

Variability and alterations of water temperatures across the Elbe and Danube River Basins

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Abstract Climate change is predicted to be a major threat to river ecosystems in the 21st century, but long-term records of water temperature in streams and rivers are rare. This study uses long-term water temperature series from the Elbe and the Danube River Basin to quantify the variability, magnitude, and extent of temperature alterations at different time scales. The observed patterns in monthly and daily water temperatures have been successfully described through statistical models based on air temperature, river discharge and the North Atlantic Oscillation Index. These models reveal that air temperature variability describes more than 80 % of the total water-temperature variability, linking anticipated changes in water temperature mainly to those in air temperature. The North Atlantic Oscillation effect deteriorates with decreasing latitude, while the discharge effect becomes more important and increases with the increase in discharge amount. The detected water temperature alterations include a phase shift in spring warming of almost 2 weeks, an increase in the number of days with temperatures above 25 °C and an increase in the duration of summer heat stress. These findings underline a significant risk for fundamental changes in river ecosystems, specifically in disruption of established patterns in food-web synchrony, and may lead to significant distortions in community structure and composition.

1 Introduction

Water temperature is one of the most important drivers of physical, chemical and ecological processes in river systems (Brown and Hannah 2008) and determines the overall health of

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aquatic ecosystems (Caissie 2006). Temperature-dependent ecosystem functions and species-specific processes include primary production, decomposition, litter processing, recruitment, growth, reproduction, metabolism, resistance to pathogens and death susceptibility (e.g. Johnson and Johnson 2009). For example, fish are known to be sensitive to temperature changes less than 0.5 °C and each species has a specific thermal range that often varies over the different life stages (cf. Johnson and Johnson 2009). Changes in the thermal regime of river systems may result in the disruption of established patterns of synchrony between the aquatic communities such as weakening or breaks in the trophic interactions (Woodward et al. 2010) and mismatches between predator requirements and resource availability (Kishi et al. 2005).

Atmospheric forcing, in particular net radiation, is commonly perceived as the major component of the heat budget of the river systems. The effect of atmospheric forcing is modified by contributions from the river discharge, bed friction, riparian vegetation, groundwater-related heat transport and various anthropogenic perturbations such as thermal pollution, embankments and deforestation (see Webb et al. 2008; Olden and Naiman 2010). Due to the hierarchical dendritic structure of river systems, site-specific aquatic thermal regimes are a result of local and cumulative upstream effects.

Although water temperature monitoring has a long tradition, there is an overall lack of long-term, continuous, quality-assured water-temperature datasets (Webb and Nobilis 2007). Consequently, studies on temporal patterns and changes are limited to trend analyses for either single stations (e.g. Pekárová et al. 2011) or multiple stations within a national station network (e.g. Webb and Nobilis 2007; Bonacci et al. 2008; Kaushal et al. 2010). In particular, Kaushal et al. (2010) reported an increasing trend of 0.009–0.077 °C year⁻¹ for streams and rivers in the US, Webb and Nobilis (2007) reported an increasing trend of 0.014–0.017 °C year⁻¹ for the water temperature in Austria and Bonacci et al. (2008) showed an increasing trend of 0.012–0.025 °C year⁻¹ for water temperatures in Croatia. In addition to the long-term temperature increase, accelerated rates of increase have been observed in the early 1980s for the Austrian section of the Danube River (Webb and Nobilis 2007). An acceleration phenomenon is especially pronounced in winter months and is generally argued to be associated with the shift of the North Atlantic Oscillation (NAO) towards a positive phase in the late 1980s (see Straile and Stenseth 2007). The focus of recent water-temperature research is on disentangling the relative effects of factors that have contributed to recent warming trends. For example, Isaak et al. (2012) have shown that air temperature is the dominant factor explaining long-term stream temperature trends and inter-annual variability for all seasons except the summer. Also, Koch and Grünewald (2010) have shown that daily water temperature can be successfully described using regression models based on air temperature over longer time periods.

The purpose of this study is to examine variability and alterations in water temperature along a latitudinal gradient that extends from northern Germany via Austria to Serbia. Specifically, the study aims to explore long term water temperature records across the Elbe and Danube River Basin including: (1) quantification of the amount of variation across different temporal scales (daily, seasonal, annual and inter-annual), (2) detection of phase shifts and changes in high and low extremes, (3) time series decomposition into central tendency (“trend”) and annual cycle, and analysis of the component properties, and (4) modelling of mean monthly and daily water temperatures to quantify the relative influence of air temperature, discharge and the NAO on water-temperature fluctuations. The combination of large spatial and temporal scales has enabled a unique trans-basin analysis of the thermal fluctuations affecting riverine ecosystems and discussion of the potential implications of the detected thermal patterns.

2 Study area and data

The Elbe River Basin (148 268 km²) extends from Krkonose Mountains in the Czech Republic to the North Sea estuary at Cuxhaven, Germany. The mean discharge at the estuary is 861 m³s⁻¹. The mean annual air temperature ranges from 1° (southern mountainous area) to 9 °C (upper Elbe) (IKSE 2005). The river flow is regulated by 292 dams (IKSE 2005), mostly located in the middle and the upper Elbe, representing the loss of the natural flow regime and significant anthropogenic pressure for these regulated river sections.

The Danube River Basin (807,000 km²) extends from the Schwarzwald Massif in Germany to the Black Sea. The mean annual discharge reaches 6,500 m³s⁻¹ at the mouth in Romania (ICPDR 2005). Due to its large extension from west to east, the Danube River basin shows high climactic differences. The mean annual air temperatures range from -6.2 °C (Sonnblick) to 12 °C (Hungarian Lowland and the Black Sea coast; Kovács 2010). The Danube is impounded along approximately 30 % of its length.

The mean monthly and mean daily time series of water temperature (WT) from monitoring stations in the Elbe and the Danube River Basin (see Fig. 1) ranged between 29 years and 108 years in length. The datasets were obtained from the Agency for flood control and water management of Saxony Anhalt, the Elbe River Consortium (ARGE Elbe), the Bavarian State Office for Environment, Water Department of the Federal Ministry of Agriculture, Forestry, Environment and Water Management of Austria (BMLFUW) and the Republic Hydrometeorological Service of Serbia (RHMZ). The daily water temperatures were available for three Elbe River and two Danube River monitoring stations while the monthly temperatures were available at 15 monitoring sites (five for the Elbe River main course, three for the Elbe River tributaries (Aland, Havel and the Mulde River) and seven for the Danube River main course). Within the Danube temperature data set there is only one missing value (December 1969, Ingolstadt) while the number of missing values in temperature data from monitoring stations in the Elbe Basin is up to 33 (Elbe, Bunthaus). Missing values were replaced by the corresponding long-term means. Instrumentation for the temperature measurements has varied over time from alcohol and mercury thermometer to platinum resistance thermometers (PT100), implying measurement error that varies within the range 0.1–1 °C. Information about changes in the geographic position of the monitoring stations was not available from our data providers.

Information on water temperatures was supported by information on air temperatures and river flows adjacent to the water temperature monitoring sites (Fig. 1), along with information on the NAO Index variation. When describing water temperature, air temperature is commonly used as a surrogate for net heat exchange (in absence of information on net radiation), while river flow is known to modify atmospheric influence through the thermal capacity and travel time effects (Webb et al. 2008). The German Weather Service (DWD), the Central Institute for Meteorology and Geodynamics of Austria (ZAMG) and the RHMZ provided the air temperatures in the form of mean monthly and/or daily values. The mean monthly and/or daily discharge values were provided by the German Federal Institute of Hydrology (BfG), the BMLFUW and the RHMZ. The monthly and daily NAO Index used within this study was obtained from the data portal of the Climate Prediction Center (<http://www.cpc.ncep.noaa.gov>).

3 Methods

To quantify variability at seasonal (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec), annual and inter-annual scales (7 years), the mean monthly water temperatures are first aggregated to the

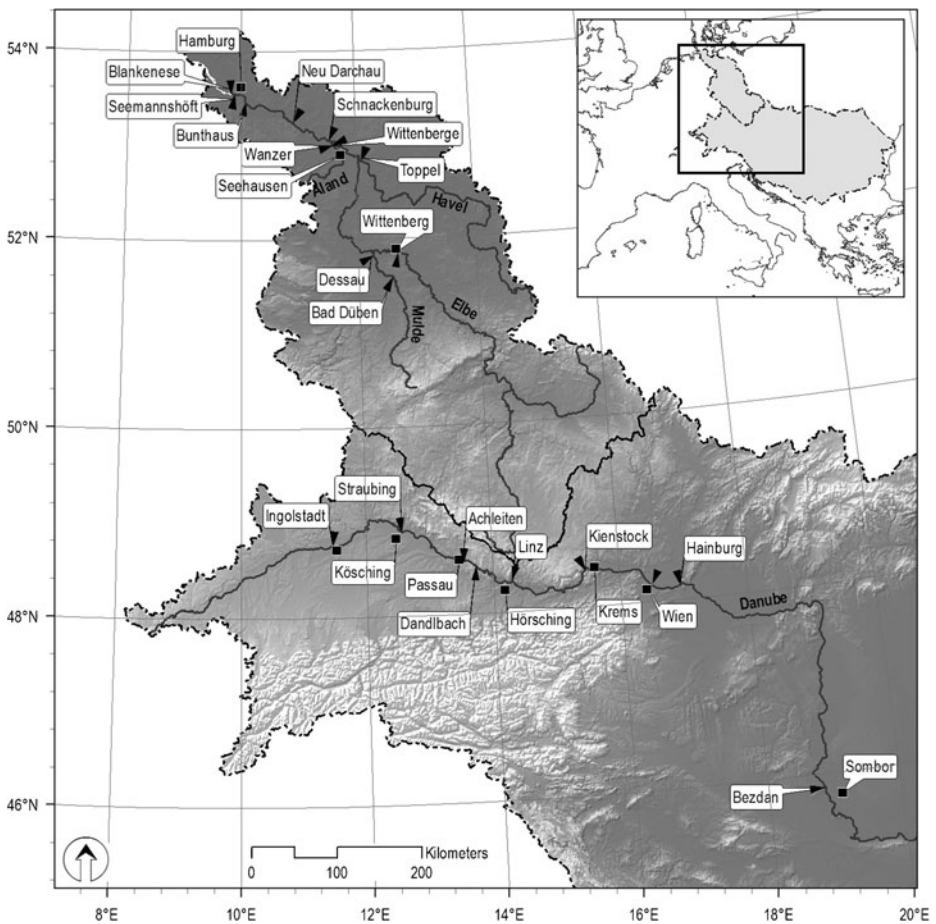


Fig. 1 Location of the monitoring stations: water temperature and/or river discharge (*triangle*) and air temperature (*square*)

appropriate scale level. The 7-year time scale corresponds to the major inter-annual variability scale of the Elbe River flows across Germany (Markovic and Koch 2006). After data aggregation, variability at the studied temporal scales is described by the corresponding water temperature range (min–max). The amount of variation is defined as the difference between the estimated maximum and minimum values.

To estimate the occurrence of both high and low temperature values, the peak over threshold (POT) method (see e.g. Ross 1987) is applied to the available daily data. Thresholds used within the POT method are 20 and 25 °C. Phase shifts are studied with respect to the start of the spring warming. The beginnings of the “early” and “late” spring warming are defined as the starting day of the first, long period of the year (minimum 5 days duration) with water temperature $T > 10$ °C and $T > 15$ °C, respectively.

For the time series decomposition, the method of Singular Spectrum Analysis (SSA, see Golyandina et al. 2001) is implemented within Matlab (version 6.0.0.88). The SSA method is applied to the mean monthly time series with the major SSA parameter, the window width L , set to $\frac{1}{2}$ of the observation time period. The annual cycle was identified using the

scatterplots of paired left singular vectors and the rule that the scatter plot of two identical periodic functions is a circle. For natural processes, such as water temperature, the annual cycle commonly describes less variability percentage (σ) than the central tendency, whereby the latter is considered the major time series component. The central tendency (commonly only X_{11}) describes the “trend” of the time series. Due to a quasi-periodic character, inter-annual cycles are often superimposed over a general trend within the central tendency. To estimate the maximum annual gradient (ΔT_{\max}), the difference between the maximum and the minimum of the central tendency for the specified time window is divided with the corresponding time span (Δt). In addition, the maximum annual gradient resulting from the application of the SSA method to the whole time series is compared with the slope coefficient resulting from the application of the linear regression (LR) method (e.g. Wilks 1995). To test the effect of auto-correlations the slope coefficients are estimated for the original and “pre-whitened” data. The “pre-whitening” procedure (von Storch 1995) consisted of lag-1 autocorrelation estimation ($\hat{\rho}$) and replacement of the original time series X_t by the series $X_t - \hat{\rho}X_{t-1}$.

Analyses of the temporal variability patterns of the raw data and the central tendency are performed for the full observation period (t_0-t_n) as well as for the 14 year duration time window. The 14-year time scale corresponds to the major inter-decadal variability scale of monthly Elbe River flows (Markovic and Koch 2006), possibly due to an atmospheric teleconnection with the NAO. As there was evidence for the influence of NAO on the inter-annual variability in air and water temperatures in the Danube Basin (see Webb and Nobilis 2007), the same window widths are used for the data from the Danube Basin. Because most of the available monitoring data ended in 2008, the 14-year non-overlapping time windows used to estimate the extent of recent temperature changes are set from Jan 1981 to Dec 1994 (W_1) and Jan 1995–Dec 2008 (W_2). Statistical significance between the statistics for W_1 and W_2 is measured using the two sample t-test (e.g. Wilks 1995).

To identify the relative contributions of air temperature (AT), discharge (Q) and the NAO variability to the variability in daily and monthly water temperatures, a multiple regression approach is applied (e.g. Wilks 1995). The model of mean monthly water temperatures considered only AT, Q and NAO as the predictor variables ($WT = \beta_{AT}AT + \beta_QQ + \beta_{NAO}NAO$), while modelling of daily water temperatures included also air temperature means across the moving window with a length of 14 days ($\beta_{AT_{mw}}AT_{mw}$). The selected window length corresponds to the minimum of the function describing dependence of the root mean squared error (RMSE) on the window length. For locations with statistically significant correlations (ρ) between the NAO and AT, the NAO effect was removed from AT data before performing the regression model ($AT-\rho NAO$). The calibration and validation periods of all models are W_1 and W_2 respectively. Goodness of fit of the calibrated and validated models is quantified by means of the RMSE and the coefficient of determination (R^2). The contribution of each predictor to the variations in water temperature is based on model outputs using normalized predictors, while the model coefficients given in the output tables refer to models using original predictor values. For all statistical test procedures the significance level $\alpha=5\%$ is used.

4 Results

4.1 Variability at seasonal, annual and the seven year scale

Analyses of mean monthly water temperature at seasonal, annual and 7-year scale revealed the following overall ranges across the study area (see Table 1): 0.2–7.3 °C (Jan–Mar),

Table 1 Basic characteristic of the water temperature during the whole observation period (t_0-t_n) at the seasonal, annual and 7-year scale

River	Location	Monitoring period t_0-t_n	Mean (°C)	STD (°C)	WT _{q1} range Jan–Mar (°C)	WT _{q2} range Apr–Jun (°C)	WT _{q3} range Jul–Sep (°C)	WT _{q4} range Okt–Dec (°C)	WT _{1year} range (°C)	WT _{7years} range (°C)	Time window with max WT _{7years}
Elbe	Blanknese	1980–09	11.7	6.9	1.2–6.5	13–17.4	17.7–21.9	6.2–11.3	10.4–12.7	11.2–12.3	2001–08
Elbe	Seemannshöft	1965–09	11.4	6.9	0.9–6.2	13.1–17.5	17.6–22.3	6.3–11.5	10–12.7	10.7–12.2	2000–07
Elbe	Bunthaus	1955–09	11.2	7.0	0.9–4.6	12.1–15.5	16.4–20.7	5.4–8.1	9.5–11.4	10.3–11.0	1970–77
Elbe	Schnackenburg	1980–09	11.3	7.1	0.8–5.6	12–17.5	17.9–21.2	6–9.3	9.8–12.3	10.9–11.5	1996–03
Aland	Wanzer	1981–09	10.3	6.3	1–7.3	12.3–17.1	13.2–19.1	4.8–8.7	9.3–11.3	9.9–10.7	2001–08
Havel	Toppel	1981–09	11.0	7.3	0.2–5.8	11.5–17.1	17.6–21.3	4.6–10	9.1–12.3	10.0–11.9	2002–08
Mulde	Dessau	1980–09	11.5	6.7	1.2–6.8	12.2–17.3	16.7–21.8	5.9–13.5	9.6–12.6	10.9–11.9	2003–09
Elbe	Wittenberg	1977–10	11.3	6.7	1.2–6.3	10.7–17.1	16.7–21.5	6.3–12.5	9.9–12.7	10.9–11.8	1984–91
Danube	Ingolstadt	1952–09	10.2	5.6	0.9–6.4	9.7–16.8	13.3–20.8	4.2–10.1	8.4–12.5	9.1–11.6	2000–07
Danube	Straubing	1981–09	10.9	6.5	1.9–5.8	11.7–17.7	16.5–21	6.5–8.9	9.6–12.3	10.1–11.8	2002–09
Danube	Dandlbach	1981–09	10.1	5.2	2.1–5.9	10.1–15.5	14.6–17.9	6.6–10	8.9–11.5	9.8–10.3	2000–07
Danube	Linz	1951–08	9.7	5.4	0.8–6	10.8–15.9	14.3–18.1	5.3–9.1	8.5–11.4	9.1–10.7	2002–08
Danube	Kienstock	1977–08	10.0	5.4	1.9–5.7	10.5–15.1	14.9–18.9	6.3–9	8.9–11.1	9.4–10.5	2000–07
Danube	Hainburg	1901–08	9.8	5.7	0.9–6.2	10.8–15.8	14.1–19.6	5–9.7	8.7–11.7	9.0–11.0	2002–08
Danube	Bezdan	1950–09	11.5	7.1	0.5–6.3	12.5–19	17.8–23	5.5–10.6	9.7–13.7	10.2–12.8	2002–09

STD the standard deviation, $WT_{q1}-WT_{q4}$ are the seasonal ranges (min–max), WT_{1year} is the annual range and WT_{7years} is the water temperature range over the moving window of 7 years

9.7–19.0 °C (Apr–June), 13.2–23.0 °C (Jul–Sep), 4.2–13.5 °C (Oct–Dec), 8.4–13.7 °C (annual) and 9–12.8 °C (7 year scale). Despite a lower latitude, the Danube water temperature at Dandlbach, Linz, Kienstock and Hainburg is for all analysed temporal scales lower than the water temperature at two northernmost Elbe gauges (i.e. Blankenese and Seemannshöft). The upper limit of the average annual temperature of the Elbe at Blankenese and Seemannshöft is 12.7 °C, only 1 °C lower than for the southernmost Danube gauge Bezdán (13.7 °C), located at a 7.7° lower latitude.

In general, there is a continuous decrease in the amount of variation as the analysed temporal scale increases. The mean amount of variation (max–min) for seasonal, annual and the studied inter-annual scale are 4.9, 2.8 and 1.4 °C respectively. Only the Apr–Jun temperatures show pronounced North-to-South latitudinal gradient and the highest difference (0.9 °C) between the means for W_1 and W_2 (see Fig. S1 in electronic supplementary material, ESM). The maximum of the 7-year running mean was generally within the first decade of the 21st century. Moreover, the temporal pattern of the 7-year running mean indicates continuous increases for both water and air temperature and an acceleration in the rate of increase since the early 1980s (see Fig. S2, ESM).

4.2 Extremes and phase shifts in daily water temperatures

The maximum observed daily water temperatures are between 22 and 27.1 °C, with a larger number of days with water temperatures above 20 °C for W_2 compared to W_1 (Table 2). The probability of the t -statistics comparing the number of peaks over 20 °C for W_1 and W_2 is statistically significant for three out of five analysed series (see Table 2).

With the exception of Danube at Linz, where no daily peaks over 25 °C were recorded during the whole observation period, the number of days with water temperatures exceeding this limit have significantly increased during W_2 . In particular, during W_1 the Danube temperature at Straubing was always below 25 °C; however, during W_2 this limit was exceeded for 24 days. Similarly, the Elbe River at Blankenese within W_1 was warmer than 25 °C for 9 days and during W_2 for 31 days. While temperature extremes during W_1 were mainly driven by isolated heat events, the extremes during W_2 were mainly a consequence of heat waves lasting several days.

No statistically significant changes in the early spring warming are detected. In comparison to W_1 , however, the late spring warming begins in W_2 on average 6 (Schnackenburg) to 12 days (Straubing) earlier (see Table 2), indicating a phase shift in the late spring water-temperature pattern. The phase shift between W_1 and W_2 is

Table 2 Basic characteristic of the water temperature data at the daily scale

Basin	Location	Monitoring period t_0 – t_n	WT range for t_0 – t_n (°C)	No. peaks >20 °C			Start of 15 °C period		
				W_1	W_2	p	W_1 (DOY)	W_2 (DOY)	p
Elbe	Blankenese	1980–09	0–26.5	644	923	0.009	133	126	0.062
Elbe	Seemannshöft	1965–09	0–26.5	640	889	0.002	134	126	0.033
Elbe	Schnackenburg	1980–09	0–27.1	687	817	0.124	132	127	0.168
Danube	Straubing	1981–09	0–27.0	283	628	0.003	142	130	0.041
Danube	Linz	1951–08	0–22.0	43	63	0.594	155	147	0.272

p is the probability of the t statistics comparing values for W_1 and W_2 while *DOY* denotes the day-of-year number

statistically significant for the Elbe temperature at Seemannshöft and the Danube temperature at Straubing.

4.3 Central tendency and annual cycle

Major outcomes of the quantitative analysis of the SSA results are summarized in Table 3. Decomposition of the mean monthly water-temperature series into central tendency and an annual cycle indicated that the former describes on average 74 % of the total variability, whereas the latter describes about 25 %. The contributions of the slowly varying central tendency and the annual cycle to the variability of the air temperature time series are on average 62 and 36 % respectively (see Table S1, ESM). Annual temperature gradients are about $0.01\text{ }^{\circ}\text{C year}^{-1}$ higher for water than for air, with negligible differences in temporal structure of their central tendencies (see Fig. S3, ESM).

The common property of all studied water temperature series is a continuous temperature increase ($\Delta T_{\max} > 0$ for $t_0 - t_n$, see Table 3). Also, ΔT_{\max} for the whole observation period is generally lower than that estimated for W_2 . Owing to differences in the data length, maximum temperature gradients of the water temperature series' central components for the full observation period are not directly comparable, unlike the gradients for W_1 and W_2 . Within W_1 , SSA central tendencies of water temperature records from the Elbe and Danube Basins indicate a mean annual temperature increase by 0.03 and $0.04\text{ }^{\circ}\text{C year}^{-1}$, respectively. Within W_2 , the mean annual increase rate across both studied basins is approximately $0.05\text{ }^{\circ}\text{C year}^{-1}$. For most records the period of increase is equal to the time window length (14 years). Although the mean annual increase rates are generally higher for W_2 compared to W_1 , the differences in the increase rates are not statistically significant.

Comparison of temperature gradients for the full observation period calculated using SSA and the linear regression indicated that the differences are within the range $\pm 0.018\text{ }^{\circ}\text{C year}^{-1}$. Assuming that the slope estimates resulting from the regression analysis of the whole time series also hold for W_1 and W_2 , then slight underestimation of “trends” in water temperature records using linear methods is apparent. Further, the slope estimates resulting from the linear regression are statistically significant only for the longest studied records (see Table 3). However, after “pre-whitening” the temperature data, none of the slope estimates are statistically significant (see Table S2, ESM).

4.4 Water-temperature-variability sources

Water-temperature modelling at the monthly scale was performed for all monitoring sites except Straubing and Toppel, where the air temperature and discharge data sets were insufficient in length. The calibration and validation R^2 is >0.9 for all models, with RMSE between 0.85 and $2.02\text{ }^{\circ}\text{C}$ (see Table 4). The average relative contribution of the air temperature is 84 and 83% for the Elbe and Danube river sites respectively. The mean discharge contribution is slightly larger (11%) for Danube sites compared to the Elbe sites (6%), while the opposite is true for the NAO contribution (Elbe, 10% and Danube, 6%). In addition, there is a slight decrease of the NAO and increase in the discharge contribution with site latitude (see Table 4). No statistically significant correlations between the NAO and Q are detected, while though small ($\rho=0.1$), the correlation between the NAO and AT is statistically significant for the Elbe gauge Bunthaus. Consequently, the results for the gauge Bunthaus (see Table 4) relate to the regression model with NAO effect removed from the AT data.

Table 3 Major SSA components of the mean monthly water and air temperatures

Basin	Location	Monitoring period t_0-t_n	SSA central tendency for t_0-t_n (%)	SSA annual component for t_0-t_n (%)	SSA WT gradient for t_0-t_n		LR WT slope for t_0-t_n	SSA WT gradient for W_1		SSA WT gradient for W_2	
					t_0-t_n σ (%)	ΔT_{max} ($^{\circ}\text{C year}^{-1}$)		Δt (years)	ΔT_{max} ($^{\circ}\text{C year}^{-1}$)	Δt (years)	ΔT_{max} ($^{\circ}\text{C year}^{-1}$)
Elbe	Blankenese	1980–09	74.7	24.2	0.046	27	0.046*	0.027	14	0.055	12
	Seemannshöft	1965–09	73.7	25.3	0.039	45	0.042*	0.043	14	0.038	14
	Bunthaus	1955–09	72.8	26.2	0.028	21	0.046	0.050	14	0.053	14
	Schnackenburg	1980–09	71.8	27.0	0.023	30	0.027*	0.009	10	0.032	14
	Wanzer	1981–09	73.3	24.6	0.046	28	0.029*	0.033	12.5	0.042	12
	Toppel	1981–09	69.7	28.8	0.098	29	0.084*	0.073	14	0.102	14
	Dessau	1980–09	74.7	23.6	0.050	13	0.021*	-0.039	12	0.053	12
	Wittenberg	1977–10	74.7	23.4	0.031	34	0.018*	0.022	10	0.032	13
	Wittenberg ^a	1951–09	62.0	35.1	0.036	57	0.028*	0.038	14	0.056	14
	Danube	Ingolstadt	1952–09	77.5	21.3	0.043	58	0.038	0.034	14	0.058
	Straubing	1981–09	74.8	24.2	0.092	29	0.078*	0.070	14	0.088	14
	Dandlbach	1981–09	78.9	20.2	0.032	29	0.026*	0.033	14	0.014	14
	Linz	1951–08	76.2	22.8	0.033	58	0.029	0.033	14	0.059	14
	Kienstock	1977–08	77.3	21.7	0.058	32	0.045*	0.057	14	0.060	14
	Hainburg	1901–08	74.7	24.3	0.014	108	0.015	0.016	14	0.024	14
	Bezdan	1950–09	73.0	26.0	0.045	60	0.046	0.054	14	0.054	14

*Not significant for $\alpha=0.05$

Table 4 Properties of the regression models of mean monthly water temperatures for W_1 (calibration period) and model statistics for W_2 (validation period)

Basin	Location (WT)	Location (AT)	Location (Q)	β_0	β_{AT}	β_Q	β_{NAO}	AT (%)	Q (%)	NAO (%)	R^2	RMSE (°C)	R^2_{val}	RMSE _{val} (°C)
Elbe	Blankenese	Hamburg	Neu Darchau	2.94	1.03	-0.0009	-0.60	84 %	6 %	10 %	0.97	1.20	0.95	1.24
	Seemannshöft	Hamburg	Neu Darchau	2.85	1.04	-0.0010	-0.60	84 %	6 %	10 %	0.97	1.14	0.95	1.21
	Bunthaus	Hamburg	Neu Darchau	2.74	1.04	-0.0008	-0.51	86 %	5 %	9 %	0.96	1.37	0.95	1.27
	Schnackenburg	Seehausen	Wittenberge	2.65	1.02	-0.0004*	-0.60	87 %	2 %	10 %	0.97	1.18	0.93	2.02
	Wanzer	Seehausen	Wanzer	2.27	0.89	0.0003*	-0.62	86 %	2 %	12 %	0.93	1.67	0.91	2.01
	Dessau	Wittenberg	Bad Dübren	4.80	0.85	-0.0146	-0.57	81 %	10 %	9 %	0.93	1.77	0.92	1.72
	Wittenberg	Wittenberg	Wittenberg	4.48	0.87	-0.0025	-0.48	82 %	8 %	9 %	0.91	1.97	0.91	1.77
	Ingolstadt	Kösching	Ingolstadt	4.99	0.76	-0.0030	-0.53	87 %	7 %	7 %	0.97	0.95	0.94	1.22
	Dandlbach	Passau	Achleiten	5.55	0.74	-0.0012	-0.29	84 %	8 %	7 %	0.97	0.86	0.93	1.16
	Linz	Hoersching	Kienstock	5.46	0.73	-0.0011	-0.32	83 %	11 %	7 %	0.98	0.85	0.94	1.03
Danube	Kienstock	Krems	Kienstock	5.82	0.74	-0.0015	-0.30	80 %	14 %	6 %	0.97	0.98	0.92	1.15
	Hainburg	Wien	Wien	5.30	0.76	-0.0013	-0.28	81 %	13 %	6 %	0.97	1.01	0.93	1.12
	Bezdan	Sombor	Bezdan	5.14	0.87	-0.0012	-0.28 ^a	82 %	15 %	3 %	0.97	1.17	0.94	1.46

* Not significant for $\alpha=0.05$

Table 5 Relative contributions of AT, Q and NAO to variability in mean monthly water temperatures at Hainburg, Danube

Time period	AT (%)	Q (%)	NAO (%)
1939–1952	90 %	9 %	2 %*
1953–1965	84 %	16 %	0 %*
1966–1980	81 %	19 %	1 %*
1981–1994	81 %	13 %	6 %
1995–2008	84 %	13 %	3 %*

*Not significant for $\alpha=0.05$

The mean monthly data from the Danube gauge Hainburg enabled an analysis of the temporal development of the AT, Q and NAO contributions across 14 years long non-overlapping time windows. Unlike the air and the water temperatures, the discharge manifested a decreasing trend after a short increasing phase over the first decade of the 20th century (see Fig. S4, ESM). As shown in Table 5, the AT contribution was largest (90 %) for the earliest analysis window (1939–1952), Q contribution was up to 19 % (1953–1965), while the NAO contribution was statistically significant only for the period 1981–1994.

Due to data availability constraints, water-temperature modelling at the daily scale could only be performed for Elbe data from Blankenese and Seemannshöft. As the model statistics are equal for both data sets, Table 6 summarizes the results for only one station (Seemannshöft). The model based on AT, Q and NAO has poor performance, while the validation R^2_{val} (0.95) and the $RMSE_{val}$ (1.62) of the model that additionally considers AT_{MW} provide confidence in the estimated predictor contributions. The NAO and Q contributions of the AT_{MW} based model are each approximately 7 % larger than the contributions estimated from the monthly records, while the total AT contribution (AT and AT_{MW}) is lower than that estimated at the monthly scale.

5 Discussion

5.1 Water temperature variability, alterations and contributing factors

Differences in the variability ranges across the latitudinal gradient are mainly attributed to differences in climatic conditions and river regimes of the upstream tributaries. Consequently, due to contributions of the alpine streams, the Austrian Danube River gauges have lower water temperatures than the studied Elbe River gauges (despite their lower latitudes). Decrease in the mean amount of variation of river temperatures with scale illustrates scale dependence of the external processes affecting water temperatures. The latter range from inter-annual (e.g. NAO), annual and seasonal cycles (e.g. atmospheric conditions and riparian vegetation) to daily and intra-day processes related to physical heat

Table 6 Properties of the regression models of mean daily water temperatures at Seemannshöft, Elbe for W_1 (calibration period) and model statistics for W_2 (validation period)

Model	β_{AT}	β_Q	β_{NAO}	β_{WT-1}	$\beta_{AT,mw}$	AT (%)	Q (%)	NAO (%)	R^2	RMSE (°C)	R^2_{val}	$RMSE_{val}$ (°C)
$f(AT,Q,NAO)$	0.84	-0.0017	-0.94	-	-	77.0	12.7	10.3	0.81	3.03	0.81	3.13
$f(AT,Q,NAO,AT_{mw})$	0.08	0.0012	-0.35	-	1.07	70.7	12.7	16.6	0.99	1.57	0.95	1.62

exchange processes (at the air–water surface and at the streambed–water interface), alongside processes related to anthropogenic activities (e.g. cooling water).

The SSA based decomposition of the water and air temperature time series indicated that up to 99 % of the variability can be described by the seasonal cycle and the slowly varying central tendency. The quasi-periodic character of the series' central tendency suggests that the inter-annual and inter-decadal cycles of the NAO are superimposed over a general warming trend. A continuous warming (ΔT_{\max} up to $0.098 \text{ }^{\circ}\text{C year}^{-1}$) was observed for all the water-temperature monitoring stations, accompanied by an accelerated rise in magnitude since the early 1980s. The rise in magnitude is generally larger during the period Jan 1995–Dec 2008 than during the period Jan 1981–Dec 1994, though these differences are not statistically significant. Overall, the size of the warming “trend” appears to depend on the method used for trend estimation and whether or not the effects of auto-correlations were considered. In particular, the SSA-based trend estimates are slightly different from those estimated using the linear regression, though the difference only becomes relevant when considering partial time series. Whilst the SSA central tendency accounts for variations in the trend pattern, the linear regression only considers the overall trend. Accordingly, the linear regression is inappropriate when dealing with series affected by changes in the trend magnitude or direction, unless applied also to the partial series. In addition, the results after “pre-whitening” the water temperature data have indicated absence of statistically significant “trends”.

Pronounced North–South temperature increase, i.e., latitudinal gradient, is found for the mean water temperatures during the spring season (Apr–Jun). The absence of the latitudinal gradient across the study area for other seasons is possibly triggered by the cold runoff from the Alpine region that partially mitigates the anthropogenic influences and effect of higher air temperatures on water temperatures (Webb and Nobilis 2007).

Air temperature variations explain more than 80 % and about 70 % of the variability in monthly and daily water temperatures respectively, suggesting that the detected water temperature warming is mainly attributed to changes in air temperature. The NAO contribution is up to 12 % and decreases with lower latitudes. Consequently, Danube water temperature at Bezdan, Serbia is not statistically related to the NAO variability, while the Danube temperature at Hainburg, Austria was only influenced by the NAO during the positive NAO phase (1981–1994). Besides increased air temperatures and the NAO effects, decreased discharges provide a further explanation for water temperature increase. The explanatory power of discharge generally increases with the increase in discharge amount, but does not exceed 15 %. The increase of the discharge contribution with decreases in latitude is most probably related to the effects of cold groundwater inputs as well as snowmelt and glacial runoff from the Alpine region.

5.2 Consequences of detected climate changes to riverine fish

In principle, riverine fish are well adapted to dynamic environments triggered by stochastic environmental disturbances like fluctuations in discharge and temperature. Temperature rise early in the year was found to be beneficial for spring spawning fish species (Ahas 1999; Wolter 2007). This clearly opposes the commonly stated match/mismatch theory considering a predator with a fixed spawning period is unable to react to dynamic prey (e.g. Fortier et al. 1995). In addition, by analysing early life-stage strategies of 65 temperate freshwater fish species Teletchea and Fontaine (2010) have identified different trade-offs at the early life-stages, ensuring that, independent of the spawning season, most larvae are first feeding when food size and abundance are most appropriate. However, Hari et al. (2006) showed that an earlier spring warming in Alpine rivers and streams suggests that brown trout fry will

emerge earlier from their gravel nest. Because the water temperature at altitudes below 700 m reaches their upper tolerance limits earlier, the estimated time available for growth of yearlings is shortened by more than 2 weeks. Thus, spring warming of almost 2 weeks is only beneficial to some fish in terms of elongated periods for growth. Also, in the long run, permanently beneficial environmental conditions of spawners might lead to a shift in species assemblage composition.

The increase in temperature and dispersal limitations may force species' adaptation or ultimately, extinction. The upper thermal tolerances of most North American or European fishes reviewed in Beitinger et al. (2000) and Bruijs et al. (2009) were well above typical ambient temperatures in their natural habitats. Even salmonid fish and other cool-water adapted fish, like burbot, have developed several strategies or adaptations to high temperatures (e.g. Underwood et al. 2012). Fish gain heat tolerance more quickly than cold tolerance and lose it relatively slowly (Beitinger et al. 2000).

The substantial extent of periods of high temperatures is most critical, as this might exhaust individuals' energy storage and capacity for growth, reproduction and survival. This is specifically relevant for large specimens with higher basal metabolisms. Further prolongation of warm water periods above 25 °C will substantially promote a turnover to more heat-tolerant species, generally non-natives (e.g. Forbert et al. 2011). Moreover, the presented results suggest that the increase in the duration of extremes pose an elevated potentially lethal risk for brown trout, one of the most important fish species for commercial and sports fisheries in Western Europe, in both the Elbe and the Danube River (see also Hari et al. 2006).

5.3 Management strategies

The models revealed that air temperature variability describes up to 90 % of the total water-temperature variability, which might raise some pessimism regarding management abilities at the local and regional level. However, there are still many options to consider: (1) rehabilitation of riparian buffer stripes and riparian tree cover to increase shading especially at the smaller tributaries; (2) increase/rehabilitation of natural river dynamics and flow regime which provides habitat diversity and refuges, thus maintaining higher overall stress tolerance; (3) floodplain rehabilitation that contributes to the management of climate change impacts through improving water retention and indirectly provides groundwater-fed cooler thermal niches; (4) facilitation of the longitudinal and lateral ecological connectivity and dam removal, enabling mobile species to compensate for unfavourable conditions through migrations to more suitable habitats/refuges; (5) water abstraction reduction. This might change local species composition, but maintains freshwater biodiversity as a whole.

Finally, limiting warm-water discharge and other factors that artificially increase water temperatures are suitable management strategies even if the heat capacity of the rivers and existing effluents did not appear as significant impacts in the model. From a precautionary perspective, there is no reason to avoid a general change from open flow-through to recirculation systems, especially for cooling water and for other industrial water withdrawals. This would substantially reduce water uses and warm-water discharges, and thus decrease the pressure for aquatic organisms without any impacts on associated socio-economic benefits.

6 Conclusion

The extent of temperature alterations described in the preceding, including accelerated rise, seasonal shifts and intensified magnitude in the duration of summer heat stress, indicate

dynamic changes in water temperatures and associated pressure on freshwater ecosystems. Due to the linkages and leverage between natural and anthropogenic effects, the results demonstrate the immediate need for multidisciplinary research coupled with sustainable management of riverine ecosystems to mitigate ongoing freshwater ecosystem degradation.

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