GLOBAL WARMING AND POTENTIAL CHANGES IN FISH HABITAT IN U.S. STREAMS

OMID MOHSENI [1], HEINZ G. STEFAN [1] and JOHN G. EATON [2]

[1] *University of Minnesota, St. Anthony Falls Laboratory, Mississippi River at 3rd Ave. SE, Minneapolis, MN 55414, U.S.A.*
E-mail: omohseni@umn.edu and stefa001@umn.edu

[2] *Formerly U.S. Environmental Protection Agency, Mid-Continent Ecology Division, Duluth, MN, U.S.A.*

Abstract. To project potential habitat changes of 57 fish species under global warming, their suitable thermal habitat at 764 stream gaging stations in the contiguous United States was studied. Global warming was specified by air temperature increases projected by the Canadian Centre of Climate Modelling General Circulation Model for a doubling of atmospheric CO_2. The aquatic thermal regime at each gaging station was related to air temperature using a nonlinear stream temperature/air temperature relationship. Suitable fish thermal habitat was assumed to be constrained by both maximum temperature and minimum temperature tolerances. For cold water fishes with a 0 °C lower temperature constraint, the number of stations with suitable thermal habitat under a $2 \times CO_2$ climate scenario is projected to decrease by 36%, and for cool water fishes by 15%. These changes are associated with a northward shift of the range. For warm water fishes with a 2 °C lower temperature constraint, the potential number of stations with suitable thermal habitat is projected to increase by 31%.

1. Introduction

Fish habitat in streams may be characterized by several interdependent factors, which include water temperature, streamflow, channel structure and food web relationships (Rundquist and Baldrige, 1990). If water temperature exceeds the maximum temperature tolerance of a fish species, the fish species is likely to be absent or disappear from that stream reach (Eaton and Scheller, 1996). Under potential global warming due to an increase of carbon dioxide and other greenhouse gases in the atmosphere, the thermal regimes of streams would change. It is quite likely that the higher water temperatures would exceed the maximum temperature tolerances of some fish species.

Studies of the potential effects of climate warming on fish thermal habitat in streams were previously conducted by Coutant (1990), Magnuson et al. (1990), Stefan et al. (1995), Rahel et al. (1996) and others. Eaton and Scheller (1996) were among the first to estimate fish habitat responses to climate change over the entire contiguous United States. They projected maximum weekly stream temperatures at 1,776 stream gaging stations by assuming a linear relationship between stream temperature and air temperature increases. The slope of the linear relationship was

Climatic Change **59:** 389–409, 2003.

set equal to 0.90 for all records. They compared the maximum weekly temperature tolerance of 57 fish species (cold water, cool water and warm water guilds) with the maximum weekly stream temperatures obtained under a baseline climate condition and a 2 × CO_2 climate condition, i.e., a climate after doubling of carbon dioxide in the atmosphere. If the maximum weekly stream temperature at a gaging station was less than the maximum weekly temperature tolerance of a fish species, then the associated river reach was considered a suitable thermal habitat for that fish species. In conclusion, they projected the change in number of stream gaging stations with suitable thermal habitat for 57 fish species. The results of their study projected a 47% decrease in suitable thermal habitat for cold water fish, a 50% decrease for cool water fish and a 14% decrease for warm water fish, under 2 × CO_2 climate conditions as projected by the general circulation model (GCM) developed at the Canadian Centre of Climate Modelling (CCC).

Mohseni and Stefan (1999) recently studied the physics behind the stream temperature/air temperature relationships and concluded that stream temperatures increase linearly with air temperatures only at moderate air temperatures, i.e., air temperatures between approximately 5 °C and 25 °C. As air temperatures rise above about 25 °C, stream temperatures level off (Figure 1a) due to extensive evaporative cooling. Mohseni et al. (1998a) showed that the stream temperature/air temperature relationship for 98% of the records studied is best explained by an S-shaped function. A linear extrapolation of the stream temperature/air temperature relationship beyond 25 °C is likely to overestimate stream temperatures, especially under a warmer climate with a 1.5 to 4.5 °C increase in mean global air temperature (IPCC, 1996, 2001).

In this paper, we have again attempted to project changes in fish habitat for the 57 fish species studied by Eaton and Scheller (1996). The *three* main differences between this and the Eaton and Scheller (1996) study are: (1) utilizing the S-shaped function introduced by Mohseni et al. (1998a) instead of a linear relationship, (2) applying a separate S-shape function to each stream gaging station, and (3) exploring the effects of minimum temperature tolerance of fish species on the projection of habitat loss/gain under potential climate warming. In addition, the stream gaging stations used in this study are not exactly the same as those used by Eaton and Scheller (1996). After a brief review of the stream temperature model and the data used, the projected effects of a warmer climate on the thermal habitat of 57 fish species will be shown. Another aspect of this paper is to demonstrate that the lower temperature constraint or tolerance is also very important for the assessment of fish habitat. Most previous studies have acknowledged the existence of this limit, but have not paid attention to its quantitative effect.

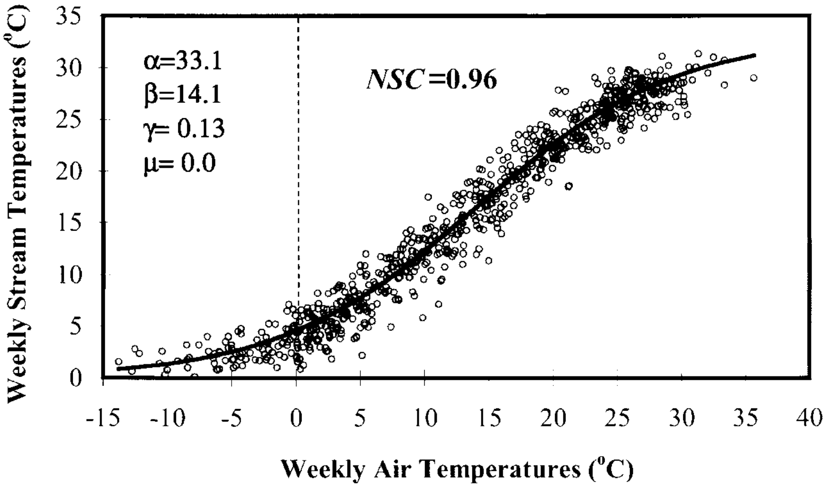

Figure 1a. Weekly measured stream temperatures at the Salt Fork of the Arkansas River near Jet, OK, versus weekly air temperatures recorded at Wichita, KS. The line represents the nonlinear least squares regression between stream temperatures and air temperatures.

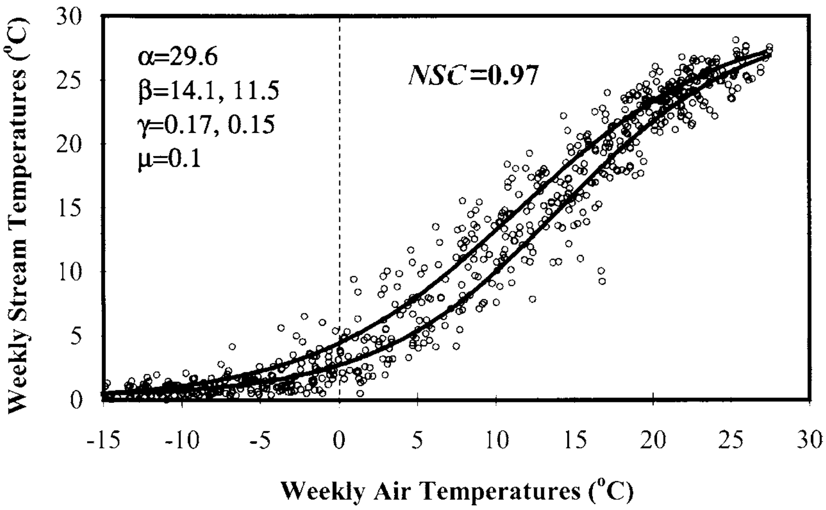

Figure 1b. Simulated and observed weekly stream temperatures at the Mississippi River near Red Wing (Lock and Dam #3), MN, versus weekly air temperatures recorded at St. Paul/Minneapolis, MN.

2. Nonlinear Stream Temperature Model

Mohseni et al. (1998a) observed that a nonlinear relationship exists between weekly stream temperatures and air temperatures. The stream temperature/air temperature relationship was explained by the following S-shaped function:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}}. \tag{1}$$

In Equation (1), T_s is the estimated stream temperature, T_a is the air temperature measured at or near the stream gaging site, α is the upper bound stream temperature, μ is the minimum estimated stream temperature, γ is a measure of the steepest slope of the function and β is the air temperature at the inflection point. Mohseni et al. (2002) developed a method to estimate α as an extreme value (probable maximum stream temperature at a gaging station) using a universal standard deviate. The values of β, γ and μ were determined by a least squares regression method. Mohseni et al. (1998a) fitted Equation (1) to 584 U.S. stream temperature/air temperature of three-year length. The goodness of fit of Equation (1) to weekly data was not significantly affected by the distance between stream gaging and weather stations when air temperatures were taken from weather stations that were 2 to 244 km away from the stream gaging stations. Matuszek and Shuter (1996) also noted the insensitivity of regression results to distances up to 250 km in their study of the relationship between air temperature and surface water temperature of small lakes in Ontario. The fit between the model and the available stream temperature data for individual streams was measured by the Nash-Sutcliffe Coefficient, *NSC* (Nash and Sutcliffe, 1970)

$$NSC = 1 - \frac{\sum_{i=1}^{n} \left(T_{sim_i} - T_{obs_i}\right)^2}{\sum_{i=1}^{n} \left(\bar{T}_{obs} - T_{obs_i}\right)^2}, \tag{2}$$

where T_{sim}, T_{obs} and $\bar{T}_{obs}$ are weekly simulated, weekly observed and mean weekly observed stream temperatures, respectively. Mohseni et al. (1998a) also noted that some streams exhibited a seasonal effect (hysteresis) in the stream temperature/air temperature relationship which was already pointed out by Webb and Nobilis (1997). To take hysteresis into account, separate functions were fitted to the data representing the rising limb and the falling limb of the stream temperature/air temperature relationship (Figure 1b). The limbs were distinguished from each other using the associated week numbers (the first week of the calendar year was denoted as week 1). The minimum of the mean weekly air temperatures was used to set the starting week of the rising limb (= ending week of the falling limb) and the maximum of mean weekly air temperatures was used to set the ending week of the rising limb (= starting week of the falling limb).

3. Data

3.1. STREAM TEMPERATURE DATA

Stream temperature records from 1961 to 1990 at 993 stream gaging stations were obtained from the U.S. Environmental Protection Agency, Mid-Continent Division, Duluth, MN, and the USGS home page on the Internet. Forty-six records with less than 100 weekly stream temperature data points were eliminated from the database (insufficient information on the stream temperature regime). The remaining records were used to obtain the four parameters of Equation (1).

A separate regression analysis was conducted for each of 947 stream gauging stations. No regression equation was found for four stream gaging stations. A very weak relationship between water temperatures and air temperatures was evident at 19 gaging stations, which were mostly downstream of deep reservoirs (*NSC*s less than 0.60). It was also found that some streams had a significant number of outliers (Mohseni et al., 1998b). It was decided to study only those stream gaging stations which were most responsive to air temperatures, i.e., those with high *NSC*s. This approach eliminates stream gaging stations affected by deep water releases from reservoirs, or those located in streams with small average daily flows and affected by effluent releases from wastewater treatment plants or industrial units. The threshold *NSC* must be high enough to exclude all those stream gaging stations which are adversely affected by anthropogenic effects, other than climate warming. After investigating different thresholds for *NSC*, a value of 0.85 was chosen, leaving 803 stream gaging stations in the database. A summary of the range of regression parameters was given by Mohseni et al. (1999). All four calibration parameters showed significant variability.

3.2. AIR TEMPERATURE DATA

Air temperature data were obtained from 197 weather stations in the Solar and Meteorological Surface Observation Network (SAMSON) provided by the National Oceanic and Atmospheric Administration (NOAA) and the National Renewable Energy Laboratory (NREL). For each stream gaging station, the closest weather station was selected. Therefore, some weather stations were used several times and others were not used at all. The total number of weather stations used in this study was 166.

3.3. CLIMATE CHANGE SCENARIO

The output from a general circulation model (GCM) developed at the Canadian Center of Climate Modelling (CCC) (McFarlane et al., 1992) was used to specify the $2 \times CO_2$ climate scenario. The second generation CCC GCM is a spectral coupled atmosphere-ocean model with a grid size of $3.75° \times 3.75°$. Climate variables are calculated at grid points. To project air temperatures under the $2 \times CO_2$ climate scenario, air temperatures recorded from 1961–1979 at the 166 weather stations were incremented by the difference between $2 \times CO_2$ and $1 \times CO_2$ values. Since on a weekly time scale, air temperature does not vary significantly within a grid cell of the CCC-GCM, except in alpine areas, no downscaling method was employed for air temperature projections. Thus, the differences between $2 \times CO_2$ and $1 \times CO_2$ values, simulated by the CCC-GCM, were taken from the grid point nearest to a weather station. Projected weekly air temperatures were used to estimate weekly stream temperatures for the $2 \times CO_2$ climate condition.

4. Errors in Projected Stream Temperatures

There are errors associated with the projection of air temperatures by the GCMs and errors in the stream temperature model simulations. Errors associated with the GCMs are not well known, even for past climate conditions, due to uncertainties in observed data (Lau et al., 1996). An error analysis was conducted for the stream temperature model simulations. It was assumed that errors associated with the stream temperature model simulations would not change under new climate conditions.

The error analysis was a two-tail paired t-test at 10% significance level between the mean of the errors

$$\bar{\varepsilon} = \frac{1}{n} \sum_{i=1}^{n} \left| T_{sim_i} - T_{obs_i} \right| \tag{3}$$

and the mean of the changes under the $2 \times CO_2$ climate scenario

$$\overline{\Delta T} = \frac{1}{n} \sum_{i=1}^{n} \left| T_{sim_i} - T_{2\times \mathrm{CO}_{2_i}} \right| \tag{4}$$

at each gaging station for the available records between 1961–1979. In the above equations, $T_{2\times \mathrm{CO}_2}$ is the projected stream temperature under $2 \times CO_2$ climate conditions and n is the number of all weekly data at a gaging station. Values of n ranged from 100 to 1038. For 39 stream gaging stations, the results projected a significant stream temperature change below the 90% confidence level under the $2 \times CO_2$ climate scenario (Table I). Stream temperature simulations at those 39 gaging stations were therefore not considered good enough for any effect study under the CCC-GCM $2 \times CO_2$ climate scenario. Figure 2 shows the locations of the remaining 764 stream gaging stations.

A separate error analysis was conducted for the projected *maximum* and *minimum* weekly stream temperatures which are of particular importance to the maximum and minimum temperature tolerance limits of fishes. For this error analysis, only maximum or minimum weekly stream temperatures were employed in Equations (3) and (4), and n now designated the number of years of record ranging from 3 to 19. Only 399 stream gaging stations showed a significant change in maximum weekly stream temperatures, and only 455 in minimum weekly stream temperatures, under the $2 \times CO_2$ climate scenario (Table I).

The notable difference between the results of the error analysis of the mean weekly stream temperatures and the maximum/minimum stream temperatures is attributed to the S-shaped stream temperature function. Maximum and minimum

Table I

Comparison between the stations showing a significant change and those showing no significant change at the 90% confidence level under the 2 × CO_2 climate scenario. The values in the table are the mean of the parameters. *RMSE* stands for root mean squared errors

	Error analysis results			Simulation characteristics	
	No. of stations	Mean absolute error (°C)	Mean change (°C)	*NSC*	*RMSE* (°C)
Mean Annual Stream Temperatures					
Stations with significant change	764	1.68	3.14	0.93	1.84
Stations with no significant change	39	2.23	2.27	0.89	1.89
Maximum Weekly Stream Temperatures					
Stations with significant change	399	1.88	2.24	0.93	1.85
Stations with no significant change	404	1.98	2.06	0.92	1.84
Minimum Weekly Stream Temperatures					
Stations with significant change	455	1.14	2.25	0.93	1.77
Stations with no significant change	349	1.61	1.85	0.93	1.93

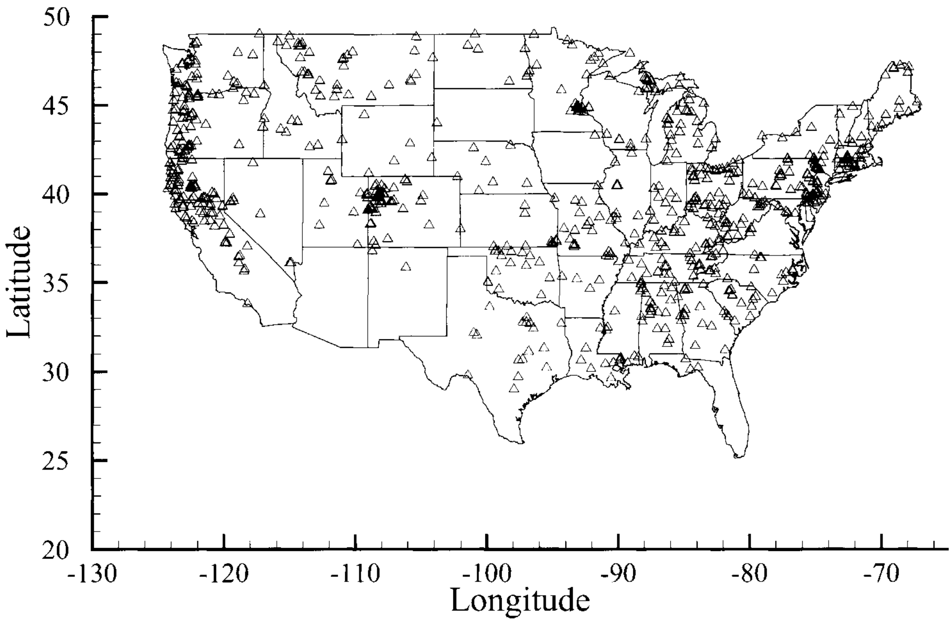

Figure 2. Locations of 764 stream gaging stations used to study fish thermal habitat in streams of the contiguous U.S.

weekly stream temperatures are often located on the tails of the S-shaped function. If the observed maximum/minimum weekly stream temperatures are in the proximity of the tails of Equation (1), where the slope is close to zero, even a large change in air temperature under a climate change scenario may not cause a change in maximum or minimum weekly stream temperatures larger than the error in the simulations. The values given in Table I illustrate this point.

On average, the mean weekly stream temperatures in the contiguous U.S. under the $2 \times CO_2$ climate scenario would be 2 to 4 °C warmer than present, but there would be only a 1 to 3 °C increase in the *maximum* and *minimum* weekly stream temperatures under the $2 \times CO_2$ climate scenario (Mohseni et al., 1999).

5. Fish Temperature Tolerances

To study the presence or absence of a fish species in a river reach, represented here by a stream gaging station, the authors focused first on the maximum weekly temperature tolerances of 57 fish species which were previously given by Eaton and Scheller (1996). Information on minimum temperature tolerances of fish species is much more sparse, although values for a few particular fish species could be found in the literature. Sheehan et al. (1990), for example, found that young green sunfish (*Lepomis cyanellus*) died as water temperature was reduced from 5 to 4 °C. Packer and Hoff (1998) observed that water temperature in the range from 2 °C to

4 °C caused mortality for summer flounder (*Paralichthys dentatus*). Scheller et al. (1999) took 2 °C as the lower temperature constraint for 15 warm water fishes in their multivariate statistical model of the influence of stream thermal regimes on fishes. Piper et al. (1982) published viable temperature ranges for 21 cold, cool and warm water fishes. For 20 of 21 fish species, a 0.5 °C was set as the lower temperature tolerance. Bell (1991) presented values for the lower temperature limits of 11 fish species. Bell's study shows that 8 of 10 cold water fishes used in the present study have a minimum temperature tolerance of 0 °C. Among the warm water species, largemouth bass (*Micropterus salmoides*) has a lower limit of 4.5 °C, which is 4 °C higher than the lower temperature tolerance provided by Piper et al. (1982).

The EPA's fish and temperature database matching system (FTDMS) data set described by Eaton et al. (1995) was also studied to determine minimum temperature tolerances of different fish species. Unfortunately, no lower limit could be inferred from the dataset because the FTDMS is biased toward fish observations during the summer and therefore high temperatures. There are few low temperature data in the FTDMS.

Because information on minimum temperature tolerance of fresh water fishes is sparse, two alternative values were assigned as the minimum temperature tolerance for cool water and warm water fishes: 0 °C and 2 °C. The rationale behind this choice was to investigate the significance of a 2 °C difference in minimum temperature tolerance on the fish habitat under a warmer climate. The minimum temperature tolerance of all (10) cold water fishes were set at 0 °C.

Not considered in this study, however, are the hydrogeological setting of the streams and the effect of thermal refuges due to groundwater inflow. Locales just downstream from springs may serve as a relatively low-temperature refuge in summer and as relatively high-temperature refuge in winter. Meisner (1990) showed the significant effect of groundwater refuges for brook trout (*Salvelinus fontinalis*) in determining winter distribution of this species. To incorporate the effects of refuges on fish temperature tolerances a more thorough and detailed analysis/modeling of fish habitat under potential climate warming is required.

In this study, stream temperatures are related to air temperature as the only independent variable, and effects of other factors such as availability of groundwater seepage areas, vegetation cover on stream banks, local elevation and latitude, and local watershed characteristics (e.g., reservoir releases) are implicitly incorporated in the four calibration parameters of the non-linear model. A more explicit discussion of such factors was given by Erickson and Stefan (2000), and further refined analysis would have to include some or all of them explicitly in the stream temperature model. Reservoir releases and groundwater inputs are probably the best candidates since they have the least connection to air temperature and are of importance creating fish refuges.

6. Results and Discussion

The number of stream gaging stations with suitable thermal habitat for the $1 \times CO_2$ (present) and $2 \times CO_2$ climate conditions using the 0 °C lower temperature constraint is listed in Table II for cold and cool water fishes and in Table III for warm water fishes. Fish species are listed in increasing order of maximum temperature tolerance. The relative frequencies of the maximum weekly stream temperatures under $1 \times CO_2$ and $2 \times CO_2$ climate scenarios are shown in Figures 3a,b for the nonlinear and the linear models, respectively. It can be seen that the projections made by the linear model are clearly too high because the water temperature/air temperature relationship is in reality non-linear as was discussed earlier in this paper. With respect to maximum temperature tolerance, only 30% of the streams used in this study are suitable for cold-water fishes given in Table II, and less than 0.5% of the streams are not thermally suitable for any fish species given in Tables II and III.

The results show that there would be a 33% to 39% decrease in the number of streams thermally suitable for cold water fishes, an 11% to 22% decrease for cool water fishes and almost no change for warm water fishes. For most warm water fishes, more than 760 stream reaches (gaging stations) of the 764 investigated had thermally suitable habitat (Figure 4). The results in Tables II and III are significantly different from those obtained by Eaton and Scheller (1996). The difference comes from the projected maximum weekly stream temperatures. The logistic function (Equation (1)) does not indicate a significant increase in stream temperatures under the $2 \times CO_2$ climate scenario. Therefore, warm water fishes and most cool water fishes would not lose much habitat by the small predicted increase (1–3 °C increase) in water temperatures. The fish guild that would be harmed the most are the cold water fishes. Figure 5 shows that under the $2 \times CO_2$ climate condition, rainbow trout (*Oncorhynchus mykiss*), for example, would disappear from the gaging stations located in the Midwest, the Ohio River basin and the East Coast. More precisely, rainbow trout would not vanish from stream reaches at higher altitudes (e.g., the Rocky Mountains and the Appalachian Mountains) because those stations are not projected to experience very warm water temperatures under the $2 \times CO_2$ climate scenario. This is similar to the shift of cold-water fish thermal habitat projected by Rahel et al. (1996) for the Platte River watershed. White sucker (*Catostomus commersoni*), a cool water fish, would find it more difficult to live in the lower Mississippi plain and the southern part of the East Coast (Figure 6), i.e., thermal range boundaries would be extended northward to higher altitudes.

If the minimum temperature tolerance is set at 2 °C for cool and warm water fishes, a very different picture of fish thermal habitat is obtained (Tables II and III). Because of the 2 °C lower temperature constraint, the number of stream gaging stations suitable for fish is smaller under the $1 \times CO_2$ (present) climate conditions. Consequently, under a warmer $2 \times CO_2$ climate, there would be a

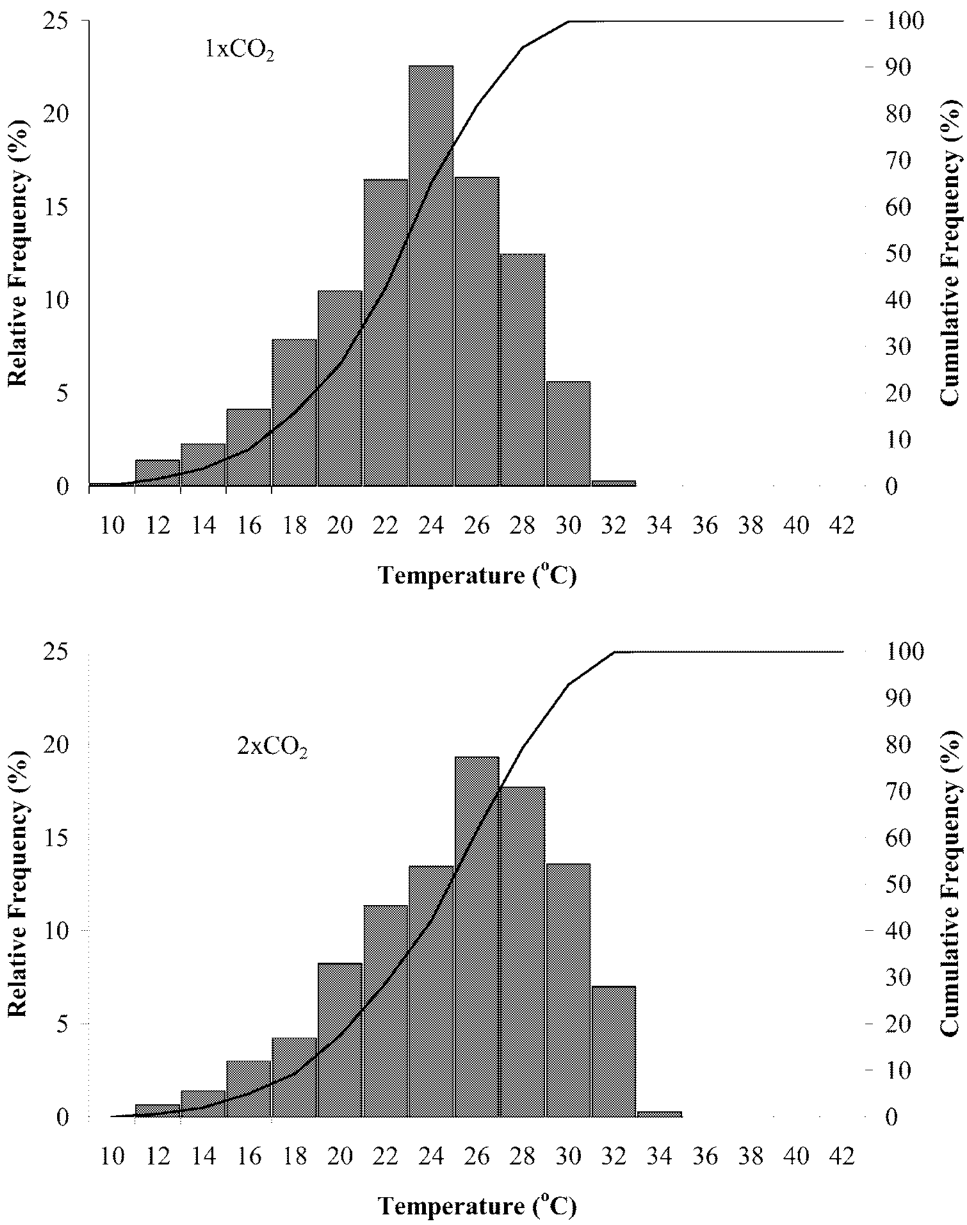

Figure 3a. Histograms of maximum weekly stream temperatures in the contiguous U.S., under $1 \times CO_2$ and $2 \times CO_2$ climate scenarios, using the S-shaped function.

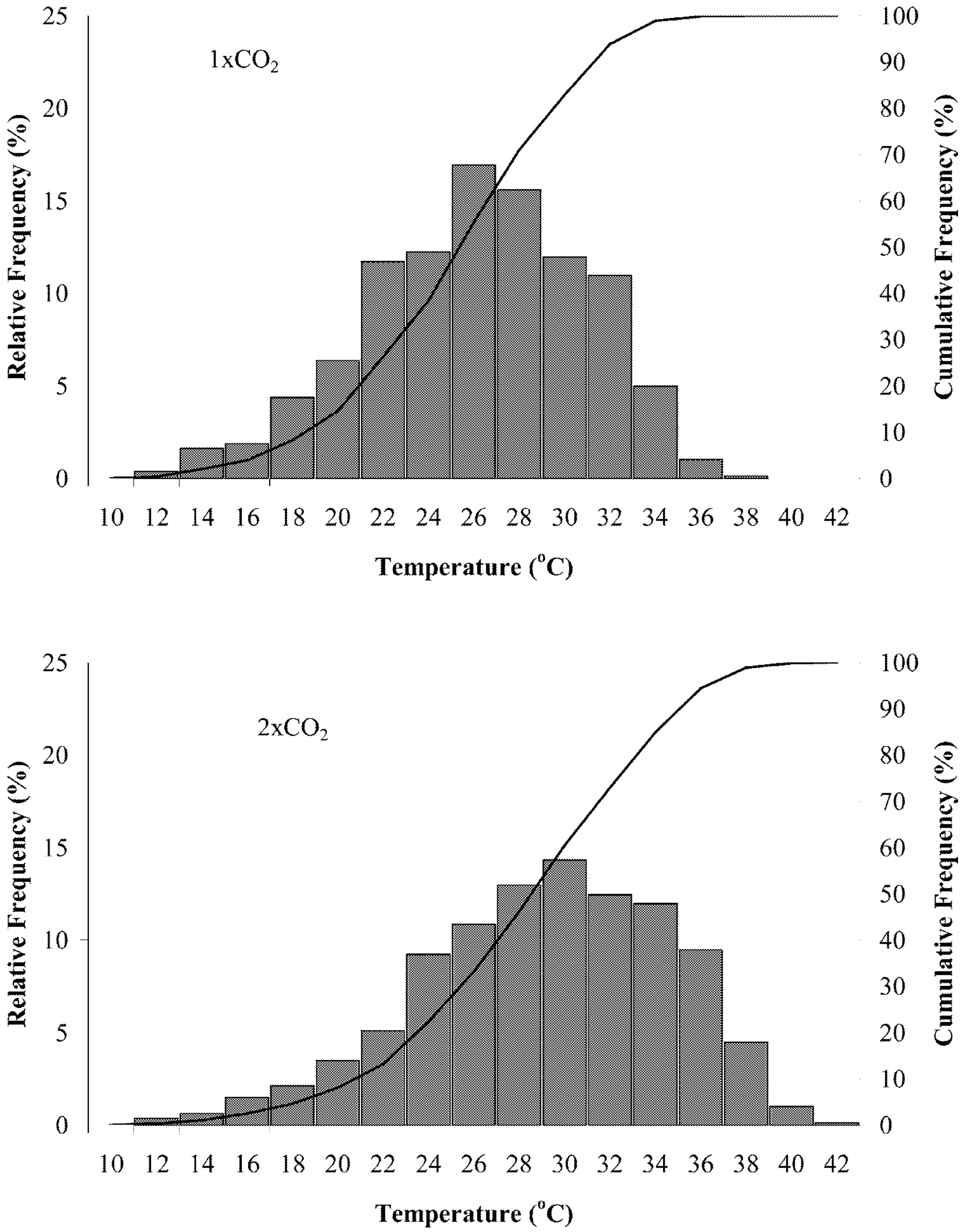

Figure 3b. Histograms of maximum weekly stream temperatures in the contiguous U.S., under $1 \times CO_2$ and $2 \times CO_2$ climate scenarios, using the linear regression function.

Table II

Number of U.S. stream gaging stations (out of 764 investigated) with thermal regimes within the maximum and minimum temperature tolerances of cold and cool water fishes under $1 \times CO_2$ and $2 \times CO_2$ climate conditions

Fish species		Maximum temperature tolerance (°C)	Min. temperature tolerance of 0 °C: Number of stations $1 \times CO_2$	Min. temperature tolerance of 0 °C: Number of stations $2 \times CO_2$	Min. temperature tolerance of 0 °C: % change in number of stations under $2 \times CO_2$	Min. temperature tolerance of 2 °C: Number of stations $1 \times CO_2$	Min. temperature tolerance of 2 °C: Number of stations $2 \times CO_2$	Min. temperature tolerance of 2 °C: % change in number of stations under $2 \times CO_2$
Cold water								
Chum salmon	*Oncorhynchus keta*	19.8	172	114	–33.7			
Pink salmon	*Oncorhynchus gorbuscha*	21.0	246	148	–39.8			
Brook trout	*Salvelinus fontinalis*	22.4	338	219	–35.2			
Mountain white fish	*Prosopium williamsoni*	23.1	401	260	–35.2			
Cutthroat trout	*Oncorhynchus clarki*	23.3	423	267	–36.9			
Coho salmon	*Oncorhynchus kisutch*	23.4	431	271	–37.1			
Chinook salmon	*Oncorhynchus tshawytscha*	24.0	484	306	–36.8			
Rainbow trout	*Oncorhynchus mykiss*	24.0	484	306	–36.8			
Brown trout	*Salmo trutta*	24.1	493	312	–36.7			
Mottled sculpin	*Cottus bairdi*	24.3	515	330	–35.9			
				Average	*–36.4*			
Cool water								
Johnny darter	*Etheostoma nigrum*	26.5	634	493	–22.2	350	380	8.6
Longnose dace	*Rhinichthys cataractae*	26.5	634	493	–22.2	350	380	8.6
Creek chub	*Semotilus atromaculatus*	27.1	662	545	–17.7	377	422	11.9
Blacknose dace	*Rhinichthys atratulus*	27.2	665	549	–17.4	380	424	11.6
White sucker	*Catostomus commersoni*	27.4	678	555	–18.1	392	430	9.7
Northern pike	*Esox lucius*	28.0	714	598	–16.2	425	468	10.1
Walleye	*Stizostedion vitreum*	29.0	753	652	–13.4	463	520	12.3
Pumpkinseed	*Lepomis gibbosus*	29.1	757	656	–13.3	467	524	12.2
Yellow perch	*Perca flavescens*	29.1	757	656	–13.3	467	524	12.2
Common shiner	*Luxilus cornutus*	29.2	757	662	–12.5	467	530	13.5
Rock bass	*Ambloplites rupestris*	29.3	759	665	–12.4	469	533	13.6
Brown bullhead	*Ameiurus nebulosus*	29.4	760	666	–12.4	470	534	13.6
Smallmouth bass	*Micropterus dolomieui*	29.5	762	672	–11.8	472	540	14.4
Golden redhorse	*Moxostoma erythrurum*	29.6	762	677	–11.2	472	544	15.3
Northern hog sucker	*Hypentelium nigricans*	29.6	762	677	–11.2	472	544	15.3
Silver red horse	*Moxostoma anisurum*	29.6	762	677	–11.2	472	544	15.3
				Average	*–14.8*		Average	*12.4*

significant increase in the thermal habitat of fishes because the projected minimum weekly stream temperatures would become higher and could more easily exceed the lower temperature constraint for fishes. Figure 7 therefore shows that there would be an increase in the thermal habitat of many fish species, especially for warm water fishes. Warmwater fishes encounter more thermally suitable habitats under $1 \times CO_2$ (present) climate conditions and a 33% increase is projected for most of them. Warm water streams would not experience a high water temperature rise under a $2 \times CO_2$ climate condition due to evaporative cooling. Hence, most stream gaging stations retain suitable thermal habitat for warm water fishes. In cool streams, minimum stream temperatures rise due to climate warming from say 0 °C to 3 °C, therefore, the presence of warm water fishes would be much facilitated.

Table III

Number of U.S. stream gaging stations (out of 764 investigated) with thermal regimes within the maximum and minimum temperature tolerances of warm water fishes under $1 \times CO_2$ and $2 \times CO_2$ climate conditions

Fish species		Maximum temperature tolerance (°C)	Min. temperature tolerance of 0 °C			Min. temperature tolerance of 2 °C		
			Number of stations		% change in number of stations under $2 \times CO_2$	Number of stations		% change in number of stations under $2 \times CO_2$
			$1 \times CO_2$	$2 \times CO_2$		$1 \times CO_2$	$2 \times CO_2$	
Warm water								
Bluntnose minnow	*Pimephales notatus*	30.1	762	707	–7.2	472	574	21.6
Sauger	*Stizostedion canadense*	30.1	762	707	–7.2	472	574	21.6
Black crappie	*Pomoxis nigromaculatus*	30.5	762	721	–5.4	472	588	24.6
Golden shiner	*Notemigonus crysoleucas*	30.9	762	737	–3.3	472	604	28.0
Spotted bass	*Micropterus punctulatus*	30.9	762	737	–3.3	472	604	28.0
White perch	*Morone americana*	30.9	762	737	–3.3	472	604	28.0
White crappie	*Pomoxis annularis*	31.0	763	743	–2.6	473	610	29.0
White bass	*Morone chrysops*	31.4	763	753	–1.3	473	620	31.1
Longnose gar	*Lepisosteus osseus*	31.6	763	758	–0.7	473	625	32.1
Emerald shiner	*Notropis atherinoides*	31.8	763	760	–0.4	473	627	32.6
Sand shiner	*Notropis stramineus*	32.1	763	761	–0.3	473	628	32.8
River carpsucker	*Carpiodes carpio*	32.1	763	761	–0.3	473	628	32.8
Suckermouth minnow	*Phenacobius mirabilis*	32.5	763	761	–0.3	473	628	32.8
Orange spotted sunfish	*Lepomis humilis*	32.6	763	761	–0.3	473	628	32.8
Freshwater drum	*Aplodinotus grunniens*	34.0	763	763	0.0	473	630	33.2
Bulkhead minnow	*Pimephales vigilax*	34.0	763	763	0.0	473	630	33.2
Black bullhead	*Amieurus melas*	34.0	763	763	0.0	473	630	33.2
Flathead catfish	*Pylodictis olivaris*	34.0	763	763	0.0	473	630	33.2
Flathead minnow	*Pimephales promelas*	34.0	763	763	0.0	473	630	33.2
Ghost shiner	*Notropis buchanani*	34.0	763	763	0.0		630	33.2
Gizzard shad	*Dorosoma cepedianum*	34.0	763	763	0.0	473	630	33.2
Green sunfish	*Lepomis cyanellus*	34.0	763	763	0.0	473	630	33.2
Longear sunfish	*Lepomis megalotis*	34.0	763	763	0.0	473	630	33.2
Mosquitofish	*Gambusia affinis*	34.0	763	763	0.0	473	630	33.2
Red shiner	*Cyrpinella lutrensis*	34.0	763	763	0.0	473	630	33.2
Smallmouth buffalo	*Ictiobus bubalus*	34.0	763	763	0.0	473	630	33.2
Warmouth	*Lepomis gulosus*	34.0	763	763	0.0	473	630	33.2
Common carp	*Cyprinus carpio*	35.0	763	763	0.0	473	630	33.2
Channel catfish	*Ictalurus punctatus*	35.0	763	763	0.0	473	630	33.2
Largemouth bass	*Micropterus salmoides*	35.5	763	763	0.0	473	630	33.2
Bluegill	*Lepomis macrochirus*	36.0	763	763	0.0	473	630	33.2
				Average	*–1.2*		Average	*31.4*

For example, there would be a 33% increase in the number of stations thermally suitable for largemouth bass, *Micropterus salmoides* (Figure 8). More rivers in the Rocky Mountains and at northern latitudes would become inhabited by largemouth bass. Figure 8 shows that there would likely be a northward spread of largemouth bass under the $2 \times CO_2$ climate scenario. The projection for largemouth bass is in agreement with that obtained by Eaton and Scheller (1996). Information on projected changes in suitable habitat for individual fish species is provided by Mohseni and Stefan (2000).

The 2 °C lower temperature constraint for cool water fish species may be too high. Similarly, a 0 °C lower temperature constraint may be too low for some

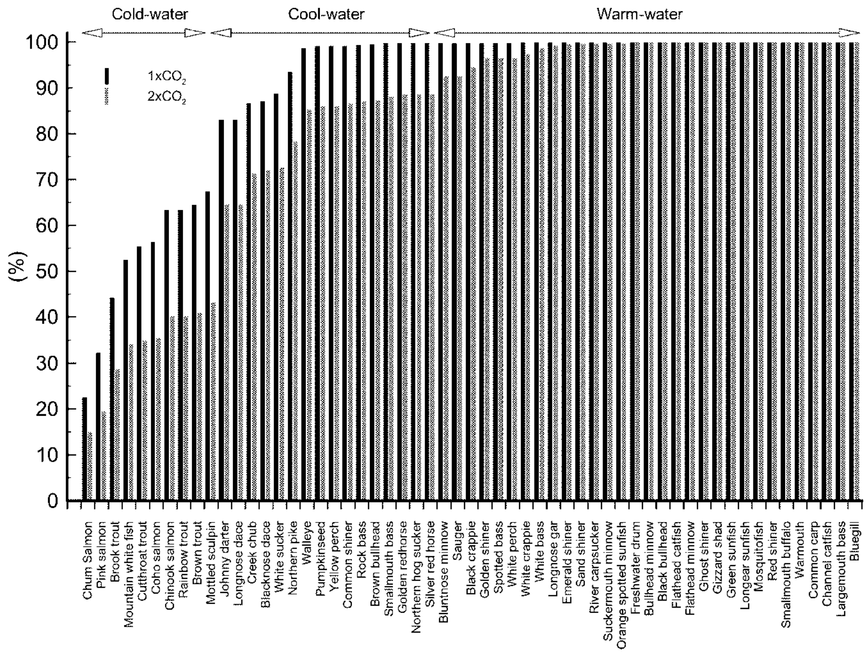

Figure 4. Suitable thermal habitats of 57 fish species as a percentage of all stream gaging stations (764) under $1 \times CO_2$ and $2 \times CO_2$ climate conditions. The minimum weekly temperature tolerance for all fishes is set equal to 0 °C.

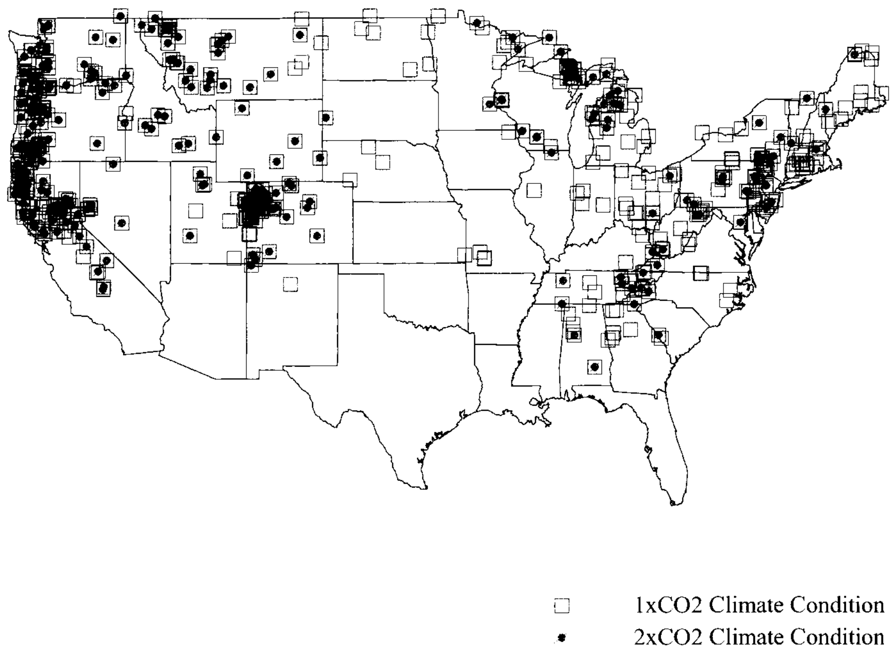

Figure 5. Stream gaging stations with suitable thermal regime for rainbow trout (*Oncorhynchus mykiss*) under past and $2 \times CO_2$ climate conditions.

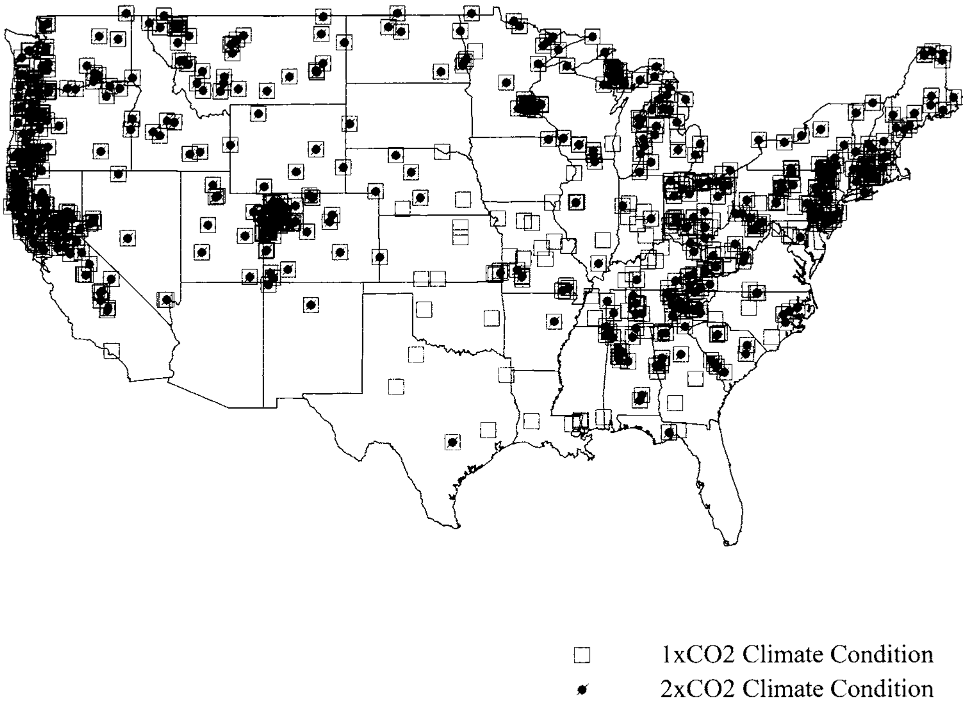

Figure 6. Stream gaging stations with suitable thermal regime for white sucker (*Catostomus commersoni*) under past and $2 \times CO_2$ climate conditions. The minimum weekly temperature tolerance is set equal to 0 °C.

warm water fishes. For that reason, Figure 4 may be more representative for cool water fishes and Figure 7 for warm water fishes. To facilitate the comparison, the difference between the changes under the $2 \times CO_2$ climate scenario for both low temperature constraints are illustrated in Figure 9. It can be seen that the projected effect of climate change (from $1 \times CO_2$ to $2 \times CO_2$) on stream thermal fish habitat is accentuated if the lower temperature constraint is set at 0 °C for cool water fishes and 2 °C for warm water fishes, rather than constant for all species. The most likely response to climate change (from a $1 \times CO_2$ to a $2 \times CO_2$ climate scenario) would therefore be a 36% decrease in thermal habitat for cold water fishes. However, for cool and warm water fishes the projected habitat changes depend upon reliable knowledge of minimum temperature tolerance of the fish species.

A comparison of the results in Figures 4 and 7 indicates that reliable lower temperature tolerances for different fish species are as important as upper temperature tolerances for projecting fish habitat under a warming climate scenario. Because of evaporative cooling, already high stream temperatures will not significantly increase, thus, the upper temperature constraint will not be a crucial factor. Cold-water streams will be warmed more than warm water streams if the climate becomes warmer. As a result, cold-water fishes will be affected by this warming

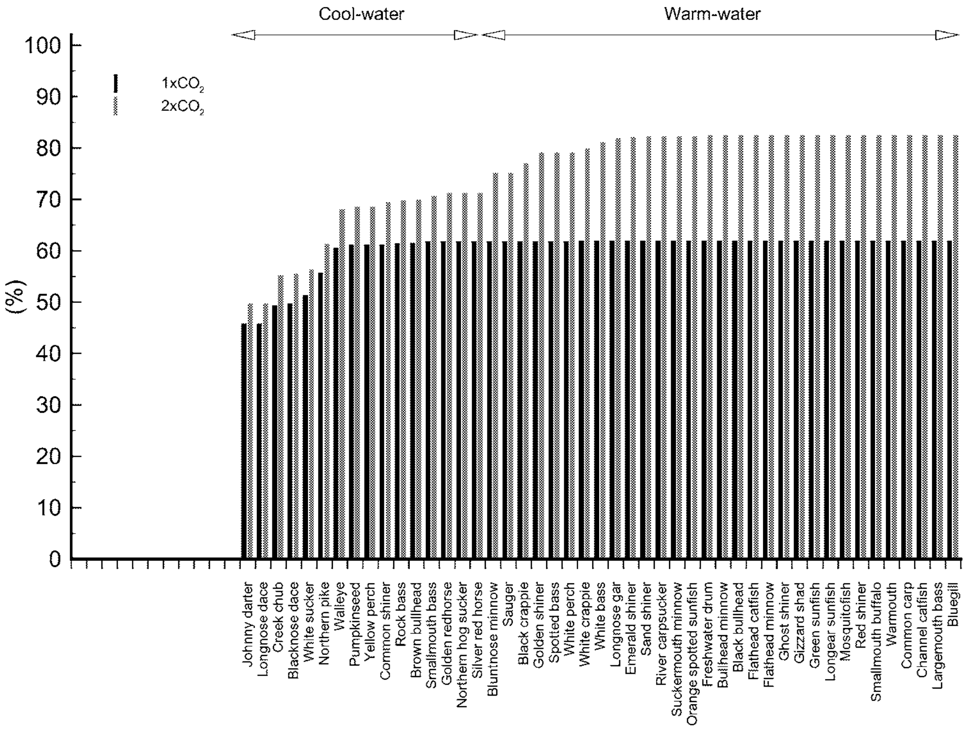

Figure 7. Suitable thermal habitats of 47 fish species as a percentage of all records (764) under $1 \times CO_2$ and $2 \times CO_2$ climate conditions. The minimum weekly temperature tolerance is set equal to 2 °C.

and lose their habitat (Figure 5). The warming would be even more dramatic for shaded cold water streams if the riparian vegetation is lost. This effect is not included in the S-shaped stream temperature/air temperature relationship derived from data and used in this study.

The projected changes in fish habitat, especially for cold-water fishes, would require important management decisions, for example regarding stocking of streams and fishing regulations.

7. Summary

The four-parameter nonlinear stream temperature model developed by Mohseni et al. (1998a) was utilized to simulate weekly stream temperatures at 764 U.S. stream gaging stations. For the $2 \times CO_2$ climate condition, weekly stream temperatures were obtained from incremented weekly air temperatures using the output of the CCC-GCM. Finally, the suitable thermal habitats for 57 fish species were projected utilizing their maximum and minimum weekly temperature tolerances. A minimum temperature tolerance of 0 °C was imposed for cold water fishes, but due to a lack

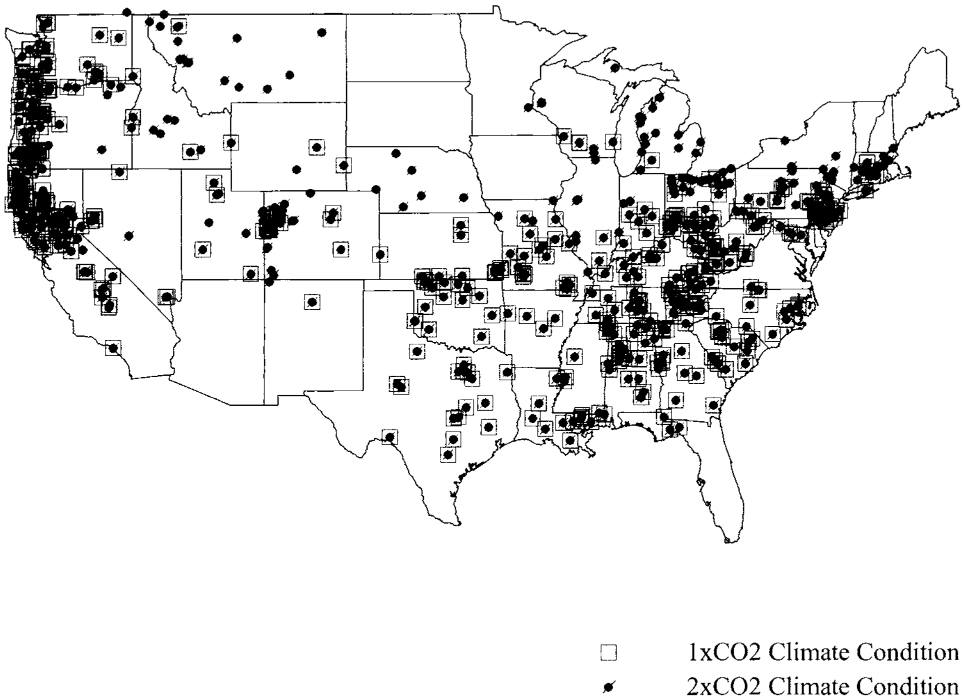

Figure 8. Stream gaging stations with suitable thermal regime for largemouth bass (*Micropterus salmoides*) under past and $2 \times CO_2$ climate conditions. The minimum weekly temperature tolerance for all fishes is set equal to 2 °C.

of information on minimum temperature tolerance of cool and warm water fishes, a 0 °C or a 2 °C lower temperature constraint was imposed alternatively. The results showed that different lower temperature constraints gave very different habitat results. A 36% decrease in thermal habitats suitable for cold water fish was projected, and with 0 °C as the lower temperature constraint, a 15% decrease for cool water fish and almost no change in warm water fish thermal habitats were projected. With 2 °C as the lower temperature constraint, a 12% decrease was projected in cool water fish thermal habitats and a 31% increase in warm water fish thermal habitats.

The results of this study also show that the maximum temperature tolerance will not have a crucial effect on warm water fish habitats because of the evaporative cooling of streams. The maximum temperature tolerance is, however, a limiting factor, which will cause the range of cold water fish to contract northward, i.e., losing habitat in lower latitudes with a northward range extension. Conversely, the lower temperature constraint plays an important role for habitats of cool and warm water fishes. The percentage decrease in suitable thermal habitat of cool water fishes, and northward expansion of the warm water fish range depend upon their minimum temperature tolerances, which need to be determined more accurately.

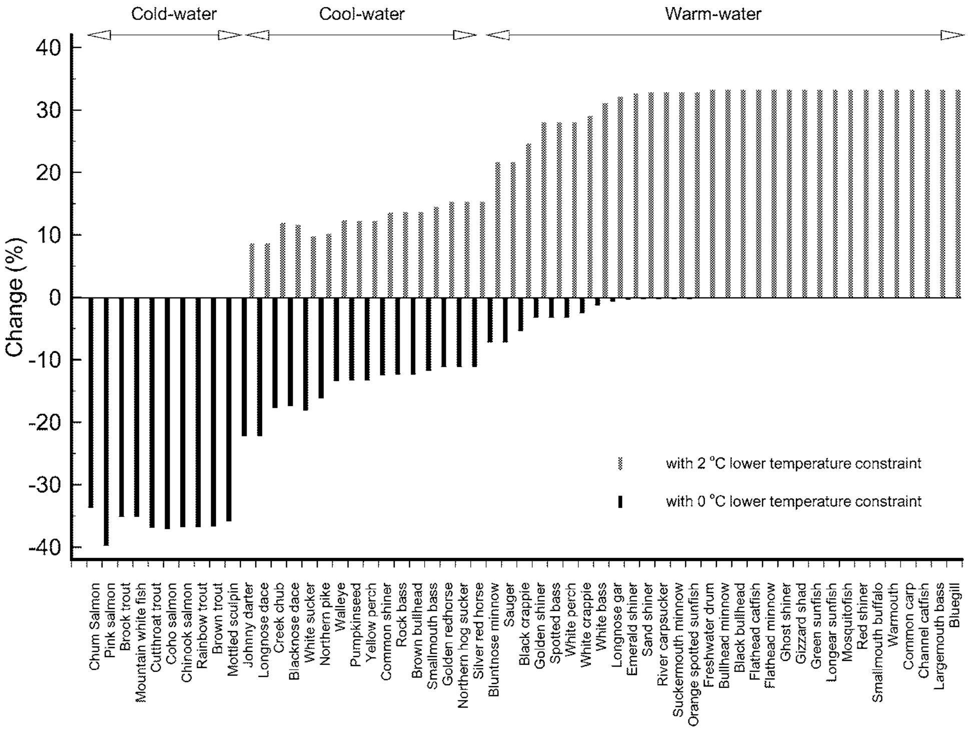

Figure 9. Changes in fish thermal habitat under the 2 × CO_2 climate scenario. For cool and warm water fishes lower temperature constraints are set at 0 °C and 2 °C. Changes are given as percentage of past conditions.

Acknowledgements

The work reported herein was supported by the Agricultural Research Service, USDA, Grazing Lands Research Laboratory, El Reno, Oklahoma in cooperation with the Mid-Continent Ecology Division, U.S. Environmental Protection Agency, Duluth, Minnesota. Dr. Robert Williams and Dr. Naomi Detenbeck were the project officers. We would like to thank Robert Scheller for providing weekly stream temperature data for the 989 USGS gaging stations. We also like to thank Travis Bogan for his valuable help with the part of the data management.

Appendix: Definitions

1. Weekly measured stream temperature is the average of daily stream temperature measurements taken over a week.
2. Maximum weekly stream temperature is the maximum of average weekly stream temperatures in the record.

3. Maximum weekly temperature tolerance of a fish species is the weekly average temperature beyond which the fish species will not survive.
4. Minimum weekly temperature tolerance of a fish species is the weekly average temperature below which the fish species will not survive.

References

Bell, M. C.: 1991, *Fisheries Handbook of Engineering Requirements and Biological Criteria*, Fish Passage Development and Evaluation Program, Corps of Engineers, North Pacific Division, Portland, Oregon, p. 322.

Coutant, C. C.: 1990. 'Temperature-Oxygen Habitat for Freshwater and Coastal Striped Bass in a Changing Climate', *Trans. Am. Fish. Soc.* **119**, 240–253.

Eaton, G. J and Scheller, R. M.: 1996, 'Effects of Climate Warming on Fish Thermal Habitat in Streams of the United States', *Limnol. Oceanogr.* **41**, 1109–1115.

Erickson, T. R. and Stefan, H. G.: 2000, 'Linear Air/Water Temperature Correlations for Streams during Open Water Periods', *J. Hydrol. Engineer. ASCE*, **5**, 317–321.

IPCC: 1996, 'Climate Change 1995', in Houghton, J. T., Meria Filho, L. G., Challander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), *The Science of Climate Change*, Cambridge University Press, Cambridge.

IPCC: 2001, 'Climate Change 2001', in Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, A., and Johnson, C. A. (eds.), *The Scientific Basis*, Cambridge University Press, Cambridge.

Lau, K.-M., Kim, J. H., and Sud, Y.: 1996, 'Comparison of Hydrologic Processes in AMIP GCMs', *Bull. Amer. Meteorol. Soc.* **77**, 2209–2227.

Matuszek, J. E. and Shuter, B. J.: 1996, 'An Empirical Method for the Prediction of Daily Water Temperatures in the Littoral Zone of Temperate Lakes', *Trans. Amer. Fish. Soc.* **125**, 622–627.

Magnuson, J. J., Meisner, J. D., and Hill, D. K.: 1990, 'Potential Changes in the Thermal Habitat of Great Lakes Fish after Global Climate Warming', *Trans. Amer. Fish. Soc.* **119**, 254–264.

McFarlane, N. A., Boer, G. J., Blanchet, J. P., and Lazare, M.: 1992, 'The Canadian Climate Center Second-Generation General Circulation Model and Its Equilibrium Climate', *J. Climate* **5**.

Meisner, J. D.: 1990, 'Effect of Climatic Warming on the Southern Margins of the Native Range of Brook Trout, Salvelinus Fontinalis', *Can. J. Fish. Aquat. Sci.* **47**, 1065–1070.

Mohseni, O., Stefan, H. G., and Erickson, T. R.: 1998a, 'A Nonlinear Regression Model for Weekly Stream Temperatures', *Water Resour. Res.* **34**, 2685–2692.

Mohseni, O., Erickson, T. R., and Stefan, H. G.: 1998b, *Projection of Climate Change Effects on Stream Temperatures in the U.S.*, Proj. Report No. 407, University of Minnesota, St. Anthony Falls Laboratory, Minneapolis, MN.

Mohseni, O. and Stefan, H. G.: 1999, 'Stream Temperature/Air Temperature Relationship: A Physical Interpretation', *J. Hydrol.* **218**, 128–141.

Mohseni, O., Erickson, T. R., and Stefan, H. G.: 1999, 'Sensitivity of the U.S. Stream Temperatures to Air Temperatures Projected under a Global Warming Scenario', *Water Resour. Res.* **35**, 3723–3734.

Mohseni, O. and Stefan, H. G.: 2000, *Projections of Fish Survival in U.S. Streams after Global Warming*, University of Minnesota, St. Anthony Falls Laboratory, Proj. Report No. 441, Minneapolis, MN.

Mohseni, O., Erickson, T. R., and Stefan, H. G.: 2002, 'Upper Bounds for Stream Temperatures in the Contiguous United States', *J. Environ. Engineer. ASCE* **128**, 4–11.

Nash, J. E. and Sutcliffe, J. V.: 1970, 'River Flow Forecasting through Conceptual Models, Part I-A Discussion of Principles', *J. Hydrol.* **10**, 282–290.

Piper, R. G., McElwain, I. B., Orme, L. R., McCraren, J. P., Fowler, L. G., and Leonard, J. R.: 1982, *Fish Hatchery Management*, United States Department of the Interior, Fish and Wildlife Service, Washington, D.C., p. 517.

Packer, D. B. and Hoff, T.: 1998, *Life History, Habitat Parameters, and Essential Habitat of Mid-Atlantic Summer Flounder*, American Fisheries Society Annual Meeting, Hartford, CT.

Rahel, F. G., Keleher, C. J., and Anderson, J. L.: 1996, 'Potential Habitat Loss and Population Fragmentation for Cold Water Fish in the North Platte River Drainage of the Rocky Mountains: Response to Climate Warming', *Limnol. Oceanogr.* **41**, 1116–1123.

Rundquist, L. A. and Baldrige, J. E.: 1990, in Ryan, W. L. and Crissman, R. D. (ed.), *Fish Habitat Considerations in Cold Region Hydrology and Hydraulics*, ASCE, New York, NY.

Scheller, R. M., Snarski, V. M., Eaton, J. G., and Oehlert, G. W.: 1999, 'An Analysis of the Influence of Annual Thermal Variables on the Occurrences of Fifteen Warmwater Fishes', *Trans. Amer. Fish. Soc.* **128**, 257–264.

Sheehan, R. J., Lewis, W. M., and Bodensteiner, L. R.: 1990, *Winter Habitat Requirements and Overwintering of Riverine Fishes*, Illinois Department of Conservation, Federal Aid in Sport Fish Restoration Project F-79-R, Final Report, Springfield.

Stefan, H. G., Hondzo, M., Eaton, J. G., and McCormic, J. H.: 1995, 'Predicted Effects of Climate Change on Fishes in Minnesota Lakes', in Beamish, R. J. (ed.), *Climate Change and Northern Fish Populations*, *Can. Spec. Publ. Fish. Aqua. Sci.* **121**, 57–72

Webb, B. W. and Nobilis, F.: 1997, 'A Long Term Perspective on the Nature of the Air-Water Temperature Relationship: A Case Study', *Hydrol. Process.* **11**, 137–147.

(Received 8 December 2000; in revised form 8 January 2003)