log-transformed seasonal shift for each site was regressed on the log-transformed watershed and stream descriptors (drainage basin size, %urban, %deforestation in the subwatershed, %deforestation in the buffer, %impervious surface in the buffer, and %impervious surface in the subwatershed), and the best model was selected by comparing adjusted r^2. The resulting power-law relationships are consistent with hydraulic geometry, i.e., characteristics of the stream that would be expected to influence water temperature, such as width and depth, are generally related to drainage basin size by power-law formulations.

Adjusting for Temperature Surges due to Summer Thunderstorms

In order to quantify summer (May to September) temperature surges, the temperature time-series at each of the 16 sites was examined for jumps of >2°C within a single 30-min interval. For each such surge, the maximum surge temperature (difference between pre-surge temperature and highest temperature attained, which was almost always in the interval directly following) and length of the temperature surge (time until the temperature fell to within 2°C of the pre-surge temperature) was recorded. The co-occurrence of the temperature surges with flow events was verified by matching the dates with the discharge measured at 5 min intervals by a continuous flow gage (Montgomery County Department of Environmental Protection, 2002). Although the gage measured local discharge at only one site, temperature surges at other sites still coincided with high discharge, probably because the gage was closest to the most urbanized sites, at which the majority of surges took place, and because the storms that caused surges at the less urbanized sites were very large.

At each site, the percentage of summer days (between May and September) with temperature surges was calculated. Single-variable regression models were used to test for associations between stream- and landscape-level predictors (discharge, %urban, %deforestation in the subwatershed, %deforestation in the buffer, %impervious surface in the buffer, and %impervious surface in the subwatershed) and several measures of summer temperature surges (frequency, maximum increase in temperature, and duration).

Calculating the Probability of Exceeding Critical Thermal Maxima Under Different Scenarios

The seasonal temperature shift and the daily storm surges were combined (Figure 2) with a daily maximum water temperature model developed by Caissie *et al.* (1998, 2001). The Caissie model was parameterized using water temperatures from a highly urbanized site within the Paint Branch watershed (site PB13), and air temperatures from the Rockville weather gage. This model involves a two-part process: fitting a deterministic "annual" curve, then fitting the residual temperature variation using a stochastic lag model. Thus, nonlinear regression was used to fit the observed daily maximum water temperature series to a deterministic equation of the form:

$$T_{\mathrm{an}}(t) = a + b \sin\left[\frac{2\pi}{365}(t + t_0)\right] \tag{1}$$

where $T_{\mathrm{an}}(t)$ is the annual component of daily maximum temperature at time t (time measured in Julian days), a is a fitted coefficient causing the curve to shift up or down, b is a fitted coefficient that determines the maximum T_{an}, and t_0 is a fitted coefficient that shifts the peak of the curve to the right or left. The fitted parameters for water temperature were $a = 14.2$, $b = -8.4$, and $t_0 = 60$, and for air temperature were $a = 14.4$, $b = -7.8$, and $t_0 = 75$. Residuals (i.e., the "error" in predicting water temperature) were then fit with a 2-day time lag:

$$R_{\mathrm{w}}(t) = i + b_0 R_{\mathrm{a}}(t) + b_1 R_{\mathrm{a}}(t-1) + b_2 R_{\mathrm{a}}(t-2) \tag{2}$$

where $R_{\mathrm{w}}(t)$ is the residual of daily maximum water temperature at time t, R_{a} is the residual air temperature at time t, i is the intercept, and b_0 through b_2 are the coefficients fit by ordinary least squares multiple regression. The fitted parameters were $i = 0.02$, $b_0 = 0.14$, $b_1 = 0.08$, $b_2 = 0.06$. All parameters for Equations (1) and (2) were fit using SAS (SAS Institute Inc., 1989), and all fits were $p < 0.01$.

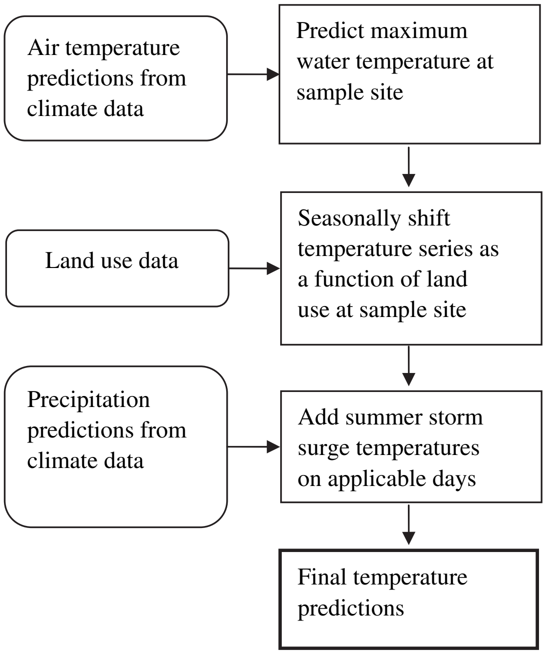

FIGURE 2. Schema for Simulation Model Developed to Predict Daily Maximum Water Temperature From Daily Air Temperature and Precipitation Time-Series.

To illustrate the use of the combined model output, scenarios with and without climate change and urbanization were postulated, and maximum daily temperatures were calculated for each site in Table 1 (except CC01, for which full land use data is not available). The four scenarios specified for water temperature were: current climate and land use (baseline), baseline plus future climate only, baseline plus urbanization only, and baseline plus both urbanization and climate change (worst case scenario). Daily air temperature and precipitation time series were drawn from Hadley CM3 (B2) output downscaled as per Dettinger *et al.* (2004); see Appendix 1 for details on the climate model used and the downscaling procedure. Future climate change scenarios used years 2090-99 and other scenarios used years 1960-69. Urbanization was defined as an increase in deforestation to 95% and an increase in impervious surface to 25% (for those sites with lower initial impervious surface).

For scenarios with urbanization, both a seasonal temperature shift and runoff-driven temperature surges were added, based on results of the empirical relationships (see Results). A temperature surge was assumed to occur only if: (1) normal stream discharge was less than 0.05 m^3/s, and (2) the daily precipitation from the climate series indicated a 10-fold increase in stream flow (stream flow was modeled using the continuous flow model HSPF as a function of precipitation and impervious surface, as described in Moglen (2000). Under these conditions, the surge was simulated by drawing from a uniform distribution between 2 and 7°C (see Results).

Finally, each scenario was evaluated by counting the number of days that exceeded 'good growth' temperatures (upper limit at which growth is possible assuming that food is plentiful) for cold and coolwater fish (Fang *et al.*, 2004a,b). This was done by summing, for each scenario, the number of summer (May to September) days in which maximum temperature exceeded 28°C (for coldwater species) and 32°C (for coolwater species) at each site.

RESULTS

Temperature Shift due to Land Use

Daily average stream temperature increased as variables relating to urban land use increased. The two-variable model with the highest predictive power included area of the subshed draining to the sampling point and proportion of deforestation in the subshed. This model had an r^2 of 0.88 in the autumn ($p < 0.01$) and 0.36 in the summer ($p = 0.10$). The regression equations were summer shift = $0.96 \times (\text{deforestation})^{0.97} \times (\text{area})^{0.05}$, and autumn shift = $1.34 \times (\text{deforestation})^{1.75} \times (\text{area})^{-0.12}$. The residuals were normally distributed with respect to both predictors and observed responses with one exception; visual inspection of the summer shift residuals suggested that large temperature shifts were slightly underpredicted in general, and those with smaller temperature shifts were slightly overpredicted.

Adjusting for Temperature Surges due to Summer Thunderstorms

Over 1,485 summer days (May through September of 2002 and 2004) at 16 sites, 37 temperature surges (>2°C increase during one 30-min interval) were recorded (Table 2). More surges were recorded in 2002 than in 2004 for two reasons: one particularly active site (PB20) was not monitored in 2004; and the summer of 2004 was much drier than 2004, particularly after mid-June. The proportion of monitored summer days with temperature surges ranged from 0% at an agricultural site to 10% at a highly urbanized site. On average, temperature jumped 3.7°C and receded over a period of 2.8 h. The maximum temperature surge was 7.4°C, and the maximum time for temperature to fall was 7.6 h.

Figure 3 shows measured discharge and temperature in June through September of 2002 at the most highly impervious site (PB20; imperviousness = 58%). This site is a headwater stream with a forested riparian buffer, but the stream 'begins' as water emerges from a culvert less than 100 m upstream of the temperature logger. The culvert drains extensive parking lots, rooftops, roads, and grassy areas associated with a large apartment complex. From June through August, with one exception, every high discharge event also brought a temperature surge in this highly urban headwater stream. The exception (July 26) represented frontal activity with rain beginning at 8 AM and continuing through the day. Large storms at the beginning of September did not cause increases in stream temperature.

Temperature and discharge during a typical summer temperature surge at the somewhat less urbanized sampling site (PB13, imperviousness = 32%) are shown in Figure 4. Temperature (thin black line) shows a typical diurnal curve for the second measurement day (June 29), but on the previous day, the diurnal curve was abruptly interrupted when runoff began to reach the stream (as shown by increase in discharge, thick gray line). Temperature rose from 23.1 to 29.3°C within 30 min. Moreover, although discharge quickly subsided, temperature remained elevated above the expected diurnal curve for approximately 3 h. Figure 5a-d shows several additional examples that occurred at the same site during the monitoring period. On 6 June 2002, water temperature increased by 6.3°C, and a smaller secondary peak occurred a few hours later with additional rain. On July 9, 2002, an evening thunderstorm increased water temperature by 7.4°C, and possibly contributed to higher water temperatures on the following day as well. On July 26 and 27, small amounts of rain caused minor temperature surges, while on May 19, 2004, a prolonged surge occurred in which temperature remained elevated for almost 8 h.

Figure 6a compares the magnitude and Figure 6b the duration of 26 surges recorded at the two most active sites. The magnitude of the surges was comparable at the two sites. However, at the most urban site (PB20), temperature surges were short-lived, probably due to the small but highly paved watershed; storm water moved into and out of the channel very rapidly, and temperatures returned to normal within 3 h on all but one date. In comparison, at PB13, which is located in an older residential neighborhood and drains a larger area, temperature surges lasted longer. On five dates, the surge lasted between 5 and 8 h.

TABLE 2. Summer Temperature Surges.

Sitecode	Date	Time	Air Temperature (maximum for day, °C)	Water Temperature (°C)			Duration of Temperature Surge (h)
				Before Surge	Peak	Difference	
CC02	5-Jun-2002	8:48	32.8	21.7	25.0	3.2	6.4
NW05	6-Jun-2002	9:36	32.8	22.9	25.1	2.2	1.6
HR19	6-Jun-2002	9:36	32.8	22.9	25.3	2.4	2.4
NW13	6-Jun-2002	10:00	32.8	23.8	29.9	6.0	0.8
HR18	6-Jun-2002	10:00	32.8	24.9	29.9	5.0	2.4
PB20	6-Jun-2002	13:12	32.8	21.5	23.8	2.4	0.4
PB20	6-Jun-2002	15:36	32.8	22.8	29.7	6.9	1.2
PB13	6-Jun-2002	15:36	32.8	20.1	26.4	6.3	4.8
PB20	13-Jun-2002	12:24	25.0	18.9	22.2	3.3	7.6
PB13	13-Jun-2002	13:12	25.0	19.2	21.4	2.3	2.0
PB20	18-Jun-2002	20:00	28.3	20.5	25.7	5.3	2.4
PB20	27-Jun-2002	19:12	32.8	23.0	27.1	4.2	1.2
PB13	28-Jun-2002	16:48	28.3	21.6	26.7	5.1	1.6
PB20	28-Jun-2002	16:48	28.3	23.2	29.3	6.2	1.6
PB13	9-Jul-2002	20:00	34.4	21.3	28.7	7.4	6.4
PB20	9-Jul-2002	20:48	34.4	22.3	26.4	4.1	2.4
HR19	9-Jul-2002	21:12	34.4	22.6	25.7	3.1	6.4
PB20	23-Jul-2002	19:36	35.0	24.0	27.3	3.3	2.8
PB13	23-Jul-2002	19:36	35.0	22.1	27.4	5.3	4.8
HR19	23-Jul-2002	20:48	35.0	23.6	28.3	4.7	6.0
HR19	26-Jul-2002	9:12	21.1	19.6	21.7	2.1	2.0
PB20	27-Jul-2002	17:12	27.8	21.8	24.7	2.9	2.4
PB13	27-Jul-2002	17:36	27.8	20.9	23.1	2.2	0.8
PB13	3-Aug-2002	17:12	35.0	23.6	25.7	2.1	0.4
PB20	3-Aug-2002	17:12	35.0	23.7	25.7	2.1	0.4
NW18	14-Sep-2002	20:36	26.1	18.6	21.9	3.3	0.4
PB13	15-Sep-2002	19:36	25.0	20.3	22.9	2.7	0.8
PB13	7-May-2004	19:00	29.4	15.8	18.5	2.7	1.5
PB13	9-May-2004	23:30	30.6	15.4	17.9	2.5	2.5
PB13	18-May-2004	16:00	28.3	17.4	19.7	2.3	7.5
PB13	21-May-2004	22:30	27.2	17.3	20.3	3.1	1.0
PB13	25-May-2004	20:00	30.6	17.7	20.0	2.3	1.0
PB13	27-May-2004	17:00	28.3	19.0	21.1	2.1	0.5
PB13	15-Jun-2004	16:30	32.2	18.7	22.6	3.9	3.0
PB13	18-Jul-2004	19:00	32.2	19.0	24.7	5.7	7.0
PB08	18-Jul-2004	20:30	32.2	22.3	25.2	2.9	2.0
PB09	18-Jul-2004	20:30	32.2	22.5	25.4	2.9	4.0

Notes: Details of 37 temperature surges observed during summer (May through September) 2002 and 2004 at sites shown in Table 1. Water temperatures were measured every 12 min (2002) or 30 min (2004). Air temperature maxima were measured at the Rockville Weather Station. The duration of the temperature surge was calculated as the difference in time between the first elevated temperature and the last temperature >2°C above the pre-surge baseline temperature.

Across all 16 sites, the best predictors of storm surge frequency were %deforestation in the buffer ($r^2 = 0.58$, $p < 0.001$, Figure 7a), and %impervious surface in the watershed draining to the sampling point ($r^2 = 0.48$, $p = 0.01$, Figure 7b). Other predictor variables were much less effective; % deforestation in the watershed had an r^2 of 0.36 ($p < 0.05$), and %urban in the watershed had an r^2 of only 0.18 ($p = 0.01$). Clearly, the number of temperature surges fell off as average discharge increased (Figure 7c); a log-log regression (after adding 0.01% to %summer days with surges) had a moderate r^2 of 0.31 ($p = 0.02$). A model using %deforestation in the buffer, average discharge, and their interaction improved the total r^2 marginally, from 0.58 for buffer deforestation alone to 0.65 for all three factors (adjusted $r^2 = 0.56$, $p < 0.01$).

No model involving watershed area, stream- or landscape-predictors, local or regional air temperature, precipitation, season or time of day, or the interactions of these variables, was able to predict either the maximum temperature surge or its duration with $p < 0.10$. This inability to predict the magnitude of the temperature surge was probably in part related to the fact that neither precipitation nor discharge was measured locally at all sites. Given the small scale of summer thunderstorms, this severely limits the ability to distinguish the local characteristics of individual temperature surges.

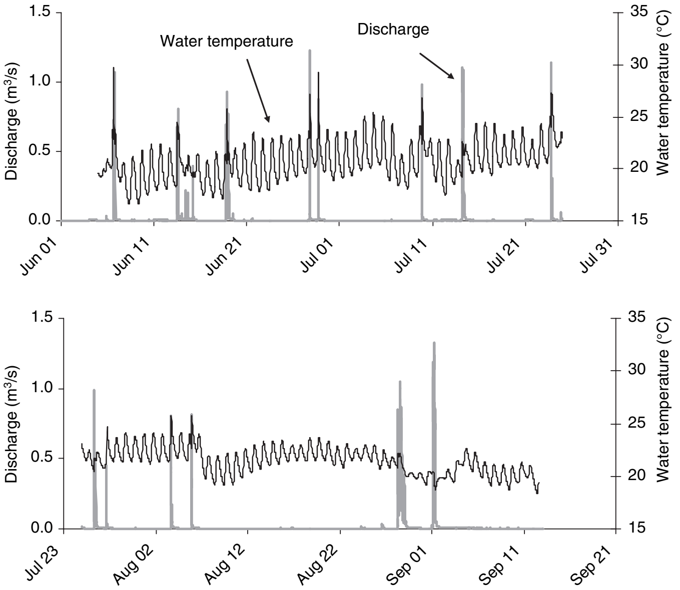

FIGURE 3. Empirically Measured Water Temperature (Thin Dark Line) at Site PB20 (58% Imperviousness) and Downstream Discharge (Thick Gray Line, Not Visible During Baseflow due to Scale) During Summer 2002.

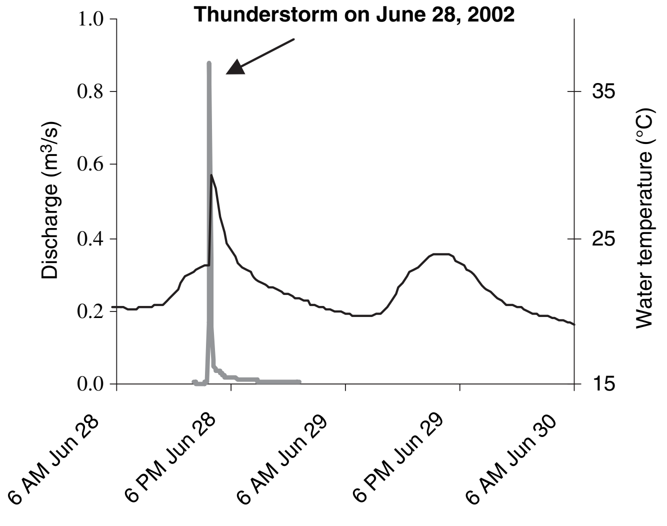

FIGURE 4. Surge in Water Temperature (Thin Dark Line) at Site PB20 (32% Imperviousness) and Downstream Discharge (Thick Gray Line) on June 28, 2002.

Modeling Exceedance of Good Growth Temperatures Under Different Scenarios

Each 10-year scenario contained a total of 1,530 simulated summer (May to September) days. Figure 8 shows the number of days in each scenario during which maximum temperature exceeded 28°C, the average "good growth" temperature maximum of cold-water species (Fang *et al.*, 2004b). For the baseline

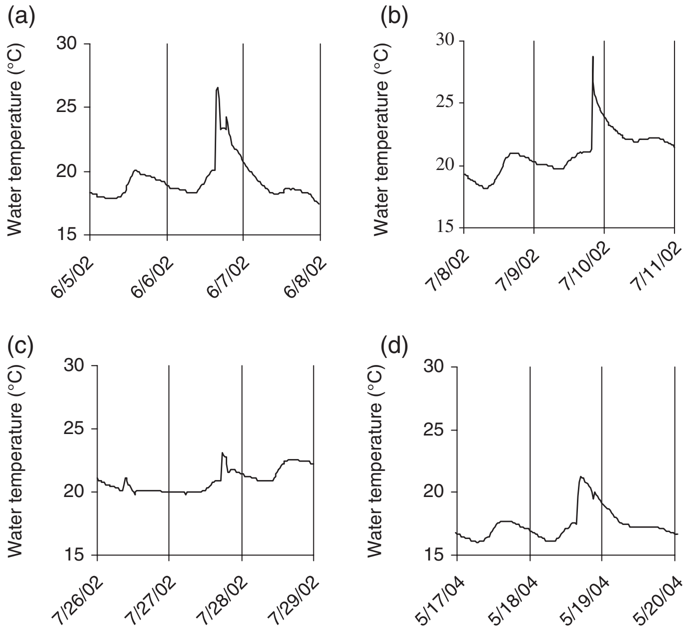

FIGURE 5. (a-d) Water Temperature Surges on Four Dates in 2002 at PB13 (32% Imperviousness).

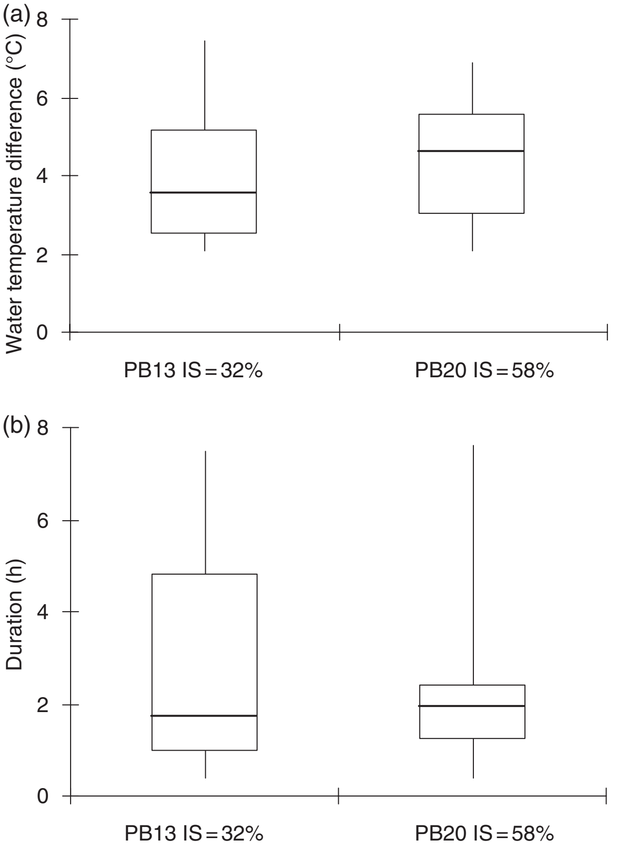

FIGURE 6. (a, b) Box and Whiskers Diagram for (a) the Magnitude and (b) the Duration of Temperature Surges at Sites PB13 and PB20 During Summers of 2002 and 2004. The boxes show the 25th and 75th percentiles, and the whiskers show the minimum and maximum data recorded.

scenario, exceedances occurred at five sites, including PB20 and PB13, the two sites at which a large number of temperature surges were observed. Climate change alone nearly doubled the number of exceedances at these five sites, from an average of 21 to 40 days per 10 years. Urbanization without climate change resulted in temperature exceedances for an average of 24 days in 10 years at 11 of the 15 sites (essentially, all sites with mean discharge below 0.05 m^3/s). Urbanization plus climate change resulted in exceedances at the same 11 sites, for an average of 49 days per year. Maximum temperature exceeded 32°C, the average "good growth" temperature maximum of coolwater species (Fang *et al.*, 2004a), only in the urbanization plus climate change scenario (not shown), and then only rarely: between 2 and 5 days at each of the 11 smaller sites.

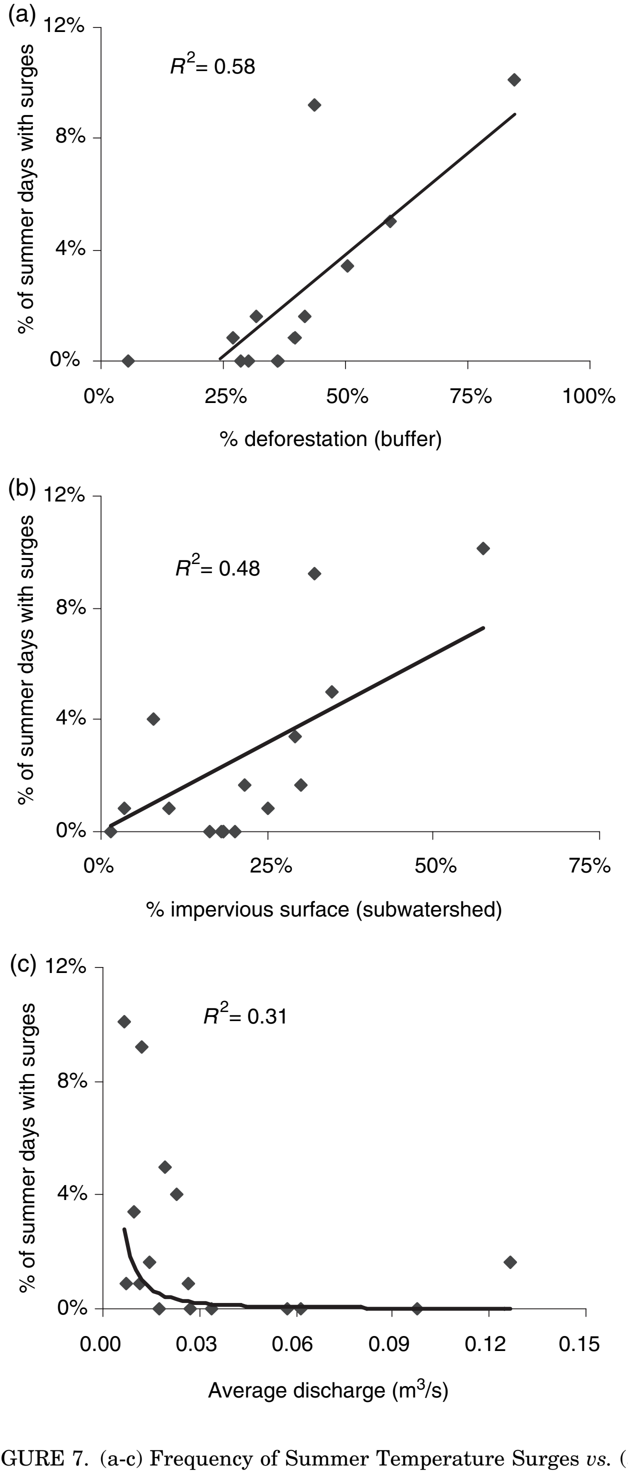

FIGURE 7. (a-c) Frequency of Summer Temperature Surges *vs.* (a) %Unforested Buffer ($p < 0.02$), (b) %Impervious Surface ($p < 0.01$), and (c) Average Baseflow Discharge at 16 Sites ($p = 0.19$).

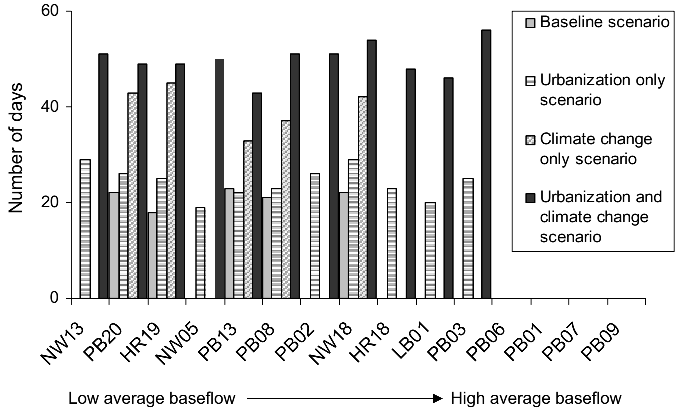

FIGURE 8. Number of Simulated Summer Days out of 10 Years on Which Temperature Exceeded 28°C Under Each of the Four Scenarios at Each Site.

The number of exceedances (approximately 2 to 3 per summer under urbanized conditions) was less than what was observed in 2002 through 2004, indicating that the model is somewhat conservative. This may be in part due to the fact, noted above, that the temperature shift model underestimates the summer temperature shift for those sites at which large shifts were observed.

DISCUSSION

Future minimum and maximum in-stream temperatures, given novel combinations of land use and climate change, were predicted using newly collected field data that links land use to stream temperature. Land use, especially deforestation in a watershed, was related to daily average stream temperature. Additionally, high runoff events associated with localized rainstorms were shown to cause surges in temperature, averaging about 3.5°C and dissipating over about 3 h. These surges occurred frequently at the most urbanized sites (up to 10% of summer days at the most urbanized sites) and could increase temperature by >7°C. Combining these results with future scenarios suggests that land use change will have significant negative ecological impacts, which could be heightened by climate change, and may result in profound shifts in community structure.

Utility and Limitations of the Model

The study includes several land use variables which probably all contribute to warming the stream, but are highly correlated and virtually impossible to disentangle. Although deforestation, particularly in the buffer, was an important predictor of water temperature, future studies must be designed to separate the influence of deforestation, buffer vegetation, and impervious surface. Existing process-based models could be used to investigate these relationships (see for example LeBlanc *et al.*, 1997; Krause *et al.*, 2004), and this may help to determine whether the thermal stresses associated with urbanization can be mitigated by maintaining buffer zones and/or moving roads and parking lots away from streams.

Simulation models are increasingly being used to predict the impact of climate change and other novel anthropogenic stressors. When applied to streams, such models require a relatively simple way to predict water temperatures across entire stream networks, where calibration at each location is not feasible. Climate data are available from weather stations across the US (National Climatic Data Center, 2004) and from downscaled climate models (e.g., Dettinger *et al.*, 2004). Fortunately, studies have shown that air temperature is a reasonable predictor of water temperature, even when the air and water temperatures are measured tens of kilometers apart (Stefan and Sinokrot, 1993; Mohseni *et al.*, 1998), as long as time lags are included in the model. The other inputs to this model, e.g., deforestation and watershed area, are generally easily obtained for use in GIS systems. In order to apply this model to other watersheds, the basic components would need to be recalibrated. The lagged temperature model and the land use-related temperature shift component could be easily reproduced because they were well predicted by watershed or stream buffer characteristics. However, the temperature surges would be more difficult to transfer, because the magnitude and duration of individual surges were not closely related to watershed characteristics. Nevertheless, temperature surges as large as 7°C clearly indicate a need to better quantify the magnitude and duration of thermal stress across urban streams.

Effects of Urbanization and Climate Change on Stream Biota

The critical thermal maxima, i.e., the temperature at which death is imminent, ranges from 32 to 40°C for most North American freshwater fish species (Beitinger *et al.*, 2000). Thus, the maximum temperatures measured, even given the temperature surges associated with summer thunderstorms, are still on most occasions below the critical limits that would cause death for most of the fish in the watersheds. Two important exceptions are blacknose dace and brown trout. Blacknose Dace (*Rhinichthys atratulus*) is the single most common species in these streams, compromising approximately 30% of the individuals across the watersheds studied (M.A. Palmer, unpublished data). This cool-water species has a critical thermal maximum of 31.9° (Kowalski *et al.*, 1978). A storm on June 6, 2002, caused temperature surges at six of the sites, three of which exceeded 32°C, and therefore may have caused mortality in this species (as well as considerable downstream displacement). In contrast, brown trout (*Salmo trutta*) makes up <0.1% of the individuals sampled from the watersheds, and its distribution is spatially patchy. Given its critical thermal maximum of 29-30°C (reviewed in Beitinger *et al.*, 2000), it is possible that the distribution of this species is in part limited by the warm temperatures occurring in the more urbanized parts of these headwater streams.

Historically, fish kills due to excessively warm water temperatures are rare (Beitinger *et al.*, 2000), and our model suggests that even with significant urbanization and climate change, this will continue to be the case. However, sublethal stress, such as the prevalence of temperatures unsuitable for growth, may still have critical impacts on the stream community. The upper temperature limit *for growth* of cold-water species is exceeded even in the baseline scenario at those sites characterized by low discharge and high impervious surface. The simulation results suggest that land use change may lead to problems at all low-discharge sites, while climate change effects would be limited to those sites that already exceed the temperature threshold. This suggests that urbanization is a more serious and pervasive threat in these east coast watersheds, although climate change should not be discounted, and the combination of both may create problems even in higher order streams.

Other sublethal effects of such large temperature increases are not well understood. Temperature surges may disproportionately affect eggs, larval fish, and young-of-year, all of which have greater surface-to-volume ratio and less ability to internally regulate or take refuge from temperature increases (Van Der Kraak and Pankhurst, 1997; Beitinger *et al.*, 2000). They may also affect the invertebrates that act as food resources for many fish species.

Finally, the suggestion that climate change may create a shift in community structure has often been made (e.g., Matthews and Zimmerman, 1990; Krause *et al.*, 2004). As shown in the simulations, temperature exceeded the growth threshold for coolwater fish only rarely, but exceeded the growth threshold for coldwater fish several times per summer under the non-baseline conditions. This indicates that either urbanization or climate change may cause a shift in species composition from cold and cool to warmwater species. Currently, 6 of the 31 species found in the watersheds are cool or coldwater species; however, these comprise 41.7% of the individuals. Thus, the community transformation could be profound.

ACKNOWLEDGMENTS

Funding and support for this project was provided by the U.S. Environmental Protection Agency, including the STAR (Science to Achieve Results) Program (EPA Number: R828012) and the Global Climate Change Program (EPA numbers: 1W0594NAEX and R83038701). We thank Michael Dettinger and Katharine Hayhoe for the local climate projections used here. Invaluable assistance maintaining the dataloggers and managing data was provided by lab managers Jennifer Morse and Matthew Reardon. We would also like to thank Paul Angermeier, Nancy Bockstael, Holly Menninger, Glenn Moglen, Jim Pizzuto, Catriona Rogers, and the entire Palmer labgroup for stimulating discussions and suggestions.

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APPENDIX 1: CLIMATE MODEL AND DOWNSCALING

Projections for temperature and precipitation were based on the U.K. Meteorological Office Hadley Centre Model v3 (HadCM3; Gordon *et al.*, 2000; Pope *et al.*, 2000). Atmospheric processes were simulated at a horizontal resolution of 3.75° × 2.5°, with 15 vertical levels. HadCM3 is a numerical model of the global climate system that couples atmospheric, ocean, sea-ice, and land-surface components to represent historical climate variability and simulate observed long-term increases in global temperatures. Climate sensitivity for HadCM3 (a metric that captures the magnitude of the model-simulated increase in global temperature in response to a doubling of atmospheric CO_2 concentration), is 3.3°C, at the mid- to high end of the IPCC range of 1.5-4.5°C.

The climate projections are based on the B2 emissions scenarios developed by the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović *et al.*, 2000). This scenario assumes an emphasis on local solutions to economic, social, and environmental sustainability and diverse technological change. CO_2 emissions under the B2 scenario are in the mid-low range, reaching 13 GtC/year by the end of the century, with corresponding atmospheric CO_2 concentrations of around 600 ppm.

A deterministic statistical approach was employed to resolve projected climate changes for the specific location of Rockville, MD. AOGCM grid-cell values of temperature and precipitation were rescaled based on simple monthly regression relations. Climate time series simulated by HadCM3 were first modified so that the overall probability distributions of simulated daily values approximated the observed probability distributions of air temperatures and precipitation at the Rockville, MD weather station (Dettinger *et al.*, 2004). The probability distributions of daily precipitation were somewhat more complex than the more Gaussian temperature structures, as they include many days with no precipitation. For this reason, a simulated threshold value was first determined that corresponded to the onset of precipitation in historical observations. Observed values less than the corresponding simulated threshold were then set to zero, and remaining wet (observed) days scaled up to conserve total precipitation, as described in Dettinger *et al.* (2004). The daily square roots of precipitation were regressed (in order to render them approximately Gaussian), and cubic or more complex equations were fitted.

The regression relations derived from the historic observed and model-simulated time series of temperature and precipitation at the Rockville station were then applied to future simulations, such that rescaled values share the weather statistics observed at the selected stations. At the daily scales addressed by this method, the need to extrapolate beyond the range of the historically observed parts of the probability distributions was rare even in the future simulations (typically, less than one percent of the future days), as most of the climate changes involve more frequent warm days than actual warmer-than-ever-observed days.

Mean annual air temperatures increased by 3.2°C in the worst-case scenario to relative to the baseline, while maximum air temperature rose 10.5°C . Total precipitation was similar in the two scenarios, but the number of large storms per decade increased from 4 in 1960-69 to 10 in 2090-99.