Is the Water Temperature of the Danube River at Bratislava, Slovakia, Rising?

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(Manuscript received 3 July 2007, in final form 28 February 2008)

ABSTRACT

This paper aims to reveal the annual regime, time series, and long-term water temperature trends of the Danube River at Bratislava, Slovakia, between the years 1926 and 2005. First, the main factors affecting the river's water temperature were identified. Using multiple regression techniques, an empirical relationship is derived between monthly water temperatures and monthly atmospheric temperatures at Vienna (Hohe Warte), Austria, monthly discharge of the Danube, and some other factors as well. In the second part of the study, the long-term trends in the annual time series of water temperature were identified. The following series were evaluated: 1) The average annual water temperature (To) (determined as an arithmetic average of daily temperatures in the Danube at Bratislava), 2) the weighted annual average temperature values (To_v) (determined from the daily temperatures weighted by the daily discharge rates at Bratislava), and 3) the average heat load (Zt) at the Bratislava station. In the long run, the To series is rising; however, the trend of the weighted long-term average temperature values, To_v, is near zero. This result indicates that the average heat load of the Danube water did not change during the selected period of 80 yr. What did change is the interannual distribution of the average monthly discharge. Over the past 25 yr, an elevated runoff of "cold" water (increase of the December–April runoff) and a lower runoff of "warm" water (decrease of the river runoff during the summer months of June–August) were observed.

1. Introduction

Water temperature is a fundamental physical characteristic describing properties of surface waters, having a direct impact on the flora and fauna of aquatic systems. The temperature of a stream is determined by its atmospheric (ambient) temperature. Other factors affecting the temperature of a stream of water are the hydrological regime of the stream and the orographical conditions of its basin (e.g., elevation, catchment area, number of natural reservoirs formed throughout the basin). The temperature of the water in streams is more and more being influenced by human activities within basins—mainly due to the construction of water reservoirs, the erection of thermal and nuclear power plants, and the diversion of sewage into surface waters (Stancikova and Capekova 1993).

The first daily measurements of water temperatures of Slovakian streams and rivers were made in 1925. Measurements of water temperature in the Danube River at the Bratislava gauging station for a period of 25 yr (1925–1950) were investigated by Dmitrijeva and Pacl (1952). The long-term characteristics of water temperatures in Slovakia's streams prior to 1960 were published in *Hydrological Conditions in Czechoslovakia* (Cermak et al. 1967). Stream water characteristics, such as the temperature records prior to 1980, were processed by Dulovic (1989). The most recent trends in water temperatures in Slovak rivers were studied by Leskova and Skoda (2003); daily data on water temperatures in the Danube River at Bratislava for the period 1956–2000 were analyzed by Lisicky and Mucha (2003). The impacts of human activities on water tem-

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DOI: 10.1175/2008JHM948.1

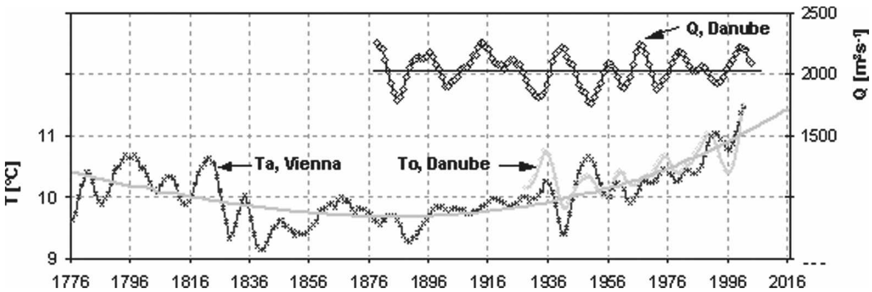

FIG. 1. Variation of the atmospheric temperature at the Vienna station: double 5-yr moving averages of the average annual air temperature Ta (1775–2004) and a long-term quadratic trend (light gray curve). Double 5-yr moving averages of the average annual water temperature To of the Danube at Bratislava (1926–2005) (heavier gray curve), and double 5-yr moving averages of the average annual discharge *Q* of the Danube at Bratislava (1876–2005) and long-term linear trend (solid thin horizontal black line).

peratures in the Danube along its entire length were investigated by Stancikova and Capekova (1993).

Over the past decade, emphasis has been placed on the increasing atmospheric temperatures as a result of the greenhouse effect and the impact of phenomena such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) on the fluctuations of instream water temperatures (Caissie 2006). The long-term water temperature trends of the rivers were studied by Webb and Walling (1992) and Webb (1996). The impacts of the NAO on multiple-year water temperature oscillations in the Danube were investigated by Webb and Nobilis (2007). Bonacci et al. (2008) analyzed the water temperature regime of the Danube River and its tributaries in Croatia. Changes in water temperature regime along the Sava, Mura, Drava, and Danube Rivers in Croatia over the past 20–60 yr were investigated in their study. Special emphasis was placed on investigating the alternations that occurred during the past 30 yr that were probably caused by climate change, climate variability, or both.

Understanding the relationship between air temperature and water temperature is important for scientists in order to estimate how the temperature of a stream is likely to respond to future projections of increases in surface air temperature (Morrill et al. 2001, 2005). Unlike air, water has a particularly high specific heat capacity; its temperature can be considered a stable indicator of long-term trends. Increased stream water temperature, as well as an increased heat flow in a river, should be viewed as an expressive signal that the aquatic environment is warming.

This study aims to analyze the annual regime and long-term trends of the average monthly and annual water temperature time series of the Danube River at the Bratislava station, particularly covering the period 1926–2005.

2. Data

Flowing 2857 km from Germany's Black Forest to the Danube Delta—bordered by Romania, Ukraine, and the Black Sea—the Danube River is the only major river in Europe that flows from west to east (from central to eastern Europe). To evaluate the hydrological regime of the Danube River, we used the average values of daily discharge readings taken at the Bratislava gauging station for the historical period 1876–2005 (Svoboda et al. 2000). The long-term annual discharge (1876–2005) of the Danube at Bratislava is 2058 $m^3 s^{-1}$ and the annual specific yield is 15.68 L s^{-1} km^{-2}. The long-term average annual discharge of the Danube at this station does not significantly change over time (see Fig. 1). For better visual assessment of the long-term fluctuations, we calculated the double 5-yr moving averages.

A series of daily river temperatures observed at the Bratislava gauging station [at 0700 central European time (CET)] was used to analyze the temperature regime of the Danube River. The first measurements of water temperatures in the Danube were made as early as 1925. Figure 2 illustrates the annual time course of the average daily water temperatures To for three periods spanning 25 yr (1931–55, 1956–80, and 1981–2005) and the time course of the lowest and highest water temperatures To for the period 1931–2005. The maximum temperature of the water in the Danube River (23.6°C) was recorded on 18–19 August 2003.

In selecting a climatic station for air temperature observations, we tested the relationship between water and air temperatures for several stations (e.g., Bratislava, Hurbanovo, Slovakia; the Klementinum in Prague, Czech Republic; Budapest, Hungary; Vienna, Austria; Hohenpeissenberg, Germany). The Vienna station turned out to be the most suitable one for the

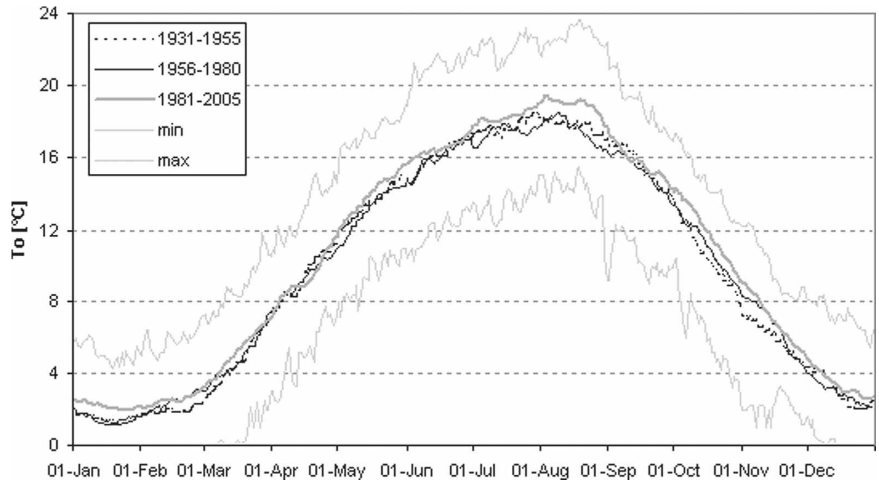

FIG. 2. Time variation of the average daily water temperature To (at Bratislava) over three 25-yr periods: 1931–55, 1956–80, and 1981–2005. Also shown are the lowest (min) and highest (max) water temperatures To from the entire period, 1931–2005.

proposed analysis, since it was capable of providing a homogeneous series of observational data. Records of air temperatures at this station have been available since 1875. The Danube River itself passes through the city of Vienna, and the long-term average annual air temperature Ta at Vienna for 1926–2005 is almost identical with that of the long-term water temperature To at Bratislava (Fig. 1). A more detailed analysis is provided in section 4b. Apparently, the river's water temperature is adjusting itself to the environment through which it flows.

3. Methods

In analyzing the long-term trends in water temperature, we used a time series of average annual values that had been calculated by two methods:

1) an arithmetic average (To) calculated from the measured daily values and
2) a weighted average of annual values (To_υ) expressed in degrees Celsius normalized to daily flow rates (in a common year) by

$$\mathrm{To}_\upsilon = \frac{\sum_{i=1}^{365} \mathrm{To}_i Q_i}{\sum_{i=1}^{365} Q_i}, \qquad (1)$$

where

To_i is the average daily water temperature for the ith day (°C),
Q_i is the average daily discharge rate for the ith day ($m^3\,s^{-1}$), and
To_υ is the weighted average annual water temperature (°C).

The decision to calculate the weighted average water temperatures (To_υ) was based on the fact that the amount of warm and cold water flowing through the profile varies throughout the year.

The annual heat flow, Z_t, in the Danube at Bratislava (referenced to 0°C) was calculated from average annual discharge rates and average annual weighted water temperatures as follows:

$$Z_t = \mathrm{To}_\upsilon \overline{Q} c \varsigma, \qquad (2)$$

where

$\overline{Q}$ is the average annual discharge rate ($m^3\,s^{-1}$),
ς is the density of water (1000 kg m^{-3}),
c is the specific heat capacity of water (4186.6 J kg^{-1} K^{-1}), and
Z_t is the annual heat flow (J s^{-1}).

To perform a test of significance on long-term trends and to identify breakpoints in the trend of the investigated time series, we deployed the Change and Trend Problem Analysis (CTPA) software developed by Prochazka et al. (2001).

4. Results

a. *Dependence of water temperature on atmospheric temperature, season of the year, and discharge*

The dependence of the average annual water temperature To at the Danube's Bratislava station on the

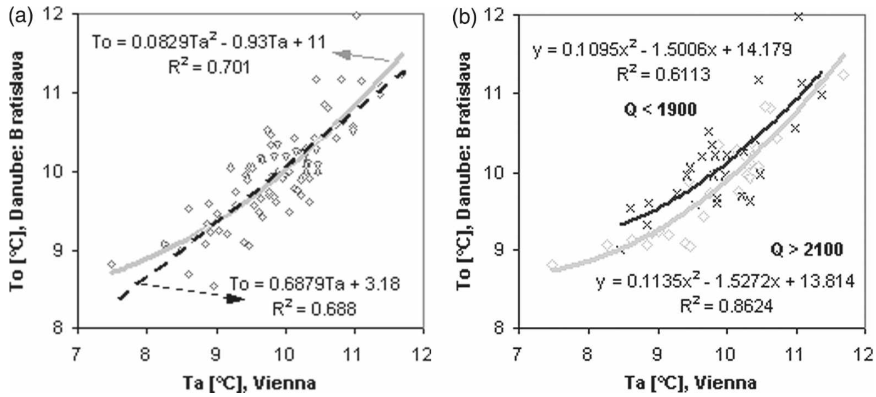

FIG. 3. Quadratic and linear relationships between average water temperature To in the Danube at Bratislava and the average air temperature Ta at Vienna for (a) annual values and (b) the distribution according to the magnitude of the annual discharge rate $Q < 1900$ m^3 s^{-1} and $Q > 2100$ m^3 s^{-1}.

average annual atmospheric temperature Ta at Vienna is depicted in Fig. 3a. The r^2 coefficient for the linear relation was 0.688, and the r^2 coefficient for annual values, when a quadratic relationship was chosen, yielded 0.701. The relation between the temperature of water and the air temperature is nonlinear. The dependence of the water temperature on the atmospheric temperature varies for different discharge rates: Higher average annual discharge is accompanied by lower water temperature, and visa versa. There is an apparent dependency (Fig. 3b) of annual water temperature on atmospheric temperature at an annual discharge above 2100 m^3 s^{-1} (which is the 60th percentile of the annual discharge), and a discharge below 1900 m^3 s^{-1} (which is the 40th percentile of the annual discharge).

The dependence of the water temperature on the atmospheric temperature was thoroughly examined using the monthly time series data. As depicted in Fig. 4a, monthly temperature values lag behind monthly atmospheric temperatures (Webb 1996; Mohseni and Stephan 1998). This delay results from the high specific heat capacity of water. Figure 4b shows a hysteresis loop of the monthly water and air temperatures. While the air temperature rises in the first half-year, the water temperatures are approximately 1.6°C lower than the temperatures observed in the second half-year accompanied with decreasing air temperature. A maximum long-term average atmospheric temperature was recorded in July (19.9°C), and the maximum long-term average water temperature was recorded in August (18°C).

Figure 5 depicts the dependence of the actual monthly water temperature To on the atmospheric temperature Ta. The water temperature dependence

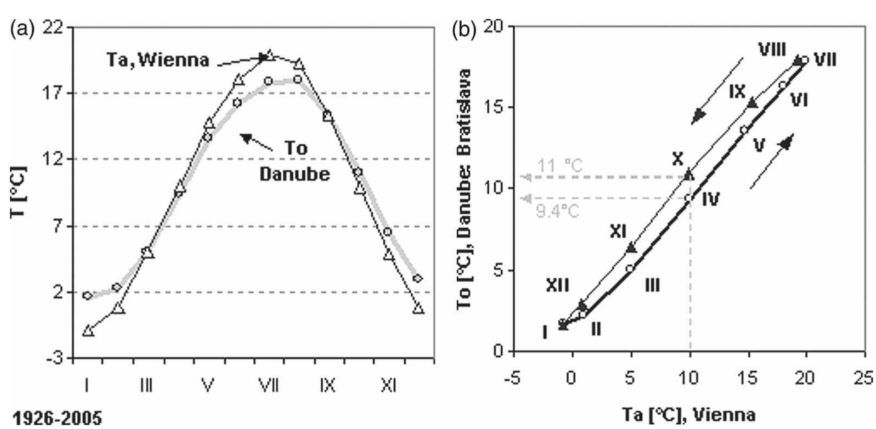

FIG. 4. (a) Annual time series of the long-term monthly average water temperatures To (1926–2005) at the Bratislava station and the atmospheric temperature Ta at Vienna. (b) Relationship between To and Ta averages for individual months; hysteresis loop shown.

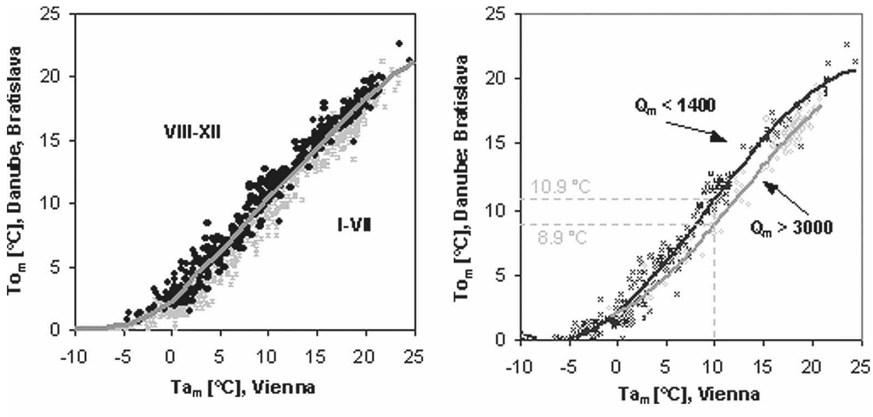

FIG. 5. Dependence of the average monthly water temperatures of the Danube River To_m on the monthly atmospheric temperatures Ta_m at Vienna. (a) Time distribution over the periods of atmospheric temperature increase (I–VII, gray) and temperature decline (VIII–XII, black). (b) Influence of the discharge rates at Bratislava Q_m on the in-stream water temperature To_m: $Q_m < 1400$ (black) and $Q_m > 3000$ (gray).

on the atmospheric temperature was approximated by a third-order polynomial. The r^2 coefficient yielded 0.97. Figure 5a shows a distribution of points divided into two sets, with the first set of points representing values of increasing temperature (I–VII), and the second set of values showing decreasing temperature (VIII–XII); this is also caused by seasonality

At high monthly discharge rates (and positive atmospheric temperatures), the monthly temperature of the water is lower than in the case of low discharges (Fig. 5b). At 10°C atmospheric temperature (in Vienna), the difference is approximately 2°C.

To assess the average monthly water temperature for the Danube River at the Bratislava gauging station, the monthly atmospheric temperature taken at the Vienna station and the monthly discharge rates at the Bratislava station were used in a multiple-regression analysis. The following empirical relationships were derived:

$$\mathrm{To} = 0.55\mathrm{Ta} + 0.034\mathrm{Ta}^2 - 0.00105\mathrm{Ta}^3 - 0.000307Q + 0.998\mathrm{sez} + 1.23, \quad \text{for} \quad \mathrm{Ta} > -5°\mathrm{C}; \quad \text{and} \qquad (3)$$

$$\mathrm{To} = 0.0155\mathrm{Ta} + 0.017 \quad \text{for} \quad -10°\mathrm{C} < \mathrm{Ta} \leq -5°\mathrm{C}; \qquad (4)$$

where To is the average monthly water temperature at Bratislava, Ta is the average monthly air temperature in Vienna, Q is the average monthly discharge rate, and sez is the season-related parameter; for I–VII, sez = 1 and for VIII–XII, sez = 2.

Modeled and measured monthly air temperatures for the period 1995–2004 are depicted in Fig. 6. Statistical results (r^2 = .981299, standard error of estimate = 0.8319, mean absolute error = 0.641994, Durbin–Watson statistic = 1.6495) confirm the good agreement between the measured and modeled values of the water temperature. Relationships (3) and (4) may be used, for example, for filling in gaps in water temperature records, or to simulate the effects of rising air temperature on water temperature in the Danube, provided that the monthly discharge at the Bratislava station is taken into account. Equation (2) indicates that the decline in annual discharge at Bratislava by approximately 330 $m^3 s^{-1}$ would cause water temperature to rise by 1°C.

b. Long-term trends

Figure 7a presents graphs showing the double 5-yr moving averages of the monthly air temperature Ta (at Vienna) and of the monthly water temperature To (at Bratislava) for the period 1931–2001. The long-term average annual water temperature (arithmetic average of daily values; Fig. 7b) in the Danube River at the Bratislava station (1926–2005) is 10.0°C. The highest average temperature of the water for the entire period of recording was 12°C (2003), while the lowest temperature of 8.55°C was observed in 1996. The Fig. 7a suggests that the water temperature (and also the atmospheric temperature) did not show any increasing trend until the 1970s. To analyze the possible existence of a long-term trend in the monthly data series, we used the CTPA software (Prochazka et al. 2001), which was aimed at detecting the breakpoint in the time series (Fig. 7b). We applied two tests: 1) a test of trend existence and 2) a test of trend appearance. However, the

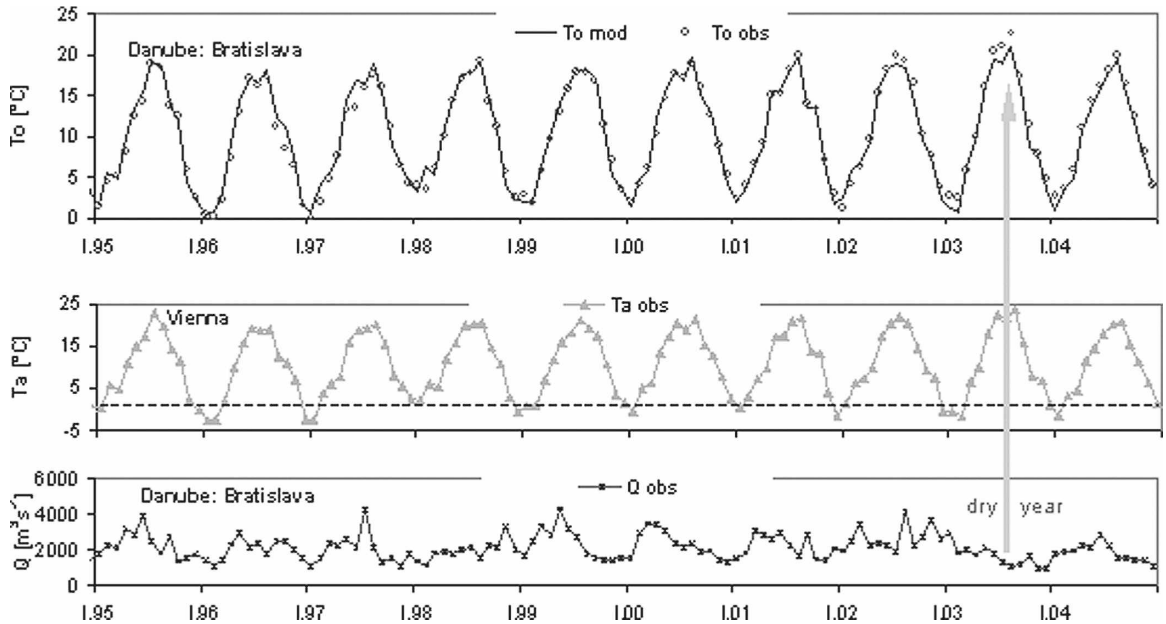

FIG. 6. (top) Time evolution of measured and modeled monthly water temperatures in the Danube River at Bratislava 1995–2004, (middle) time evolution of measured air temperatures at Vienna, and (bottom) Q observed at Bratislava from input data.

coefficient of the linear monthly water temperature increase for the period 1931–2001 is smaller than the trend in atmospheric temperature increase.

c. Heat export

Using the average daily discharge rates and the daily water temperatures, we calculated the average annual water temperature weighted by the discharge [Eq. (1)]. A transformed temperature time series is shown in Fig. 8. The long-term trend of this series is near zero (flat); the weighted long-term temperature did not show any change. This is a remarkable result indicating that the average heat load in the moving water has not changed over the last 80 yr. What has changed is the intrayear monthly runoff distribution of the Danube at Bratislava

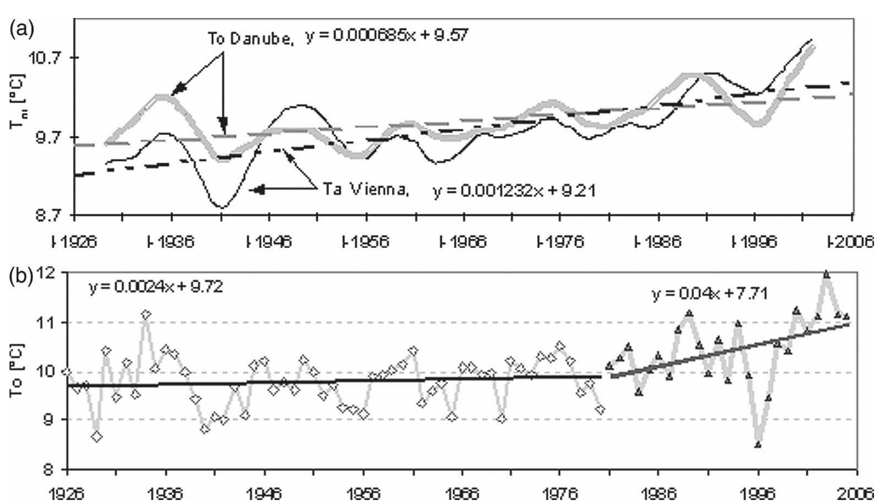

FIG. 7. (a) Double 5-yr (60-month) moving averages and linear long-term trend of the average monthly air temperatures Ta at Vienna and of the average monthly water temperature To at Bratislava for 1926–2005. (b) Identification of trend breakpoint year for water temperature series—Test for a change in the mean based on cumulative deviations of the yearly values. Change in mean occurs at observation $k = 45$, year 1980.

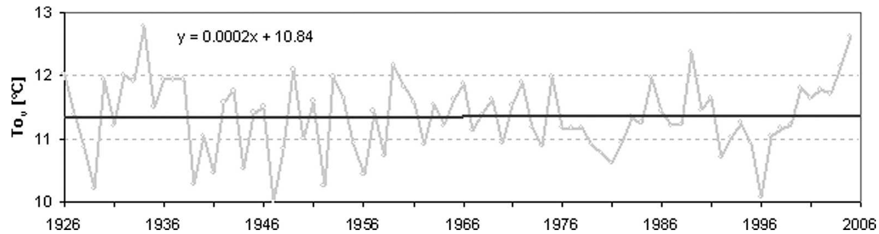

FIG. 8. Weighted average of the annual Danube water temperatures $To_υ$ at Bratislava, during 1926–2005, with the long-term trend shown.

(Figs. 9a and 9b). Over the past 30 yr, the runoff of "cold" water (average monthly discharges during the months of November–April) increased, while the runoff of "warm" water (months of June–August) decreased. Over the past three decades the onset of the snowmelt period comes 1 month earlier, probably because of the increased atmospheric temperature, compared to the 30-yr period, 1901–30 (Fig. 9a). Also, due to the construction of numerous water reservoirs on the Danube confluences in Germany, Austria, and the Czech Republic, the annual variability in the monthly discharge has declined. The reason for this transformation of the discharge may be explained by the altered monthly precipitation totals in the upper basin. Unfortunately, data on monthly areal precipitation totals over the Danube upper basin for the studied period were not available.

The long-term average annual water temperature weighted by the daily discharge rate was 10.8°C. The highest average annual water temperature weighted by the daily discharge rate over the entire period of measurements was 12.3°C (in 1934, which was one of the driest years recorded in Bratislava since 1876), while the lowest value (9.5°C) was found in the dry year 1947, and the second lowest average weighted water temperature was 9.57°C (1996).

Finally, Fig. 10 indicates the time course of the annual heat flow [Eq. (2)]. The annual heat flow through the Bratislava profile ranged from 60 to 135 GJ s^{-1}. Statistical tests did not reject the hypothesis H0 that the series fluctuates along its constant mean. The highest annual heat pollution of the Danube (at Bratislava) was observed in 1965, which was a very wet year. On the other hand, the lowest heat pollution was identified in the dry year of 1947.

5. Conclusions

In the first phase of this study the contribution of the individual factors affecting the Danube's water temperature was analyzed. The atmospheric temperature was identified as the main factor affecting the water temperature. The water temperature in the river equalizes to the ambient air temperature. To indirectly assess the average monthly water temperatures in the Danube (at Bratislava), we derived an empirical relationship, deploying multiple-regression analysis of monthly atmospheric temperatures recorded at the Vienna station and monthly discharge rates measured at the Bratislava gauging station.

The second part of the study focused on the identification of long-term trends in the annual time series of water temperatures in the Danube River. Average annual water temperatures in the Danube River and at-

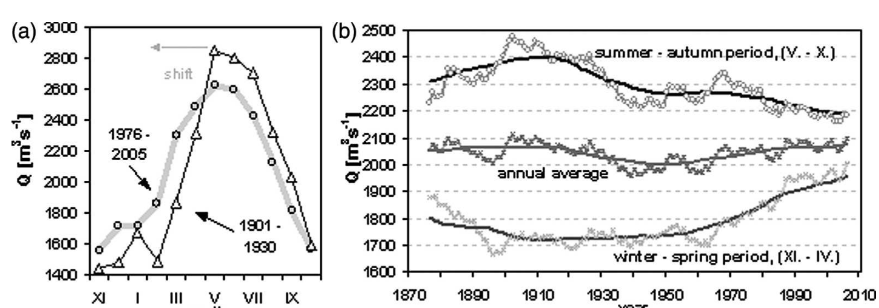

FIG. 9. (a) Interannual distribution changes of the discharge Q in the two 30-yr periods: 1901–30 and 1976–2005. (b) Long-term Danube runoff variability (1876–2005), increase in winter discharge and decline in summer discharge over the period of 1970–2005.

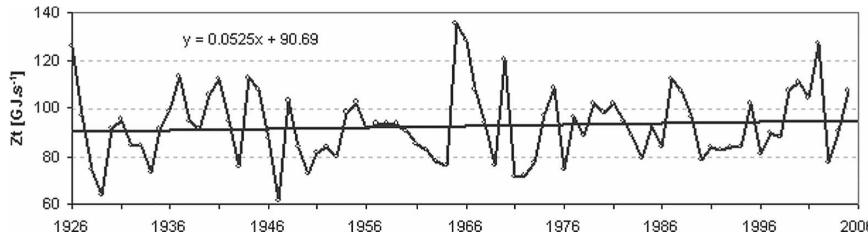

FIG. 10. Long-term development of annual heat flows, Zt, at Bratislava.

mospheric temperatures at Vienna (arithmetic average) showed a rising trend over the last 25 yr. The Danube River water temperature increased by 0.6°C in comparison with the previous 25 yr, while the air temperature in Vienna increased by 0.8°C.

Nevertheless, the time series of weighted average annual temperatures of the Danube's water for the period 1931–2005 show a near-zero trend. This is caused by the fact that over the past 25 yr more "cold" water flowed in the cool season and less "warm" water flowed in the warm season. The intrayear redistribution of flow can be explained by the climate change. A warmer climate causes an early snowmelt in winter (Szolgay et al. 2007) and, thus, more cold flows in winter and less runoff in summer. The lower summer streamflow can result from the lower summer precipitation over the upper Danube basin.

The outcomes of this study indicate that the increase in arithmetic average annual water temperatures is a natural consequence of the lower summer streamflow. However, in order to confirm these conclusions, more comprehensive analyses are necessary, using additional data from observation stations on the Danube as well as on other streams.

In general, the use of water temperature data series weighted by water discharge represents an additional tool for the assessment of "heat transport" from the basin in the form of river runoff. It would be interesting if the heat transport (of this order of magnitude) was comparable with other heat exchange components of the basin. Heat transport in rivers and streams could serve as a useful tool for climate studies and climate change projections.

Acknowledgments. This work was supported by the Science and Technology Assistance Agency under Contract APVT-51-017804, and by VEGA Project 0096/08.

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