CLIMATE WARMING AFFECTS WATER TEMPERATURE IN THE RIVER DANUBE AND TRIBUTARIES – PRESENT AND FUTURE PERSPECTIVES

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Global warming increasingly impacts rivers and streams worldwide. Long-term water temperature data from the River Danube and selected tributaries collected by the Austrian Hydrographic Survey were analysed. To show trends unequivocal, monthly mean water temperature data are investigated from stations in the Austrian Danube covering the period 1901–2015. These data are related to air temperature, precipitation and discharge. Significant relations of air to water temperature are established at all stations. Results indicate a highly significant increase of about 1.4°C, equivalent to 0.01°C per year. Temperature trends are extrapolated to 2050 using multiple regression analyses and scenarios of future changes in air temperature and discharge.

Key words: climate change, rivers, long-term trend, surface water temperature, prediction

INTRODUCTION

The climate warming presently observed and their future projections indicate increase in temperatures of inland water, changes in timing and quantity of river-runoff, and rise in precipitation with great variations across Europe (KOVATS et al. 2014). The latest update on water temperature by the European Environment Agency (EEA 2016) indicates water temperature increase by 1-3°C over the last century in major European rivers which will further increase as air temperatures rise. Similar increase has been calculated and projected by VAN VLIET et al. (2011) for global river temperatures using data from rivers world-wide including the River Danube at Bratislava. In Europe, investigations on river temperature have a long tradition (FORSTER 1894). Recent advances have been summarized by WEBB et al. (2008).

Earlier investigations on the Danube and tributaries for the period 1901 to 1995 have shown that temperature rise varied largely between sites and that the thermal regime was altered by heated effluents, damming, forestry practices and water abstraction (WEBB and NOBILIS 1995, 2007).

An understanding of the thermal regime of rivers is essential for sustainable use, impact assessment, management and catchment orientated planning (CAISSIE 2006). This is particularly important when competition for water among countries become a problem. In the Danube River Basin 14 countries are involved.

Here the intention and main aim of the study is to present an update to earlier findings from the Austrian Danube and an outlook on future developments. The Null Hypothesis is no temperature increase due to climate warming.

MATERIAL AND METHODS

Long-term data from the River Danube and some of its tributaries were selected for analysis.

DATA ORIGIN AND TREATMENT

All data are annual or monthly averages of daily measurements extracted from the Yearbooks of the Austrian Hydrological Survey (HYDROGRAPHISCHER DIENST IN ÖSTERREICH 1964a,b, 1973, 1985, 1986-2013, or downloaded from eHYD, http://ehyd.gv.at/). Ten gauging stations are available with water temperature measurements from which the four stations were selected for analysis. These stations are Linz-St. Margareten, Stein-Krems, Wien-Nußdorf and Hainburg. In addition, data from two tributaries, the River Inn at Schärding and the River March at Marchegg were analysed. Variables analysed were surface water

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temperature (SWT, °C), air temperature (AT, ° C), discharge (DI, $m^3 s^{-1}$) and precipitation (PR, mm).

Discharge weighted SWT (T_0) was calculated from

$$T_0 = \frac{\sum_{i=1}^{12} T_0 Q_i}{\sum_{i=1}^{12} Q_i} \qquad 1$$

and annual heat flux (Z_t) from

$$Z_t = T_0 Q_{cs} \qquad 2$$

both from PEKAROVA et al. (2008).

STATISTICAL TREATMENT

Descriptive statistics for all stations and variables are summarised in **Tab. 1**. Prior to analysis, all variables were tested for Normality (Kolmogorov-Smirnov) and equal variance using Levene's test. Time series were pre-whitened by robust regression analysis. Trends fitted using Lowess routines, linear and quadratic regression. Break points visualised by Rescaled Adjusted Partial Sums (RAPS) according to GARBRECHT and FERNANDEZ (1994)

$$\sum_{t=1}^{k} \frac{Y_t - \bar{Y}}{S_Y} \qquad 3$$

Parametric analysis and forecasts used linear and polynomial regression.

RESULTS

The statistical data in **Tab. 1** show great consistence between all four variables of the four stations. Annual averages, minima and maxima increase slightly downstream except for precipitation. The high coherence of the four locations is substantiated in the cross-correlation coefficients of the variables in **Tab 2.**

Detailed results will therefore be presented only for the upstream station Linz and the downstream location at Hainburg. The well-established connection between AT and SWT (e. g. WEBB et al. 2003, TOFOLON 2015)) is shown for the River Danube at Linz in **Fig. 1**. The mean monthly cycle results in a hysteresis with SWTs higher than AT in Fall (**Fig. 1A**) and winter (**Fig. 1B**)

Annual average SWTs are shown for station Linz and station Hainburg for the period 1901 to 2015 in **Fig. 2**. Data indicate a regime shift at about 1980 which is substantiated by RAPS. The resulting data pattern can best be described by quadratic regression allowing extrapolation to the year 2050. The SWTs estimated for 2050 are in close agreement (12.8°C for Linz and 12.9 for Hainburg). Similar results are obtained when a linear trend is calculated for the period after 1980 and extrapolated to 2050 (Linz 13.0°C, Hainburg 13.4°C). Coefficients and statistics for linear and quadratic regressions are summarized together with the corresponding SWTs estimated for 2050 in **Tab. 3**.

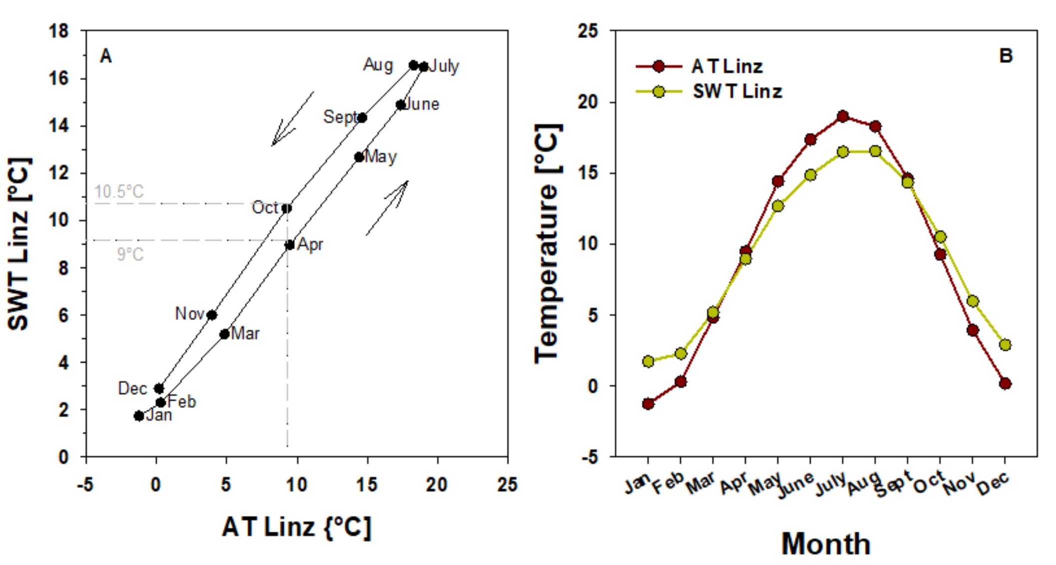

Fig. 1 Monthly mean long-term hysteresis of air temperature (AT) versus surface water temperature (SWT) of the River Danube for station Linz (A) and average annual temperature cycle for AT and SWT (B).

	SWT Linz	SWT Krems	SWT Wien	SWT Hainburg	AT Linz	AT Krems	AT Wien	AT Kittsee
Observation	115	115	115	115	115	115	115	115
Missing	0	8	1	0	0	9	3	7
Minimum	8.29	8.32	8.48	8.69	7.08	7.61	7.64	7.78
Maximum	11.36	11.58	11.86	11.95	11.58	11.49	13.17	11.82
1. Quartile	9.00	9.09	9.10	9.42	8.70	9.12	9.43	9.57
Median	9.40	9.47	9.65	9.90	9.33	9.67	10.01	10.09
3. Quartile	9.83	9.89	10.08	10.28	9.84	10.09	10.47	10.46
Mean	9.46	9.52	9.72	9.95	9.29	9.62	10.00	10.03
Variance	0.45	0.41	0.58	0.47	0.72	0.55	0.79	0.56
Std. error	0.67	0.64	0.76	0.68	0.85	0.74	0.89	0.75

	DI Linz	DI Krems	DI Wien	DI Hainburg	PR Linz	PR Krems	PR Wein	PR Kittsee
Observation	115	115	115	115	115	115	115	115
Missing	0	8	0	76	2	9	0	2
Minimum	956	1,326	1,395	1,543	533	297	323	383
Maximum	1,997	2,525	2,580	2,506	2,092	761	952	959
1st Quartile	1,241	1,652	1,672	1,760	759	453	508	536
Median	1,416	1,843	1,890	1,855	837	532	602	623
3rd Quartile	1,624	2,067	2,141	2,049	921	616	701	688
Mean	1,438	1,852	1,908	1,914	853	535	613	616
Variance	52,870	74,936	84,694	54,043	31,159	10,061	17,678	13,271
Std. error	230	274	291	232	177	100	133	115

Tab. 1 Descriptive statistics for the four stations. SWT = Surface water temperature, AT = Air temperature (both as °C), DI Discharge ($m^3 s^{-1}$), PR = Precipitation (mm y^{-1}). Annual data

MM AT	**Krems**	**Wien**	**Hainburg**
Linz	0.992	0.993	0.993
Krems		0.994	0.995
Wien			0.997
MM SWT	Krems	Wien	Hainburg
Linz	0.993	0.991	0.993
Krems		0.996	0.997
Wien			0.997
MM DI	Krems	Wien	Hainburg
Linz	0.996	0.996	0.996
Krems		0.993	0.992
Wien			0.993

Tab. 2 Cross-correlation between stations. Monthly means (MM) of air temperature (AT), surface water temperature (SWT) and discharge (DI), N >1000, P <0.0000 for all.

Average surface water temperature in the River Danube has increased at all four sites by about 1°C from the pre-1980 period (1901-1980) to the post1980 period (1981-2015). The prediction for 2050 is a further rise by mor than 2°C. This means that long term averages of SWTs for 1901-1980 which ranged from 9.15°C to 9.65°C at the four sites, rose to mean values between 10.18°C and 10.64°C in 1981-2015 and are likely to further increase to 12.8-12.9°C until 2050 (**Tab. 3**, last column). These predictions of an increase by about 0.5°C per decade are conservative estimates assuming that the rise in AT will be no more than 2°C. Fall and winter have already changed in 1960 1nd 1972 respectively while shifts occurred in spring and sum-

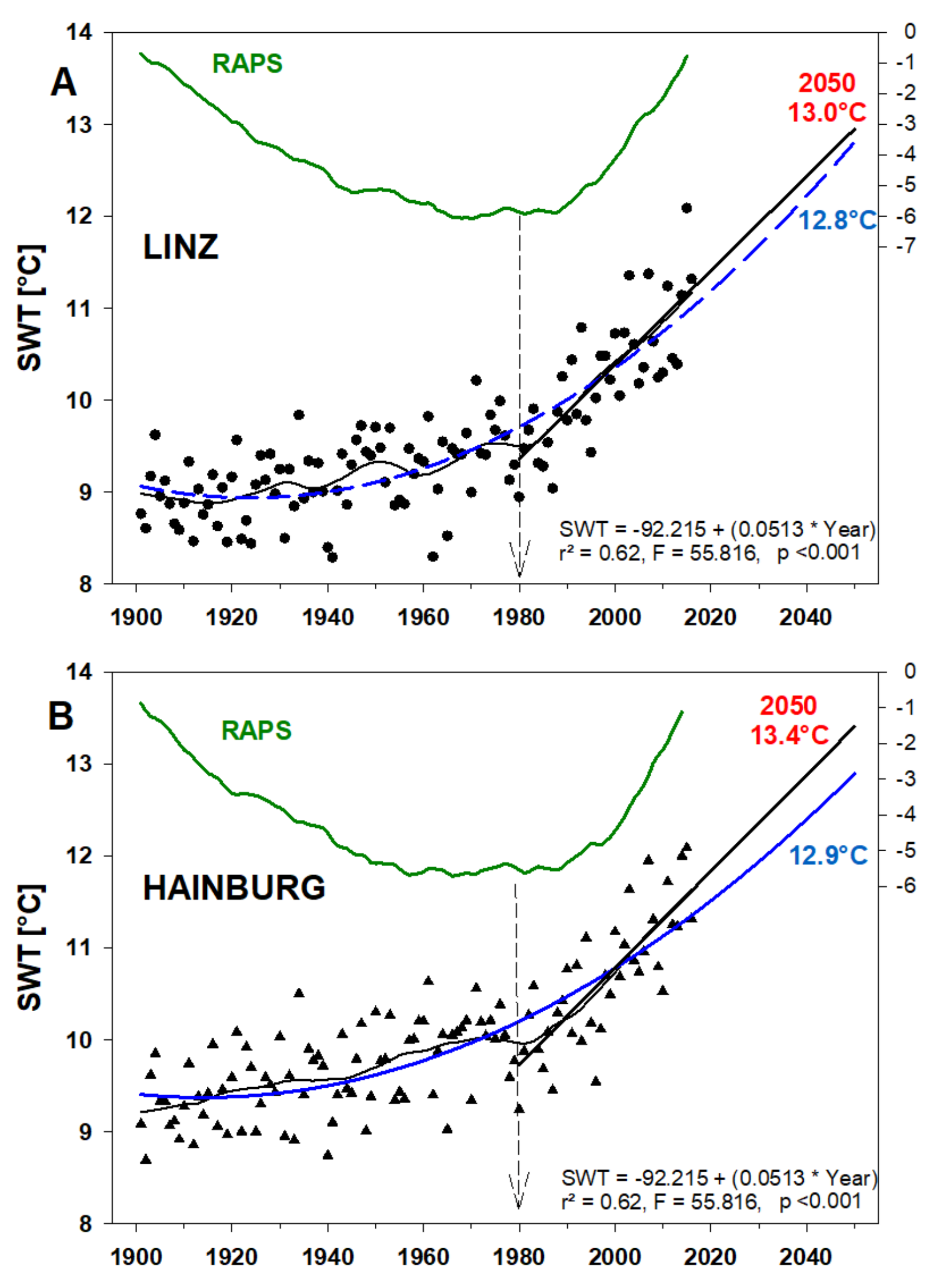

Fig. 2 Annual average surface water temperature (SWT) for the River Danube at station Linz (A) and Hainburg (B) for the period 1901 to 2015. Data are smoothed by lowess function. The overall trend is described by a nonlinear (quadratic) regression also used for extrapolation to 2050. Readjusted partial sums (RAPS) of the data indicate a break point in 1980. The trend thereafter can be defined by a linear regression extrapolated to 2050.

mer in 1988. This illustrates different sensitivity to warming.

An analysis of the long-term changes in seasonal SWTs for the location Linz reveals that all four seasons are equally impacted. SWTs will increase by about 0,2°C per decade in autumn and winter while 0.3°C per decade are likely in spring and summer. Break points according to RAPS however, were rather different. Long term annual SWTs of most of the larger tribute-

Linear		**Coefficient**	**Std. Error**	**t**	**P**	**R²**	**N**	**°C 2050**
Linz	Const.	-92.215	13.717	-6.723	<0.001	0.615	37	13.0
	Slope	0.0513	0.00687	7.471	<0.001			
Hainburg	Const.	-94.219	13.957	-6.751	<0.001	0.617	37	13.4
	Slope	0.0525	0.00699	7.515	<0.001			
Quadratic								
Linz	y_0	903.762	147.474	6.128	<0.0001	0.687	115	12,8
	a	-0.930	0.151	-6.177	<0.0001			
	b	0.0002418	0.00003845	6.289	<0.0001			
Krems	y_0	1032.063	189.942	5.434	<0.0001	0.533	106	12.6
	a	-1.060	0.194	-5.450	<0.0001			
	b	0.0002745	0.00004975	5.517	<0.0001			
Wien	y_0	696.105	178.599	3.898	0.0002	0.614	115	12.8
	a	-0.719	0.183	-3.939	0.0001			
	b	0.0001881	0.00004662	4.034	0.0001			
Hainburg	y_0	706.608	156.132	4.526	<0.0001	0.649	115	12.9
	a	-0.729	0.159	-4.568	<0.0001			
	b	0.0001903	0.00004071	4.675	<0.0001			

Tab. 3 Coefficients and statistics for linear and quadratic regressions shown in Fig 2. SWTs estimated by extrapolation are summarized in the last column.

ries seem to increase at a rate of 0.3°C per decade as results from the River Inn, Traun and March (Morava) indicate (results not shown here).

Using discharge (DI) weighted mean SWTs according to equation (1), trends, break points, results and predictions are almost similar (not shown here). Long term average discharge however, has somewhat declined at all sites and will perhaps further decline as air temperatures increase and precipitation patterns change.

The heat flux can be used a s further indication of warming because water has a high specific heat capacity. The calculated annual heat flow at Vienna ranged from 67 to 122 GJ s^{-1}. Interannual variability was high throughout the 1901-2015 period with an insignificant trend of 0.6 GJ per decade.

An attempt was made to model the dependent variable SWT from a linear combination of independent variables. The best performace was achieved using a combination of air temperature (AT), discharge (DI) and a periodic function. For the SWT at Vienna the resulting equation turned out as:

$SWT_{Vie} = 1.500 + (0.744*ATVie) – 0.000391*DI_{Vie}) + (1.058*Per)$, N = 1248, $R^2 = 0.967$, $P < 0.001$ Result are not shown here and will be published separately.

To test whether the observed SWT warming is related to climate via teleconnection to the influence of the North Atlantic Oscillation (NAO), relations of AT and SWT to the NAO index were calculated for the four stations analysed. NAO indices were obtained from HURRELL et al. (2017). Both AT and SWT were positively correlated (statistical significance $p < 0.001$ or better) to the NAO signal in winter and spring as well as annually. Warming rates during summer and fall however, were negatively related. Air temperature was generally stronger correlated than was SWT.

DISCUSSION

The long-term data from the River Danube show a significant rise in surface water temperature in the 20th century. As the RASPs from the time series indicate, temperature rise became more pronounced after 1980 and continued into the 21st century until now. WEBB and NOBILIS (2007) suggested a somewhat earlier break point in the years after 1970). The increase of the SWT is largely related to the rising air temperature as has been shown. Changes of mean river temperatures of up to and more than 2°C, as anticipated for 2050 could have a profound impact on the freshwater fauna (DOKULIL et al. 1993, 2015, PÖCKL et al. 2003). Correlations of AT and SWT from the Danube stations to the NAO signal were very similar to the results obtained by WEBB and NOBILIS (2007) for several river locations in Austria described by a nonlinear (quadratic) regression also used for extrapolation to 2050. Readjusted partial sums (RAPS) of the data indicate a break point in 1980. The trend thereafter can be defined by a linear regression extrapolated to 2050.

Trends of warming and relations to the NAO reported from the Serbian stretch of the Danube by BASARIN et al. (2016) are rather like to the results obtained here. Observations from the River Rhine in Germany point into the same direction as for the Danube.

Finally, all key message of the EEA (2016) point in the same direction as mentionad already; increase of SWT in rivers by 1-3°C, projected further increase with mar-ked changes in species composition and functioning of the ecosystems.

SUMMARY

All investigated stations on the River Danube are significantly cross-correlated. Surface water temperature (SWT) largely depends on Air Temperature (AT). Average AT and WT have increase by 0.7 and 1.2°C respectively and will likely further increase until 2050 by 0.7°C for AT and 1.3°C for WT. Discharge weighted SWT has significantly increase since 1979 while annual heat flux marginally increased. Correlations of both AT and SWT to the NAO were significant in winter and spring as well as annually. SWT can be predicted to a very high degree from AT, DI and a Periodic function.

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