IDŐJÁRÁS

QUARTERLY JOURNAL
OF THE HUNGARIAN METEOROLOGICAL SERVICE

Special Issue: Climate variability of the past millennium in Hungary

Guest Editor: **Andrea Kiss**

CONTENTS

****

http://www.met.hu/Journal-Idojaras.php

VOL. 113 * NO. 4 * OCTOBER – DECEMBER 2009

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service

Editor-in-Chief
LÁSZLÓ BOZÓ

Executive Editor
MARGIT ANTAL

EDITORIAL BOARD

Editorial Office: Gilice tér 39, H-1182 Budapest, Hungary
P.O. Box 39, H-1675 Budapest, Hungary
E-mail: bozo.l@met.hu or antal.e@met.hu
Fax: (36-1) 346-4809

Indexed and abstracted in Science Citation Index Expanded™ and
Journal Citation Reports/Science Edition
Covered in the abstract and citation database SCOPUS®

Subscription by

mail: IDŐJÁRÁS, P.O. Box 39, H-1675 Budapest, Hungary
E-mail: kenderesy.k@met.hu or antal.e@met.hu

Editorial

Climate variability of the past millennium in Hungary

Due to recent environmental change issues, climate research of the past millennium has gained special interest in the past few decades. Among other things, this is caused by the fact that the process of making short- and medium-term climate projections requires much better understanding of climate cycles and past climate processes. The growing relevance of historical climate research can be seen as well in European climate studies. Within the framework of the currently ongoing European project (FP-6) entitled *Millennium – Climate and Its Past Dynamics*, significant efforts have been made, funded by the European Union, to provide complex and precise multi-proxy reconstructions of the variability of the European climate over the last thousand years. In a joint investigation by European scientists, studies and records from various fields and different parts of Europe, including Hungary and the Carpathian Basin are gathered.

Both in Hungary and the surrounding areas of the Carpathian Basin, either in the form of medium- or long-term climate reconstructions or impact case studies of weather anomalies and extremes, in the recent decades and especially in the last few years, a rapidly developing interest among scientists and historians can be perceived. In this issue we will present new results of long-term climate investigations in Hungary, provided by 16 scientists from various fields like paleoecology, geology, geochemistry, dendroclimatology, geography, and environmental history.

The paper of *Siklósy et al.* provides a reconstruction of climate variations that have occurred in the past millennium. In their paper temperature, precipitation, as well as vegetation changes in northeastern Hungary (Bükk Mountains), based on high-resolution stable isotope (oxygen, carbon) and trace-element analyses for a 1100-year long stalagmite record with decadal cycles, are discussed. While oxygen isotope content is mainly related to temperature and carbon is related to precipitation, a combined trace-element (Mg, Sr, and P) variation method was applied to detect changes in evapotranspiration. A significant result was that the predominantly wet and warm Medieval Warm Period, after a transition period of several dry spells, was followed by a colder, humid Little Ice Age.

In a study by *Sümegi et al.*, based on geoarchaeological methods (pollen, macrofossil, sediment analyses), a palaeoecological and palaeoclimatological reconstruction for northern Hungary was carried out for a period of two millennia. Also, based on the evidence derived from sediment depositions, after the high water level of Nádas Lake, which lasted until the mid-Holocene period, a 5000-year gap in deposits occurred due to the deepening of the lake basin in the Imperial period. At the same time as the depth of the lake was increasing, around 200 AD the water level decreased, which caused an eutrophication of the water. This process was followed by paludification, which occurred from ca. 1300 onwards. Their investigation suggests that warm conditions prevailed in the Imperial period, and then in the late Migration period. Once again, warm (and dry) conditions returned in the 8–12th centuries and ended around the mid-1200s.

Kern et al. carried out an investigation on August-July precipitation, focusing on the southern sections of the Bakony Mountains in west central Hungary, based on the ring widths of oak trees. Their reconstruction covers a period of 258 years, starting from 1746 AD. The reconstructed precipitation series suggests that very dry conditions occurred in the late 1740s, while the wettest part of the period occurred in the late 1700s. This was followed by a downward trend in precipitation, with short dry spells in the 1840s, 1860s, and 1940s. However, the driest period of the last 258 years in west central Hungary occurred in the period after the 1980s.

Following the three papers on data analysis, the review article of *Andrea Kiss* provides a synthesis of research in historical climatology and a study of hydrometeorological extremes in Hungary, based on documentary evidence, for the past millennium. In addition to compilations and analyses of long-term climate variability, case studies on hydrometeorological extremes (e.g., droughts and floods) and their impact over the past thousand years are also elaborated.

Andrea Kiss
Guest Editor
University of Szeged, Hungary

Acknowledgement—We would like to thank IDŐJÁRÁS for giving us the opportunity to present a cross-sectional view of the multidisciplinary themes of historical climate changes, mainly occurred in the last 1000 years, as well as for the support of the EU project called Millennium (No. 017008).

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 4, October–December 2009, pp. 245–263

Reconstruction of climate variation for the last millennium in the Bükk Mountains, northeast Hungary, from a stalagmite record

Zoltán Siklósy[1*], **Attila Demény**[1], **István Szenthe**[2], **Szabolcs Leél-Őssy**[3], **Sebastian Pilet**[4], **Yin Lin**[5], and **Chuan-Chou Shen**[5]

[1]*Institute for Geochemical Research, Hungarian Academy of Sciences,*
Budaörsi út 45, H-1112 Budapest, Hungary; E-mail: siklosy@geochem.hu

[2]*Múzeum krt. 5, H-1055 Budapest, Hungary*

[3]*Department of Physical and Applied Geology, Eötvös Loránd University,*
Pázmány P. stny. 1/C, H-1112 Budapest, Hungary; E-mail: losz@iris.geobio.elte.hu

[4]*Institute of Mineralogy and Geochemistry, University of Lausanne,*
Bâtiment Anthropole, CH-1015 Lausanne, Switzerland; E-mail: Sebastien.Pilet@unil.ch

[5]*Department of Geosciences, National Taiwan University,*
No. 1, Sec. 4, Roosevelt Rd., Taipei 106, Taiwan ROC; E-mail: river@ntu.edu.tw

(Manuscript received in final form August 31, 2009)

Abstract—This paper presents the high-resolution stable isotope and trace element records from a stalagmite from Hungary (Kiskőhát Shaft, Bükk Mts.). Based on the variation of the isotopic and chemical composition of the carbonate deposit along the growth axis, changes in temperature and precipitation amount are assumed.

Our first results on the younger part (ca. last 1100 years) of the deposit suggest that not only major changes but several short period cycles can be recognized within the stalagmite, which are partly caused by temperature, precipitation amount, and vegetation changes. The oxygen isotope variation of the stalagmite can be explained mainly by the changes of the temperature, while carbon isotope ratios mainly reflect the changes in water recharge or precipitation amount. Combined trace element (Mg, Sr, and P) variations were used to reconstruct evapotranspiration changes.

The stalagmite recorded a generally wet and warm Medieval Warm Period, a colder but humid Little Ice Age, and several variably dry periods between.

Key-words: stalagmite, cave, paleoclimate, stable isotopes, trace elements, last millennium, Hungary

---

[*] Corresponding author

1. Introduction

During the past four decades, the majority of the paleoclimatological studies was concerned either with investigating marine records and/or polar ice cores. Efforts in reconstructing climate change from continental records have renewed interest in the use of speleothems as climatic proxies (e.g., *Gascoyne*, 1992; *Lauritzen*, 1995).

These deposits have specific advantages: stalagmites are widespread in continental area, they develop in relatively protected environments, practically free from re-deposition and alteration, and can be dated by absolute radiometric methods at relatively high precision. TIMS or ICP-MS uranium series dating of only a few 100 milligrams allow dating speleothem calcite with a precision better than 1% (*Shen et al.,* 2002).

Carbonate speleothems are formed when water saturated in CO_2 from the soil zone enters a cave where the CO_2 degasses. If degassing proceeds slowly in a stable-temperature environment, calcite can be precipitated in isotopic equilibrium with the parent drip water (*Hendy,* 1971). In this case, the reconstruction of environmental conditions existing during the formation of the calcite can be possible mostly based on the stable isotope analyses of speleothems.

Recently published preliminary studies in Hungary have reported significant isotopic and chemical variations within stalagmites related to interglacial/glacial climate transitions (Marine Isotope Stage 5e-5d; *Siklósy et al.,* 2008a) or volcanically induced climate changes (*Siklósy et al.*, 2007; *Siklósy et al.*, 2009). Speleothems that record decadal-scale environmental changes in the Carpathian Basin during the last millennium are of particular interest, as this time range is not fully covered by historical and/or instrumental climate records (e.g., *Réthly*, 1962; *Rácz*, 1989; *Kiss*, 2009). Although tree-ring growth series may preserve climatically induced climate proxy signals (*Kern* and *Popa*, 2007; *Kern et al.*, 2009) the lack of corresponding series further back in the past prevents the establishment of detailed studies. Ground-surface temperature (GST) may reflect past climate conditions, but the resolution and precision of the reconstruction for Hungary (*Bodri* and *Dövényi*, 2004) need to be improved for direct comparison with other records. Biostratigraphic evidences for Holocene climate changes (based on vertebrate paleontology) cover several localities in northeast Hungary (*Kordos*, 1977; *Kordos* and *Ringer*, 1991), however, the precise age control and the lack of continuous records prevent the establishment of high-resolution reconstruction for the last thousands of years.

There is a need, therefore, for well-dated climate records from this continental area to increase the input for general climate models. High-resolution geochemical data on speleothems may fill the gap also for this period.

In this study, we conducted complex trace element and stable C and O isotope analyses on a speleothem from Hungary (*Fig. 1*) acquired at high spatial and temporal resolution using various mass spectrometric techniques in order to test and validate independently recognized climate changes (e.g., Little Ice Age [LIA]) and to apply *geochemical results as a climate driven proxies* for future research.

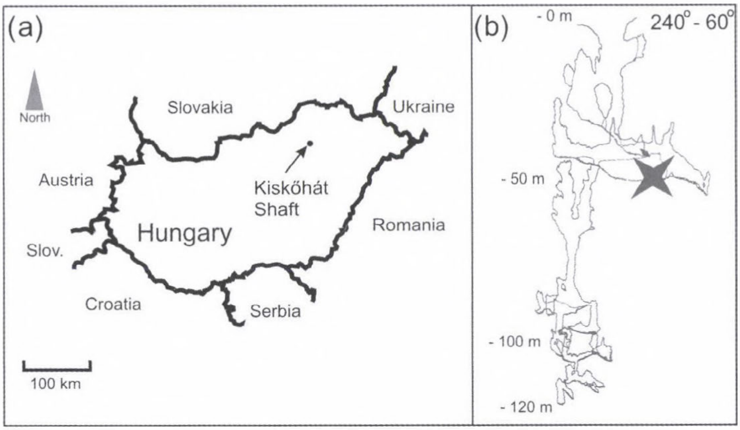


Fig. 1. Location of Kiskőhát Shaft in northeast Hungary (a) and vertical cross-section of the Kiskőhát Shaft with the sample location, indicated by a cross (mapped and created by the BEAC cave explorer group) (b).

2. *Site and sample*

The speleothem analyzed in this study originates from the Kiskőhát Shaft (*Fig. 1*), northeast Hungary (N 48° 4.086' and E 20° 29.422'). The cave is located at the southern rim of the Bükk Highland, at 915 m a.s.l. The 117 m deep inactive sinkhole opens up the cave with a total length of 479 m, situated in the Bükk National Park, under the Kiskőhát peak (938 m) at 915 m elevation, in Triassic limestone. The interior of the cave where the sample was located has a constant temperature of 5.5 °C, with only a minor variability over a year, except the shaft, close to the cave entrance, where freezing can occur during winter. In situ CO_2 measurements at the site revealed that the air masses within the cave can only change during wintertime because of the general, temperature dependent atmospheric circulation of sacklike chambers. When cold and dry winter air sinks into the cave, the environment may become totally dry and, therefore, the growth rate of the deposits becomes practically zero.

The stalagmite consists of dense, well-laminated dark crystalline and milky-colored calcite. Apparently, deposition has been continuous along the length of the sample (ca. 250 mm), except the top part of the stalagmite where hiatus in deposition are marked by small changes in crystal structure and layers of detrital inclusions (*Fig. 2*, shown by dotted lines). A polished section of the studied section of the stalagmite (ca. top 65 mm) was examined for calculating the number of growth bands along the growth direction.

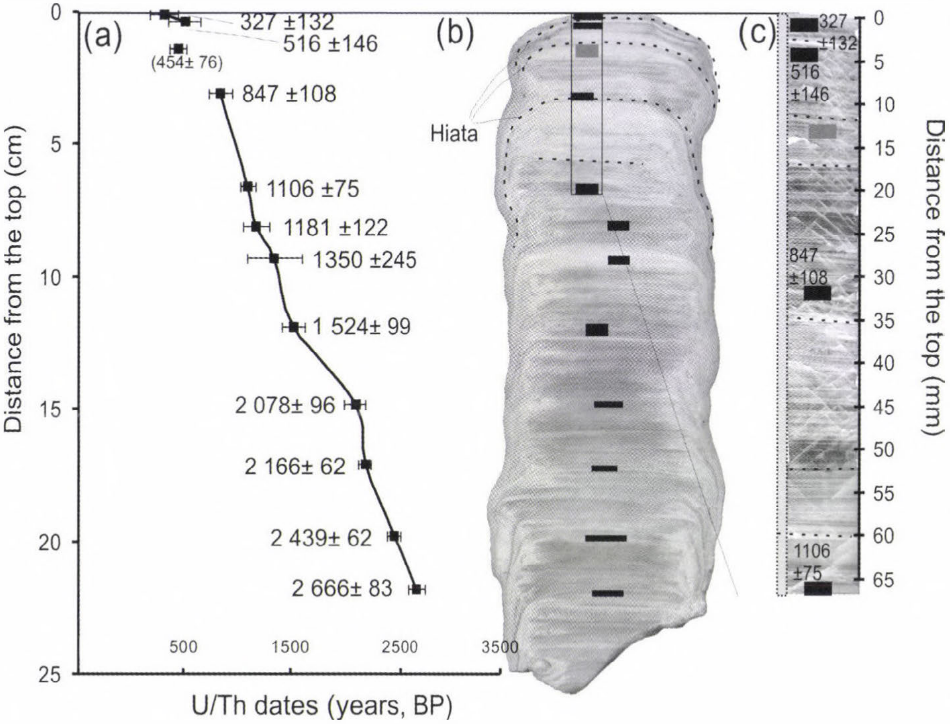


Fig. 2. The determined U-Th data series vs. the depth (a) of the studied Kiskőhát Shaft stalagmite (b), and the selected part for this study (c). Vertical gray bar shows the position of the stable isotope profile (c). Position of the Multi Collector-Inductively Coupled Plasma-Mass Spectrometry (MC-ICP-MS) age data are indicated by the black regions (b and c). Dotted line represents textural changes and/or hiata during the deposition of the stalagmite. Errors of the age data are also indicated.

3. Methodology

3.1. Age determination

To place the observed isotopic changes into a time frame for comparison with other records, *precise age determinations* of the cave deposits is required. The technique is based on the precipitation of small amounts of uranium at the moment of deposition of natural samples (e.g., calcite speleothems) in the absence of thorium. After carbonate deposition, a gradual increase of the ^{230}Th concentration occurs in the speleothem through radioactive decay of ^{234}U. The ratio ^{230}Th/^{234}U is a function of the speleothem age, which can be determined by chemical separation of ^{230}Th and ^{234}U from the sample and by measuring each nuclide (*Edwards et al.*, 1987; *Richards* and *Dorale*, 2003).

Subsamples (ca. 0.1–0.3 g) were drilled for U-Th chemistry (*Shen et al.*, 2003) and ^{230}Th-dated isotopic measurements on a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS), Thermo Electron Neptune in the High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University. A triple-spike, ^{229}Th-^{233}U-^{236}U, isotope dilution method was employed to correct mass bias and determine uranium concentration (*Shen et al.*, 2002). A protocol, using one newly-developed MasCom secondary electron multiplier (SEM) with repelling potential quadrupole (RPQ), was employed. Only 1–4 ng of U is required to earn the 2-sigma reproducibility of 1–2‰. No significant difference between measurements of standards and carbonate samples on ICP-sector-field-MS (*Shen et al.*, 2002) and on MC-ICP-MS certify the developed MC-ICP-MS methodology.

Dating of the youngest part of the stalagmite was possible by applying the U-Th method due to its low detrital Th content. Age corrections are applied anyway, as even small amount of U-derived Th may have effect on the U/Th age for young samples. Thus, we used the corrected values for all dated subsamples (*Table 1*). The obtained ages are absolute ones and given as years BP (before present; here: before the chemistry date 2007 AD).

3.2. Stable isotopes

Carbon and oxygen isotope compositions of drilled calcite samples at a spatial resolution of ~ 0.5 mm were determined using the conventional H_3PO_4 digestion method (*McCrea*, 1950; *Spötl* and *Venneman*, 2003) at 72 °C and an automated GasBench II preparation unit attached to a Thermo Finnigan delta plus XP continuous flow mass spectrometer at the Institute for Geochemical Research in Budapest. Standardization was conducted using laboratory calcite standards calibrated against the NBS-19 standard. The results are expressed according to the following equation:

$$\delta^{18}O \text{ or } \delta^{13}C = \frac{R_{sample} - R_{standard}}{R_{standard}} \cdot 1000 \quad (‰). \qquad (1)$$

The variations of stable ^{18}O and ^{16}O or ^{13}C and ^{12}C are measures by a mass spectrometer relative to a standard, therefore expressed in a „delta" (‰) notation, here, relative to the carbonate standard named Vienna Pee Dee Belemnite (V-PDB). Reproducibilities for C and O isotope analyses are better than ± 0.15‰.

In temperate regions, cave air is characterized by high-humidity (typically 95 – 99%), minimizing the evaporation that might otherwise cause kinetic isotope fractionation by preferred loss of easier water molecules ($H_2{}^{16}O$). In this case the variations in $\delta^{18}O$ value of a carbonate reflects primarily the changes in oxygen isotopic composition of precipitation in the area ($\delta^{18}O_{water}$) and the temperature of formation (*McDermott*, 2004 and references therein). Since the isotopic composition of dripping water is closely related to the meteoric precipitation at the studied region (*Harmon et al.*, 1979; *Yonge et al.*, 1985) and the cave temperature reflects the mean annual temperature at the surface (*Fairchild et al.*, 2006), the O isotope compositions of meteoric water that infiltrates into the cave, and from which the carbonate precipitates, reflect regional climate conditions. However, in order to interpret the $\delta^{18}O$ value of the stalagmite correctly, the factors that may influence the O isotope compositions of infiltrating water have to be listed here. As mentioned above, the $\delta^{18}O$ in cave seepage waters reflect the $\delta^{18}O$ of the local precipitation but may reflect evaporative processes that modify the $\delta^{18}O$ of the infiltrating water along the flow path from the surface across the vadose zone into the cave. The oxygen isotope composition of precipitation is temperature and site dependent.

Over the mid and high latitudes, *Rozanski et al.* (1993) calculated an average modern-day $\Delta\delta^{18}O_{precipitation}/\Delta T$ of approximately $+0.6‰/°C$. This value may have been different in the past, however, we may assume that the positive correlation remained. The equilibrium fractionation (*Friedman* and *O'Neil*, 1977) that accompanies calcite deposition from drip-waters inside the cave ($\Delta\delta^{18}O_{calcite}/\Delta T$) is approximately $-0.24‰/°C$ at 25 °C (*O'Neill et al.*, 1969). Since the temperature dependence of $\delta^{18}O$ in rainfall (ca. $+0.6‰/°C$) exceeds the calcite-water fractionation ($-0.24‰/°C$), in principle the *temperature dependency* of the O isotope compositions of meteoric water define the $\delta^{18}O$ value of the calcite (i.e., a positive correlation between $\delta^{18}O$ in the calcite and temperature).

The $\delta^{13}C$ values of the stalagmites can also provide important palaeoenvironmental information. The carbon isotopic composition of the drip water is the most important factor determining the $\delta^{13}C$ of speleothem carbonates. Carbon dissolved in drip water mainly derives from three sources: atmospheric CO_2, soil CO_2, and dissolution of the karstic host rock. Among these, the *amount of soil CO_2* has a major factor. Thus, changes of the vegetation activity or in the microbial activity within the oxidation process of soil organic matter plays a key role in the CO_2 production. Part of the precipitation will penetrate plant cover and pass through the soil and epikarst zone, where it takes up the CO_2, produced by plant respiration. The CO_2 uptake produces carbonic acid, which in turn dissolves limestone (Eq. (2)). The $\delta^{13}C$ value of soil CO_2 varies according to the photosynthetic pathway of plants (C3 and C4-types), however, the C4-type drought-adapted grasses can be ruled out for this region at the time range for this study (*Sümegi*, 2007). The $\delta^{13}C$ values of the stalagmite may become more positive also in case of above or within-cave phenomena, mostly related to rapid *outgassing* of CO_2, caused by stronger *ventillation* or *evaporation* which leads to kinetic fractionation, thus the enrichment of calcite precipitation (i.e., stalagmite) in isotopically heavier carbon isotope.

The carbon isotopic values, therefore, mainly reflect the influence of biogenic activity of soil above the cave and the degree of limestone dissolution. The driving force of karstification and speleothem deposition is the meteoric water circulation system in combination with soil carbon dioxide production, as expressed by the following equation:

$$CaCO_3(s) + CO_2(g) + H_2O(l)_{(\text{precipitation})} <=>_{(\text{dissolution})} Ca^{2+}(aq) + 2HCO_3^-(aq). \quad (2)$$

Table 1. U/Th isotopic compositions and ^{230}Th ages for Kiskőhát Shaft on MC-ICP-MS

	Distance (cm)	Weight	^{238}U	^{232}Th	δ^{234}U	[^{230}Th/^{238}U]	[^{230}Th/^{232}Th]	Age		Age		δ^{234}U initial	Growth rate
Sample ID	**From the top**	**g**	**ppb**	**ppt**	**Measured**[a]	**Activity**[b]	**ppm**[c]	**Uncorrected**	**Error**	**Corrected**[b,d]	**Error**	**Corrected**[e]	**δm/yr**
Kiskőhát 12.	0.1	0.298	35.7	356	317	0.0051	8.5	427	± 86	327	± 132	317	16
Kiskőhát 11.	0.4	0.249	33.9	334	335	0.0075	12.5	614	± 108	516	± 146	336	
Kiskőhát 10.*	1.4	0.352	41.8	100	374.6	0.0060	41	477	± 73	454	± 76	375	43
Kiskőhát 9.	3.1	0.222	38.7	58	349	0.0106	116.5	862	± 107	847	± 108	350	135
Kiskőhát 8.	6.6	0.332	39.4	115	358	0.0140	79.8	1135	± 70	1106	± 75	360	199
Kiskőhát 7.	8.1	0.221	34.0	60	349	0.0147	137.3	1199	± 121	1181	± 122	350	71
Kiskőhát 6.	9.3	0.159	27.1	171	366	0.0176	45.8	1412	± 240	1350	± 248	367	150
Kiskőhát 5.	11.9	0.416	35.4	47	374.6	0.0192	238	1537	± 98	1524	± 99	376	52
Kiskőhát 4.	14.8	0.116	37.4	177	391.9	0.0268	93.4	2123	± 85	2078	± 96	394.2	260
Kiskőhát 3.	17.1	0.197	35.0	98	396.0	0.0278	164.5	2193	± 56	2166	± 62	398.4	99
Kiskőhát 2.	19.8	0.171	128.1	215	420.3	0.0316	310.2	2455	± 60	2439	± 62	423.2	88
Kiskőhát 1.	21.8	0.143	340.0	2584	420.6	0.0352	76.5	2737	± 43	2666	± 83	423.7	

Analytical errors are 2s of the mean.

[a] $d^{234}U = ([^{234}U/^{238}U]_{\text{activity}} - 1) \times 1000$.

[b] $[^{230}Th/^{238}U]_{\text{activity}} = 1 - e^{-\lambda 230 T} + (\delta^{234}U_{\text{measured}}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda 230 - \lambda 234)\, T})$, where T is the age.

Decay constants are 9.1577×10^{-6} yr^{-1} for ^{230}Th, 2.8263×10^{-6} yr^{-1} for ^{234}U, and 1.55125×10^{-10} yr^{-1} for ^{238}U (*Cheng et al.*, 2000).

[c] The degree of detrital ^{230}Th contamination is indicated by the [^{230}Th/^{232}Th] atomic ratio instead of the activity ratio.

[d] Age corrections were calculated using an ^{230}Th/^{232}Th atomic ratio of 2 (± 2) ppm.

[e] $\delta^{234}U_{\text{initial}}$ corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{\text{initial}} = \delta^{234}U_{\text{measured}}\ X\ e^{\lambda 234 * T}$, and T is corrected age.

*: U fraction lost during chemistry; estimate age using "Kiskőhát 11." U data.

3.3. Trace elements

As the speleothem grows, it incorporates trace elements into its structure, and their concentrations and ratios reflect environmental conditions at the time of deposition, e.g., temperature and water throughput (rainfall at the surface).

Trace element compositions were determined by laser-ablation (LA-)ICP-MS technique using a Perkin-Elmer ELAN 6100 DRC ICP-MS coupled with a LAMBDA PHYSICS excimer laser (193 nm) at the University of Lausanne. The measurements were performed using the following settings: laser: 7 Hz, 28 kV, energy ~170 mJ, fluency ~13 J/cm^2; spot size 60 μm, acquisition time: gas blank ~30s, data ~60s. Data were reduced using the CONVERT and LAMTRACE programs. NIST612 glass was used as external standard and Ca electron microprobe measurements served as an internal standard. BCR-2 glass was monitored during all analytical sessions for phosphoros and treated as unknowns during data reduction. The error is estimated to lie between 5–10% on a relative basis. With the applied method, elements incorporated into the structure of the calcite with low concentration and high spatial resolution could be followed along the growth axis.

In this paper we focus on prominent changes and cycles of the following trace elements: Mg, Sr, and P.

Mg can substitute Ca in the calcite lattice (*Mucci* and *Morse*, 1983). The main factors that can modify the Mg-signal in stalagmites are the following:

- Experimental results have demonstrated that Mg partitioning into calcite from water is temperature-dependent (*Mucci*, 1987; *Burton* and *Walter*, 1991). *Gascoyne* (1983, 1992) calculated that a 1 °C increase would increase the Mg content of the stalagmite with 7%, however, the long-term (millennial) temperature control on Mg abundance have proved to be over-simplified (*Fairchild et al.*, 2006).
- Under isothermal conditions or during short-term changes (yearly or decadal), variation in solution composition is much more important, hence Mg variation on decadal time scales reflects variations in solution Mg. This mostly reflect changes in hydrological parameters, with solution Mg / Ca tending to be lower under high flow-rate (i.e., wet) conditions, as a result of dilution.
- Furthermore, the enrichment of Mg in cave waters can be explained by prior low-Mg calcite precipitation from the cave waters along the flow path, which are consequently enriched in Mg. The partition coefficients (Kd) for Mg (and also for Sr) between cave waters and cave calcite are $<< 1$ (*Katz*, 1973; *Mucci* and *Morse*, 1983), therefore, Mg / Ca and Sr / Ca ratios increase in solutions that have precipitated calcite ("prior calcite precipitation"). This can explain co-variations of Mg and Sr in the seepage waters and consequently in the speleothem.

- Prolonged water residence time in the vadose zone linked to the reduced amount of precipitation may also enhance the Mg concentration in the solution and stalagmite due to the dissolution of the host rocks.

In the case of Sr variability, the increase in the speleothems can be interpreted by:

- Increased water residence time in the vadose zone and /or by an increase in prior calcite deposition caused by an increase in calcite saturation of the waters.
- In addition to varying solution Sr/Ca, the growth rate, or more specifically crystallographic changes can also influence Sr incorporation at higher growth rates (*Huang* and *Fairchild*, 2001). Higher Sr at a given Mg content represents faster growth rate of the stalagmite (*Huang et al.*, 2001).

Phosphate is one of the strongest adsorbents onto defect sites on the calcite surface (*Meyer*, 1984). It is directly linked

- to the vegetation productivity and its decay (*Fairchild et al.*, 2001), and
- the P incorporation into the calcite structure is sensitive to phosphate concentration in seepage water and rate of supply of dripwater (dilution).

Therefore, P concentrations can be used as an indipendent proxy together with carbon isotope values to estimate the change of biogenic activity. A control on P incorporation by rate of supply of inorganic P, rather than by defects produced during faster growth, is inferred from the lack of correlation of P and Sr in this case.

4. Results

4.1. ^{230}Th-^{234}U results of age determinations

Uranium-series dating results indicate that the stalagmite growth started some 2700 years BP. We obtained a total of 12 U-Th series dating along the growth direction (*Table 1*) and all subsamples were in stratigrapic order (*Fig. 2a*). The section selected for this study (ca. top 65 mm of the stalagmite) cover ca. 1100 ±75 years.

The age data demonstrate that the growth rate varied in time, from ca. 199 μm/year at the bottom of the studied section to ca. 16 μm/year at the top. This change may be due to the (i) real decreased rate in continuous growth or (ii) the presence of hiata. The visible laminae counts and width calculations using the CAROTA software (*Popa*, 1999) revealed that regular, high-frequency cycles can be recognized along the studied section (*Fig. 3a*) with a sum of 373 laminae within the determined age ranges for the studied section (from the bottom to the top of the stalagmite, between 1106 ± 75 and 327 ± 132 years BP, respectively). For the majority of the deposition, therefore, the stalagmite suffers from the lack of visible laminae. Fewer counted laminae than expected may probably represents brake during the stalagmite deposition. The average thickness of the bands is ca. 173 μm (*Fig. 3a*).

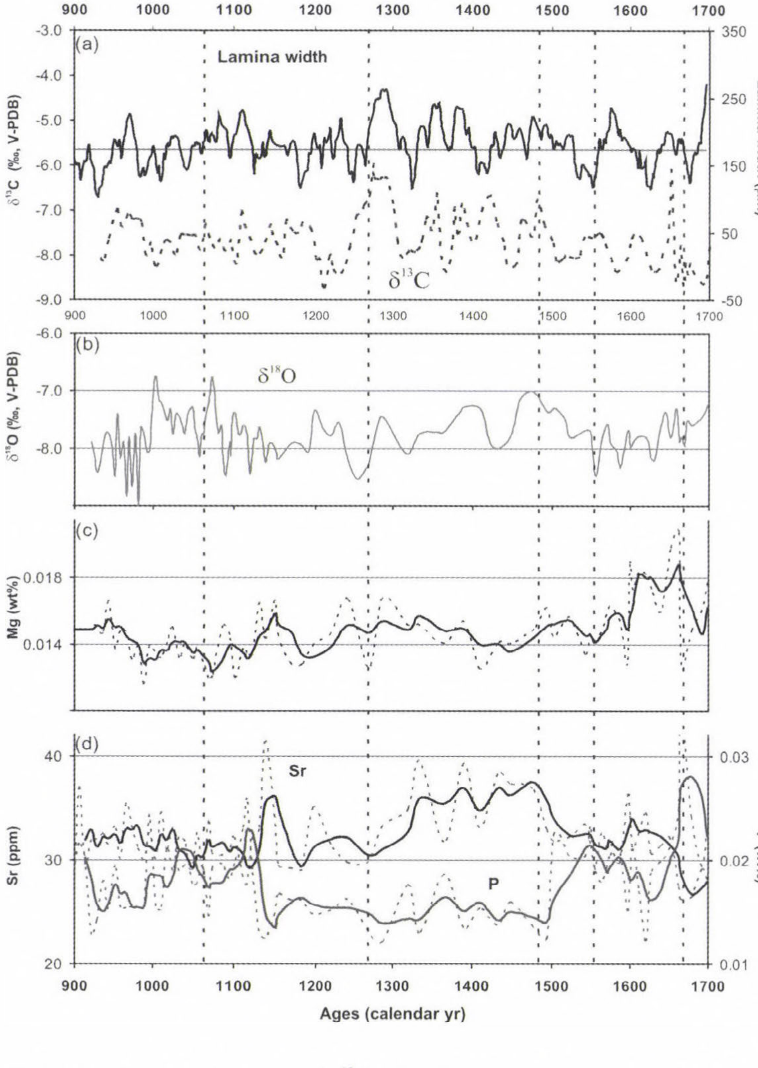


Fig. 3. Lamina thickness (upper) and $\delta^{13}C$ value (bottom) along the growth direction of the stalagmite. Horizontal line represents the average lamina width of 173 μm (a); Stable oxygen isotope composition of the studied section (b); Mg (c) and Sr-P (d) variations in the studied section of the Kiskőhát stalagmite. The thick line in each case shows smoothed data (3 running means). All data are plotted against the ages (calendar years or AD), based on the U-Th data. Vertical dotted lines mark the recognized textural changes and/or hiata (see *Fig. 2*).

The slowest growth rate based on the age-depth relationship (*Fig. 2a*) occurs at the top of the stalagmite, coinciding with the observed hiata. To put the observed changes in the isotopic composition and trace element concentration into the time-frame, U–Th ages along the growth direction were used to create time dependent proxy rather than distance.

In most speleothems from Hungary, growth rate changes and hiata during the deposition may indicate the occurrence of favorable (warm and humid) or unfavorable (cold and/or dry) conditions for calcite precipitation (*Siklósy et al.*, 2008a), thus, the observed features may represent climate changes.

4.2. Stable isotopes

The stable oxygen and carbon isotopic values were plotted against the ages (*Figs. 4a* and *4b*) according to the determined U-Th data of the selected section (ca. top 63 mm of the stalagmite). The profile consists of 125 samples obtained at ca. 0.5 mm increments. $\delta^{18}O$ values range between –9‰ and –6.7‰ (V-PDB) and $\delta^{13}C$ values range between –8.7‰ and –6‰ (V-PDB). The correlation between the two isotopes is very weak (0.13), and there is no systematic variation along a single growth layer, that suggest the sample deposited in isotopic equilibrium. However, distinct parts of the section studied (especially between ca. 1250 and 1500 AD) are characterized by fluctuations in both $\delta^{18}O$ and $\delta^{13}C$ values with higher correlation coefficient in response of possible kinetic fractionation. Processes including evaporation or rapid degassing of CO_2 from the cave dripwaters may explain this isotopic signal. In the case of $\delta^{18}O$ values (*Fig. 3b*), high-frequency cycles (with amplitudes of 1–1.5‰) are superimposed on low-frequency signals. Calcite at the bottom of the section exhibit $\delta^{18}O$ value of ca. –8‰ (V-PDB) with rapid fluctuations. Within a short period (at 1000 AD), a marked increase of >1‰ can be observed towards to less negative values of the section. These higher values remain and caracterize the section between 1000 and 1150 AD. Furter up-section, towards the younger part, lower averaged values were measured with some abrupt jumps towards higher $\delta^{18}O$ values, from which some coincide with similar $\delta^{13}C$ peaks. Between 1550 and 1680 AD there is a remarkable shift to lower $\delta^{18}O$, while the very top of the stalagmite (>1680 AD) shows slightly higher values again.

The carbon isotope composition of the stalagmite (*Fig. 3a*) is characterized by similar high-frequency cycles with even more abrupt changes. Smaller variability can be observed at the bottom part of the section (before 1200 AD), while more variable values of $\delta^{13}C$ are present between ca. 1200 and 1500 AD. An abrupt change at ca. 1250–1300 AD resulted the highest $\delta^{13}C$ value of the stalagmite. From this point to the top, a trend towards lower values appear with another sharp peak at 1650 AD, which coincides with darker calcite just below the observed hiata at the top of the section (dotted lines in *Figs. 2* and *4*).

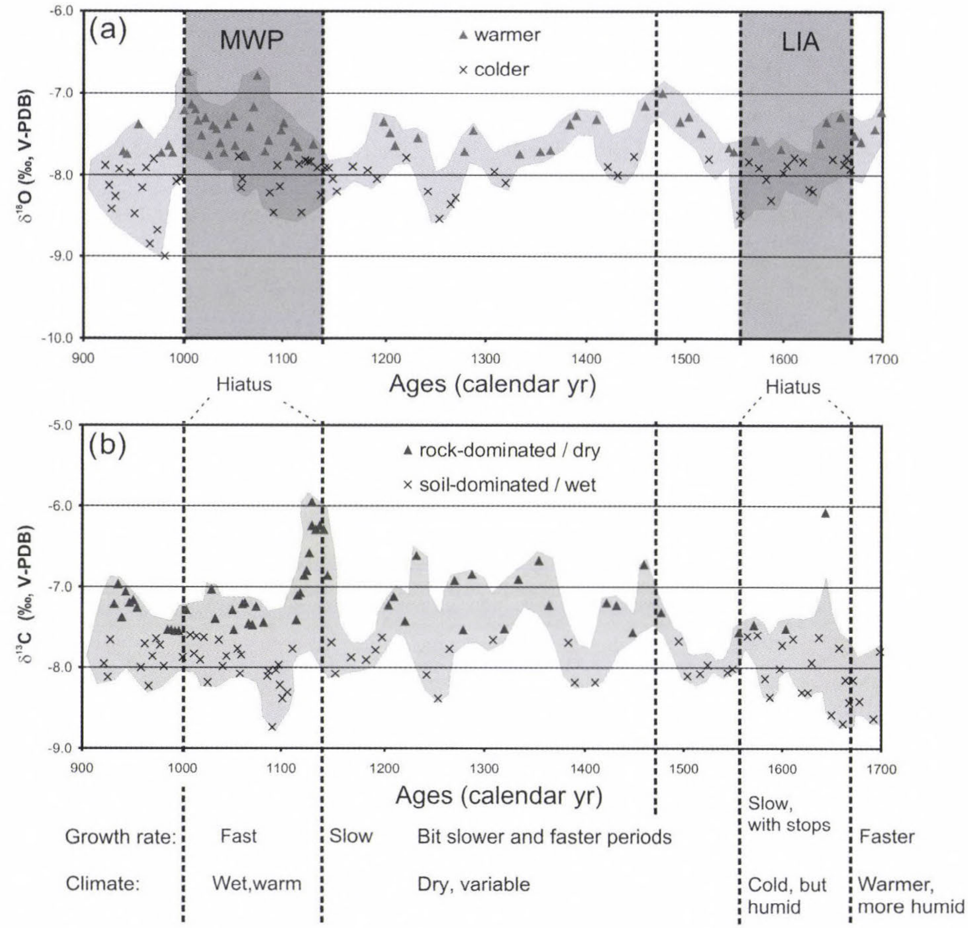


Fig. 4. Stable oxygen (a) and carbon (b) isotope record plotted against the age-relationship of the studied stalagmite. Vertical dotted line indicates hiata and/or marked textural changes during the selected growth period (see *Fig. 2*). See text for details.
(a) Triangles represent higher oxygen isotope values and crosses represent lower oxygen isotope values compared to the average of the total section.
(b) Triangles represent higher carbon isotope values and crosses represent lower carbon isotope values compared to the average of the total section.

4.3. Trace elements

Trace element data are plotted against the ages (AD) from the top of the sample (*Fig. 3c* and *d*). The stalagmite is practically free from detrital-derived impurities as the textural and prelimintary chemical scanning showed, therefore, they are not mentioned in this study or they are not responsible for the laminae observed in the stalagmite. The selected trace elements (Mg, Sr, and P) display similar oscillations along the studied section of the stalagmite, although there are some obvious differences (peaks and trends) at different parts of the concentration profiles.

Magnesium exhibits short-time cycles along the growth direction superimposed on a long-term increasing trend towards the top of the stalagmite (*Fig. 3c*). Low concentration appears between ca. 950 and 1100 AD, whereas the top part (between 1600 and 1680 AD) is characterized with higher Mg values. Mg shows no covariation with Sr or P.

Strontium displays high-frequency cycles superimposed on long-term changes as well. The highly variable Sr concentration clearly reveals a similar pattern as the $\delta^{13}C$ values in most of the section. The highest Sr values and peaks between 1300 and 1500 AD coincide with elevated $\delta^{13}C$ values, while there is a general decreasing trend between 1650 and 1700 AD for both profiles (*Fig. 3d*).

Phosphorus displays anticorrelation with Sr, but not with any other element (*Fig. 3d*). The overall anticorrelation is 0.61. The lowest values are observed between ca. 1150 and 1550 AD, with some troughs around 1600 AD. P peaks and elevated values (1000–1150 AD) generally encompass the lower values of Mg.

5. Discussion on the stable isotopes and trace element records

Before discussing the temperature and precipitation amount information obtained from the Kiskőhát Shaft, stable isotope data points were separated and colored according to their relative values to the averaged value of both (C and O isotope) datasets (*Fig. 4*), and plotted against the age.

As shown in *Fig. 2*, the older part of the studied section (35–40 mm to ca. 65 mm, which value represents ages between 847 and 1106 years BP) is characterized by faster growth rate (ca. 135 µm/year), opposit to the top of the stalagmite. In order to reconstruct the paleoenvironmental changes during this period, the $\delta^{18}O$ values of the stalagmite was first investigated. $\delta^{18}O$ of the seepage water is not controlled by the routing of the water but the composition of the local precipitation, thus the climate of the region (*Harmon et al.*, 1979; *Yonge et al.*, 1985). As abovementioned, higher $\delta^{18}O$ values of the precipitated carbonate primary reflect warmer climate. Evaporation may also have caused elevated $\delta^{18}O$ values, but this would be also indicated by the elevated Sr and Mg concentration. This period (between ca. 1000 and 1150 AD) is characterized by the highest values with positive shift of $\delta^{18}O$ (*Fig. 4)*, indicating warmer and/or arid climate conditions. This latter possibility can be ruled out, as the P and $\delta^{13}C$ show no systematic shifts towards low and high values, respectively, therefore towards drier conditions (*Fig. 3c* and *d*). Instead, the high P and the slight shift of $\delta^{13}C$ to more negative values imply increased soil biogenic activity, most probably due to the increased precipitation amount. Low Mg and decreasing Sr values can be also explained by dilution effect related to the elevated infiltration (i.e., wet conditions). According to the determined U–Th ages, this warmest period with the highest oxygen isotope values around 1000–1150 years may represent the Medieval Warm Period (MWP).

Just before this time period, the very bottom of the section (between ca. 900 and 1000 AD) represents colder and drier period, but the lack of interpretable data preceeding this time prevent the precise comparison.

In contrast to the MWP, the next few hundred years (ca. 1150–1500 AD) are characterized by highly variable geochemical parameters with sharp peaks of $\delta^{13}C$ values and Sr concentrations. In the case of Kiskőhát Shaft, the overall $\delta^{13}C$ values are determined by the contribution of biogenic CO_2 (plant respiration within the soil zone) and the degree of rock-water interaction. The resulted overall value is then modified or obscured by secondary processes as mentioned above (varying kinetic isotope effects, e.g., rapid degassing of CO_2 caused mostly by increased ventilation). In the case of the Kiskőhát Shaft, the $p(CO_2)$ of cave air falls strongly in winter because of the more ventilated system during cold seasons as a result of temperature dependent atmospheric circulation in sacklike chambers. This leads to a strong degassing of CO_2, therefore, a kinetic effect and an increase of $\delta^{13}C$ values in cave water. As the dissolved CO_2 degasses, the solution becomes supersaturated, and there is a tendency for $CaCO_3$ to precipitate. The maximum rates of $CaCO_3$ precipitation is, therefore, generated in the winter or cold periods, but only if the hydrologic system remains active for water infiltration.

As a result of slower flow rates within the karst system (i.e., dry climatic period), enhanced prior calcite precipitation along the flow-path may occur from waters due to Ca^{2+} supersaturations by CO_2-degassing. This prior calcite precipitation will lead to trace element enrichment (e.g., increased Sr and Mg concentration) of the dripping water and consequently in the stalagmite.

Sr incorporation into the calcite structure is dependent on precipitation rate. The overall good correlation between Sr, $\delta^{13}C$ (*Fig. 3a, d*) and – interestingly – also to lamina width, therefore, can be attributed to elevated precipitation rate most probably due to the temporal variations (i.e., sharp decrease) in $p(CO_2)$ in the cave air, which is mainly controlled by ventilation. We assume that both above mentioned processes, i.e., rapid degassing of CO_2 caused mostly by elevated, temperature dependent ventillation and prior calcite precipitation along the flow-path as a result of reduced precipitation amount occurred. Therefore, periods of low precipitation amount (dry conditions) and decrease in mean annual temperature (or longer winters) recorded during the deposition between ca. 1150 or 1200 and 1500 or 1550 AD. Low P concentration (*Fig. 3d*) supports our assumption, since the drier conditions prevent soil activity and, therefore, the biogenic production. Decreased soil biogenic CO_2 production via plant respiration and microbial activity leads to less negative $\delta^{13}C$ values, which, again record dry or drier conditions during the deposition of this part of the stalagmite. We assume that the increased $\delta^{18}O$ values may also represent drier conditions as a result of kinetic effect of evaporation events (e.g., at around 1280, 1400, and 1480 AD).

The rapid decrease of $\delta^{18}O$ values and change in trace element composition of the stalagmite imply remarkable change during the deposition at ca. 1500 AD. P shows rapid increase paralel to the decrease in Sr concentration, while Mg shifting towards more positive values. Textural studies indicate that there are small, but obvious variations in the petrographical features along the studied part of the stalagmite. The recognized hiata (vertical dotted lines in *Figs. 2* and *4),* represent ceased growth, especially near the top of the stalagmite (younger part). Non-uniform calcite growth rates were also shown by the age-depth relationship (*Fig. 2a*) and by the variable lamina width values (*Fig. 3a*). The lack of continuous growth reveals that the formation of the stalagmite suffer optimal conditions (i.e., warm and/or wet) in certain time period(s). The most remarkable hiatus can be seen close to the top of the stalagmite (ca. 1600–1700 AD). As the recent mean annual temperature in the cave interior is ca. 5.5 °C, we could exclude solely the temperature decrease for widespread freezing of the cave system. A gradual cooling would inevitability resulted in significant $\delta^{18}O$ shift for the deposited carbonate (*Siklósy et al.*, 2008b), however, in the case of Kiskőhát Shaft, only minor variability were observed before and after the growth cessation. Restricted growth can be explained by reduced drip rate of infiltrating water in dry periods, or because of heavy water flows in the wet season within the cave, when the water is no longer supersaturated for $CaCO_3$. This latter option can be ruled out as the trace element composition (especially Mg) exhibit higher values rather than the diluted, low values. The rapid increase in Mg after between 1600 and 1700 AD is possibly due to an important increase in water residence time followed by the cessation of speleothem growth as indicated by hiata at the top. Decreasing Sr concentration values after 1500 AD and especially after 1650 AD also suggest reduced growth rate. By the end of this process, stalagmite growth ceased. Therefore, our data suggest that the lack of infiltrated water would explain the marked growth break. It is important to distinguish internal and external dryness, as the second option would definitely imply regional climate variability, and the P concentration and $\delta^{13}C$ values would reflect aridity induced changes in the vegetation and soil system. On the contrary, P concentration increases and $\delta^{13}C$ values decrease, representing prosperous conditions in the soil zone. We, therefore, argued that internal (”within cave”) dryness and, subsequently, the decrease in water availability during this period were responsible for the pausa of the growth. Water deficit in the interior can emerge by the advanced ventilation caused by enhanced winter (cold and dry) air masses entering the cave. In situ seasonal changes in $p(CO_2)$ were recorded and supported our assumptions. Therefore, we suggest that elevated ventilation during this time period was caused by longer winters. Based on the determined ages, this section of the studied stalagmite deposited during the LIA. As a consequence of external cooling, $\delta^{18}O$ of the stalagmite during this period exhibits lower values, while averaged growth rate decreased (to ca. 16 – 40 μm/year), according to the determied U–Th ages and distances (*Fig. 2a*). As a first approach, the observed ca. 2‰ isotopic shift between the MWP and LIA can be translated into temperature change using the above mentioned temperature dependency factor of the local precipitation (ca. + 0.6‰ / °C) and the equilibrium fractionation that accompanies calcite deposition from drip-waters (– 0.24 ‰ / °C) inside the cave. These two factors would result a range of ca. 5 °C cooling, which is higher than the realistic value. Thus, more complex scenario required for the interpretation of the isotopic record, therefore, we need to consider additional factors than solely the temperature dependency that may modify the $\delta^{18}O$ values of the calcite. We assume that a combination of the following processes shifted the $\delta^{18}O$ values of the stalagmite towards less negative values during the MWP:

- a slight evaporation of the local precipitation and the infiltrating water resulted in elevated $\delta^{18}O$ value for the dripping water, thus for the precipitated calcite as well, or
- the decrease of the ratio between winter/summer precipitation resulted in positive shift of the annual infiltrating water.

To summarize, the coldest years (most probably longer or colder winters) spans around from 1550 to ca. 1700 AD. The missing periods (hiata) and the relatively bigger age errors around the top of the stalagmite prevent the better resolution of the LIA, however, the minimum growth rate and the complex geochemical record support our assumptions.

6. Conclusions

We investigated the textural characteristics, stable carbon and oxygen isotope composition, and the trace element content of the subrecent part of a laminated stalagmite from northeast Hungary (Kiskőhát Shaft) in order to reveal a climate induced geochemical record for the last millennium. The high-resolution record from the cave deposit revealed a number of paleoenvironmental proxy. We interpreted the changes in this speleothem as a result of complex changes in the environmental parameters:

1. Cold and/or arid years (lower annual mean temperature or longer winter) reduce the average growth rate or even stop the growth of the stalagmite, while warm and humid periods results in optimal conditions for the accretion (faster growth rate).
2. More positive $\delta^{18}O$ values represent warmer periods (Medieval Warm Period), with a favorable conditions (wet and warm) for biogenic activity in the soil zone.

3. Cooling at the end of the Medieval Warm Period resulted in a reduced soil biogenic activity revealed by the increased stable carbon isotope values.
4. The climate experienced several warmings and coolings and important changes in the precipitation amount over the Medieval Warm Period – Little Ice Age transition, both with slower and faster growth rates, compared to the previous time period (MWP).
5. During the Little Ice Age, the cave was colder, the growth rate of the deposits was practically zero (presence of hiata). In the case of growing, stalagmite recorded colder but humid conditions.

Acknowledgements—This study was financially supported by the Hungarian Scientific Research Fund (OTKA T 049713). Measurements of U-Th isotopic compositions and ^{230}Th dates were supported by the National Science Council grants (94-2116-M002-012, 97-2752-M002-004-PAE & -005-PAE to C.C.S.). This paper is a contribution to the European Millennium Project (017008). Financial support of the Hungarian Meterological Society is greatly appreciated.

References

Bodri, L. and *Dövényi, P.,* 2004: Climate change of the last 2000 years inferred from borehole temperatures: data from Hungary. *Global Planet Change 41*, 121–133.

Burton, E.A. and *Walter, L.M.,* 1991: The effects of PCO_2 and temperature on magnesium incorporation in calcite in seawater and MgCl2–CaCl2solutions. *Geochim Cosmochim Ac 55*, 777–785.

Cheng, H., Edwards, R.L., Hoff, J., Gallup, C.D., Richards, D.A., and *Asmersom, Y.,* 2000: The half-lives of uranium-234 and thorium-230. *Chem Geol 169*, 17–33.

Edwards, R.L., Chen, J.H. Ku, T.-L., and *Wasserburg, G.J.,* 1987. Precise timing of the last interglacial period from mass spectrometric analysis of Th-230 in corals. *Science 236*, 175–192.

Fairchild, I.J., Baker, A., Borsato, A., Frisia, S., Hinton, W.R., McDermott, F., and *Tooth, F.A.*, 2001: Annual to sub-annual resolution of multiple trace-element trends in speleothems. *Journal of the Geological Society, London, 158*, 831-841.

Fairchild, I.J., Smith, C.L., Baker, A., Fuller, L., Spotl, C., Mattey, D., McDermott, F., and *E.I.M.F.*, 2006: Modification and preservation of environmental signals in speleothems. *Earth-Sci Rev 75*, 105–153.

Friedman, I. and *O'Neil, J.R.,* 1977: Compilation of stable isotope fractionation factors of geochemical interest. In *Data of Geochemistry* (ed.: *M. Fleischer*). *U.S. Geological Survey Professional Paper 440-KK, 6th Ed.*, Reston, VA.

Gascoyne, M., 1983: Trace element partition coefficients in the calcite-water system and their paleoclimatic significance in cave studies. *J. Hydrol. 61*, 213–222.

Gascoyne, M., 1992: Palaeoclimate determination from cave calcite deposits. *Quaternary Sci Rev 11*, 609–632.

Harmon, R.S., Schwarcz, H.P., O'Neil, J.R., 1979: D/H ratios in speleothem fluid inclusions: a guide to variations in the isotopic composition of meteoric precipitation? *Earth Planet Sc Lett 42*, 254–266.

Hendy, C.H., 1971: The isotopic geochemistry of speleothems 1. The calculation of the effects of the different modes of formation on the isotopic composition of speleothems and their applicability as palaeoclimatic indicators. *Geochim Cosmochim Ac 35*, 801–824.

Huang, Y., Fairchild, I.J., Borsato, A., Frisia, S., Cassidy, N.J., McDermott, F., and *Hawkesworth, C.J.,* 2001: Seasonal variations in Sr, Mg and P in modern speleothems (Grotta di Ernesto, Italy). *Chem Geol 175*, 429–448.

Huang, Y. and *Fairchild, I.J.*, 2001: Partitioning of Sr^{2+} and Mg^{2+} into calcite under karst-analogue experimental conditions. *Geochim Cosmochim Ac 65*, 47–62.

Katz, A., 1973: The interaction of magnesium with calcite during crystal growth at 25–90 °C and 1 atmosphere. *Geochim Cosmochim Ac 37*, 1563–1586.

Kern, Z. and *Popa, I.*, 2007: Climate–growth relationship of tree species from a mixed stand of Apuseni Mts., Romania. *Dendrochronologia 24*, 109–115.

Kern, Z., Grynaeus, A., and *Morgós, A.*, 2009: Reconstructed precipitation for southern Bakony Mountains (Transdanubia, Hungary) back to 1746 AD based on ring widths of oak trees. *Időjárás 113*, 299-314.

Kiss, A., 2009: Historical climatology in Hungary: Role of documentary evidence in the study of past climates and hydrometeorological extremes. *Időjárás 113*, 315-339.

Kordos, L., 1977: A sketch of the vertebrate biostratigraphy of the Hungarian Holocene. *Földrajzi Közlemények 25*, 144–160.

Kordos, L. and *Ringer, Á.*, 1991: Climatostratigraphic and archeostratigraphic correlation of Arviocolidae stratigraphy of the late Pleistocene in Hungary (in Hungarian). *MÁFI évi jelentése az 1989. évről*. Budapest, 523–533.

Lauritzen, S.E., 1995: High-resolution palaeotemperature proxy record for the last interglaciation based on Norwegian speleothems. *Quaternary Res 43*, 133–146.

McCrea, J.M., 1950: On the isotopic chemistry of carbonates and a paleotemperature scale. *J Chem Phys 18*, 849–857.

McDermott, F., 2004: Palaeo-climate reconstruction from stable isotope variations in speleothems: a review. *Quaternary Sci Rev 23*, 901–918.

Meyer, H.J., 1984: The influence of impurities on the growth rate of calcite. *J Cryst Growth 66*, 639–649.

Mucci, A., 1987: Influence of temperature on the composition of magnesian calcite overgrowths precipitation from seawater. *Geochim Cosmochim Ac 51*, 1977–1984.

Mucci, A. and *Morse, J.W.*, 1983: The incorporation of Mg^{2+} and Sr^{2+} into calcite overgrowths: influences of growth rate and solution composition. *Geochim Cosmochim Ac 47*, 217–233.

Popa, I., 1999: Aplicaţii informatice utile în cercetarea silvică. Programul CAROTA şi programul PROARB. *Revista pădurilor*. 2, 41–42.

Rácz, L., 1989: Climate history of the Middle and Modern Ages (in Hungarian). *Agrártörténeti Szemle 31*, 118–147.

Réthly, A., 1962: Natural disasters and calamities untill the year of 1700 (in Hungarian). Akadémiai Kiadó, Budapest.

Richards, D.A. and *Dorale, J.A.*, 2003: Uranium-series chronology and environmental applications of speleothems. *Rev Mineral Geochem 52*, 407– 460

Rozanski, K., Aragulas-Aragulas, L., and *Gonfiantini, R.* 1993: Isotopic patterns in modern precipitation. In *Climate Change in Continental Isotopic Records* (ed.: *P.K. Swart, K.C. Lohmann, J. McKenzie, S.* Savin). *Geophysical Monograph 78*. American Geophysical Union, Washington, DC, 1–36.

Shen, C.-C., Edwards, R.L., Cheng, H., Dorale, J.A., Thomas, R.B., Moran, S.B., Weinstein, S.E., and *Hirschmann, M.*, 2002: Uranium and thorium isotopic and concentration measurements by magnetic sector inductively coupled plasma mass spectrometry. *Chem. Geol. 185*, 165–178.

Shen, C.-C., Cheng, H., Edwards, R.L., Moran, S.B., Edmonds, H.N., Hoff, J.A., and *Thomas, R.B.*, 2003: Measurement of attogram quantities of ^{231}Pa in dissolved and particulate fractions of seawater by isotope dilution thermal ionization mass spectroscopy. *Anal Chem 75*, 1075–1079.

Siklosy, Z., Demeny, A., Vennemann, T.W., Kramers, J., Lauritzen, S.E. and *Leel-Ossy, Sz.*, 2007: Middle bronze age climate change recorded in a Hungarian stalagmite: triggering by volcanic activity? *Geophysical Research Abstracts, 9*: 1607-7962/gra/EGU2007-A-00777.

Siklósy, Z., Demeny, A., Leel-Ossy, Sz. and *Szenthe, I.*, 2008a: High-resolution stable isotope and U-Th study of Hungarian stalagmites, related to climate optima (in Hungarian). *Hungeo2008 abstract book*, 40–41.

Siklósy, Z., Demény, A., Pilet, S., Leel-Ossy, Sz., Lin, K. and *Shen, C.-C.*, 2008b: Stalagmite geochemistry and the timing of the last interglacial-glacial transition in Central Europe (NE Hungary). *EPICA2008* Conference Abstract.

Siklósy, Z., Demény, A., Vennemann, T.W., Pilet, S., Kramers, J., Leel-Ossy, Sz., Bondár, M., Shen C.-C. and *Hegner, E.,* 2009: Bronze Age volcanic event recorded in stalagmites by combined isotope and trace element studies. *Rapid Communications in Mass Spectrometry 23*, 801-808.

Spötl, C. and *Vennemann, T.* 2003: Continuous-flow isotope ratio mass spectrometric analysis of carbonate minerals. *Rapid Communications in Mass Spectrometry 17*, 1004–1006.

Sümegi, P., 2007: Late Quaternary environmental history of Hungary (in Hungarian). *D.Sc. Thesis for Hungarian Academy of Science*. University of Szeged, the Faculty of Science, Department of Geology and Palaeontology.

Yonge, C., Ford, D.C., Gray, J., and *Schwarcz, H.P.,* 1985: Stable isotope studies of cave seepage water. *Chem Geol 58*, 97–105.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 4, October–December 2009, pp. 265–298

Middle Age paleoecological and paleoclimatological reconstruction in the Carpathian Basin

Pál Sümegi[1,2*], Gusztáv Jakab[3], Péter Majkut[1], Tünde Törőcsik[1], and Csilla Zatykó[2]

[1]*Department of Geology and Paleoecology, University of Szeged,*
P.O. Box 658, H-6722 Szeged, Hungary
E-mail: sumegi@geo.u-szeged.hu

[2]*Institute of Archaeology, Hungarian Academy of Sciences,*
Úri út 49, H-1014 Budapest, Hungary

[3]*Institute of Environmental Sciences, Tessedik Sámuel College,*
Szabadság út 1-3, H-5540 Szarvas, Hungary

(Manuscript received in final form November 19, 2009)

Abstract—Three programs of medieval environmental history research of fourteen sites was undertaken between 1998 and 2008 as part of the "*Evolution of the Hungarian mires, peats and marshes*", "*Environment history of Hungary*", and "*Geoarcheological investigations of Hungary*" projects. This present study was to demonstrate the facilities of paleoecological and paleoclimatological investigations (pollen, macrofossil, sediment works) completed on the core sequence of the Nádas Lake at Nagybárkány (Hungary). The Nádas Lake at Nagybárkány is a small peat-bog in the eastern Cserhát Mountains. The formation of the lake can be traced back to the late Glacial. The sediments deposited in the lakebed provide a record of climatic and hydrologic changes. A higher water level could be demonstrated from the late Glacial to the mid-Holocene, when the reed-beds covered a small area only. This was followed by a hiatus spanning about 5000 years, caused by the deepening of the lakebed during the Imperial Age, around 20–50 AD. The water level decreased and the water quality was more eutrophic. A reed-bed evolved around the lake. Paludification started with a bulrush floating mat phase at the close of the Middle Age, ca. 1300 AD. The initiation of the *Sphagnum*-bog underwent similar phases as in the other Hungarian peat-bogs. Although some anthropogenic disturbances can be reconstructed in the development of the peatland, some climatic effects and authogenic processes might be separated by paleoecological analyses.

Key-words: peatland development, macrofossils, pollen, geochemistry, paleoclimate, Holocene

---

[*] Corresponding author

1. Introduction

The application of macrofossil analysis to peat and lacustrine deposits enables to identify long-term vegetation changes in aquatic ecosystems. The composition of aquatic plant communities is largely influenced by the hydrological conditions prevailing in the basin harboring them. These, on the other hand, are highly prone to centennial-scale fluctuations in the climate. Former studies aimed at deciphering past climatic conditions via detailed analysis of peatland deposits primarily focused on the investigation of *Sphagnum*-peats of so-called ombrotrophic peatlands (*Barber et al.*, 2000; *Barber* and *Langdon*, 2001; *Barber* and *Charman*, 2005; *Mauquoy* and *Barber*, 1999). Due to various methodological problems, high-resolution quantitative macrofossil studies on the eutrophic peatlands of continental Europe were generally lacking so far. A slight modification of the method proposed by *Barber et al.* (1994) enabled us to retrieve proxy-climate data from the eutrophic peatlands of continental areas as well (*Jakab et al.*, 2004).

The total number of *Sphagnum* occurrences hardly exceeds 50, and in the central driest areas of the Great Hungarian Plain they are completely absent. Only sporadic *Sphagnum*-bogs are known in the country with a total number well below 20, most of them being extremely small with an area of a mere couple ha. Real raised bogs are completely missing. The majority of *Sphagnum*-bogs is restricted to the western parts of the country enjoying oceanic climatic influences, and to those of the areas of the Northern Mountains and the northern part of the Great Hungarian Plain, enjoying montane-type climatic influences of the Carpathians (*Boros*, 1968; *Szurdoki* and *Nagy*, 2002).

The present paper is discussing the findings regarding the development of small eutropic peat-bog from northern Hungary. Autogenic succession processes, climatic conditions, and anthropogenic influences largely contributed to creating the modern view of the referred peatland. Other aim was to put the reconstructed anthropogenic impacts and their changes to the context of the settlement strategies and landscape usages in the central parts of the Carpathian Basin.

Besides the radiocarbon-dated (Table 1) results (Tables 2–5) presenting some similarities and differences between local strategies in adopting and using marginal landscapes, this project will contribute to future research in Hungary on similar topics. In order to shed light onto the interrelations of vegetation changes and climate change, the model of *Davis et al.* (2001, 2003) was adopted in our work (Table 6). In our model the plants inferred from the palynological and plant macrofossil records were assigned to groups of plant functional types (*Prentice et al.*, 1998; *Peyron et al.*, 1998).

2. *Study site*

The Nádas Lake (360 m a.s.l.) at Nagybárkány lies on the northern side of Mt. Hármas-Határhegy, rising to a height of 516 m in the eastern Cserhát Mountains (*Fig. 1*). There are two other lakebeds in its vicinity, but these are smaller than the Nádas Lake. The lakebed has an elongated, north-west oriented form, with a strongly narrowing extension in the south. Its length is roughly 100 m, its greatest width is 40 m, and it covers an area of roughly 2000 m^2. The narrowing section is about 5–10 m wide. Accumulation in the catchment basin of the lake started in the late Glacial, when a mass movement (exactly rotation landslide) process was formed on the slope of the Miocene sandy and silty sediment covered land surface. A slump hollow formed in the source area between the landslide toe, and the scarp which was filled up by water forming a small round-form lake. This mass movement process is characteristic in the analyzed region. The annual rainfall is between 600–700 mm. The origin of the peat-bog's water is ombrotrophic and topogenic. There is not any visible watercourse in the drainage area.

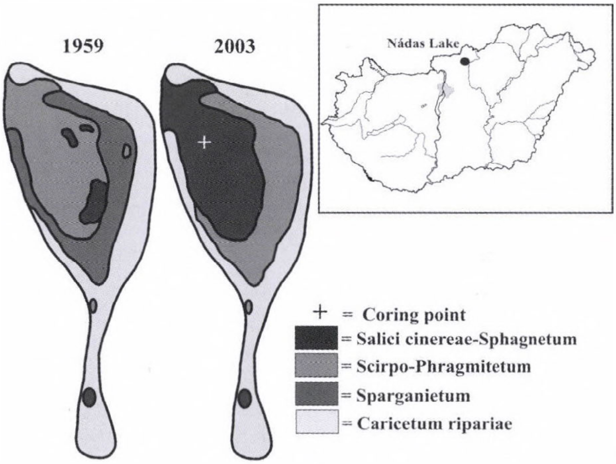


Fig. 1. Site location of the Nádas Lake and core location on the vegetation map in 1959 (after *Máthé* and *Kovács* (1959)) and in 2003 *Jakab-Sümegi* (2005).

The lakebed is fringed by a sessile oak forest. Three plant communities can be distinguished in the recent bog (*Fig. 1*). The central part of the bog is covered with Sphagnum willow swamp (*Salici cinereae-Sphagnetum recurvi*). This community is rather poor in species; it is characterized by a dominance of *Salix cinerea* and a carpet of *Sphagnum squarrosum*. This association is rather rare in Hungary, occurring in the well watered, undrained valleys of the Great Hungarian Plain and the Northern Mountains, as well as in smaller local hollows. The willow swamp is fringed by reed-beds (*Scirpo-Phragmitetum*), except on the western side. The reed-beds are similarly poor in species; the presence of *Lythrum salicaria, Lycopus europaeus*, and *Utricularia vulgaris* can be noted. Tall sedge communities (*Caricetum ripariae*) line the reed-beds. These communities are dominated by *Carex riparia*.

3. Methods

Overlapping cores were extracted using a Russian corer conforming to the general practice in quaternary paleoenvironmental studies. The samples submitted to lithological analyses were identical with the ones used for the paleobotanical, macrobotanical, and radiocarbon analyses. Results of pollen analyses of the peat-bog sequence were presented in *Juhász*, (2005) and *Juhász et al.* (2004).

The sampling of the 340-cm-deep, undisturbed sedimentary sequences from basin of the Nádas Lake was carried out using a 5-cm-diameter Russian type corer. The main lithostratigraphic features of the sedimentary sequence were determined and analyzed. For the description of the cores, the internationally accepted system and symbols of *Troels-Smith* method developed for unconsolidated sediments were adopted (*Troels-Smith*, 1955).

Radiocarbon dating of the sequence was obtained by both bulk and AMS (accelerator mass spectrometry) analyses. Four bulk samples of sediment were analyzed for radiocarbon ages at the Nuclear Research Centre of the Hungarian Academy of Sciences, Debrecen, Hungary, and one sample of plant macrofossils was analyzed for AMS date at the radiocarbon dating facility in Poznan, Poland. In order to allow comparison with other archaeological data, the dates were calibrated using the Oxcal v.3.9 calibration program (*Bronk Ramsey*, 2001), using atmospheric data of *Stuiver et al.* (1998). The original dates are indicated as uncal BP, while the calibrated dates are indicated as cal BC, cal BP, or cal AD (*Table 1)*. Depth-age modeling and determination of the age of the samples were constructed by using radiocarbon data and sedimentation rate (*Bennett*, 1994; *Valanus*, 2008).

The core was divided into 4 cm samples. The organic content of the core samples was estimated by loss-on-ignition at 550 °C for 5 hours and the carbonate content by the further loss-on-ignition at 900 °C for 5 hours (*Dean*, 1974). The inorganic content was further analyzed using the sequential extraction method. *Mackereth* (1966) was the first to recognize the potential of geochemical investigations on the sediments of the catchment basin for the purpose of environmental reconstructions in his review of bulk chemical analyses on deposits from the Lake District. The application of bulk analysis, however, is quite problematic since it does not shed light unequivocally onto the origin of the chemical constituents (*Engström* and *Wright*, 1984). Mackereth' work was later enhanced by researchers working on the combination of chemical analyses with palynological investigations.

Table 1. Radiocarbon dates for the lake Nádas at Nagybárkány. Calibrated with Radiocarbon Calibration Program 4.4.2

Sample number	Depth (cm)	Sediment type	$\delta^{13}C$(PDB) ± 0.2 [‰]	^{14}C age (uncal BP)	cal AD/BC (2 σ)
deb-11110	NB-45	Peat	–28.02	100% ± 0.40 pM ^{14}C	1950–1960 cal AD
deb-11098	NB-100	Peat	–27.73	740 ± 60	1230–1300 cal AD
deb-11009	NB-180	Peat	–28.49	1600 ± 60	400–540 cal AD
deb-11100	NB-250	Charcoal	–27.52	6090 ± 60	4956–5146 cal BC
Beta-194559	NB-280	Charcoal	–24.90	8050 ± 40	6875–7061 cal BC

A new, so-called sequential extraction method (*Dániel*, 2004) with a long established history in the analysis of geochemical composition of lacustrine sediments was adopted in our work. From the full procedure, the step of water extraction for unseparated samples was sufficient to suit our analytical needs. As it was shown by previous works (*Dániel*, 2004), the most important paleo-hydrological and paleoecological data originate from water extraction samples. Distilled water was purified using a Millipore 5 Plus water purification system for water extraction samples. 100 ml distilled and purified water was added to 1.0 g sample and was shaken for 1 hour (*Dániel*, 2004), and then the water extract elements of Na, K, Ca, Mg, Fe were analyzed using a Perkin-Elmer AAS spectrometer. The results from the geochemical analyses are plotted against depth. Statistical procedures were used to zone the data. Principal components analyses computed on correlation matrices were preformed after logarithmic transformation of the geochemical data (*Rollinson*, 1993). The geochemical zones were identified by cluster analysis of principal components (*Dowdeswell*, 1982) using squared Euclidean distance and Ward aggregation method.

For the description of macrofossils, we used a modified version of the QLCMA technique (semi-quantitative quadrat and leaf-count macrofossil analysis technique) of *Barber et al.* (1994). Organic remains from peat and lacustrine sediments rich in organic matter can be divided into two major groups. Some remains can be identified with lower ranking taxa (specific peat components), while others cannot be identified using this approach (non-specific peat components). The most important specific peat components are seeds, fruits, sporogons, mosses, rhizomes, and epidermis (e.g., *Carex* species), leaf epidermis, other tissues and organs (hairs, tracheids, etc.), insect remains, and Ostracoda shells. The identification of herbaceous plant tissues was based on the procedure described by *Jakab* and *Sümegi* (2004). We defined the amount of peat components on the 1 cm^3 level, and the amount of seeds on the 3 cm^3 level. The samples were washed through a sieve with a 300 μm mesh size.

Concentration levels were determined by adding a known amount of indicator grains (0.5 g poppy seed, ca. 960 pieces) and by counting the poppy seeds and the remains using a stereo microscope in ten 10 mm by 10 mm quadrates in a Petri dish. Similarly to mosses, rhizomes can only be identified with a light microscope.

We removed a hundred monocotyledon remains and mounted them in water on microscopic slides for determining the percentages of individual taxa and of Monocot. undiff. The values for different moss species and UBF were determined using a similar procedure. We used the Psimpoll (*Bennett*, 1992) and Syn-Tax (*Podani*, 1993) programmes for plotting the analytical results.

4. Results

4.1. Chronology and sediment stratigraphy

Coring was carried out in the north-western part of the bog, now occupied by a willow swamp (*Fig. 1*). We found peat down to a depth of 110 cm, with an underlying water pocket (floating mat) down to 130 cm. Between 130–300 cm, we found peat and peat-mud with varying organic content. Between 300–340 cm, there was a silty lacustrine sediment layer (*Table 1*). The radiocarbon dates indicate a hiatus of roughly 4400 years (from 4970 BC to ca. 20–50 AD) between 248–240 cm, meaning that we have no data of any kind for this period. The results of the radiocarbon measurements analyses of the sequence described in this study are shown in *Table 2*.

Table 2. The lithological description of the sequence of Nádas Lake (*Jakab* and *Sümegi*, 2005)

Depth (cm)	***Troel-Smith* (1955) system**	**Description**
0–40	Tb4 (Sphag.)	*Sphagnum* peat
40–110	Dg2Th1Tb1(Sphag.)	*Sphagnum* peat mixed with limus detritus, made up mostly of *Phragmites* (40–80 cm) and *Typha* rhizomes (80–100 cm)
110–130	–	Water
130–134	Dg2Tb1Th1	Burnt, charcoal rich peat layer with *Phragmites* rhizomes
134–255	Ld3Sh1 Tb+(Sphag.)Th+Tl+	Dark brown eutrophic lacustrine deposits (clayey silt) with varying organic content, large amount of wood fragments at 225 cm
255–277	As3Ld1 Th+Gs+(min.)	Pale yellow, brownish-grey slightly laminated silty clay with yellow spots
277–295	Ld3Sh1Tb+(Sphag.)Th+Gs+(min.)	Brownish-grey and pale yellow clayey silt with yellow spots
295–300	As3Ld1Gs+(min.)	Transitional layer
300–340	As3Ag1Gs+(min.)	Greenish-grey, clayey silt with frost marks (oligotrophic lacustrine deposists)

4.2. Geochemistry

A distinctive elemental and lithological stratigraphy was identified in the studied core sequence, which can serve as a potential record of paleohydrological and paleoecological history of the catchment basin of the Nádas Lake. According to the retrieved geochemical data (*Majkut*, 2009), 6 geochemical zones (*Table 3*) developed in the sediment profile of the core at Nagybárkány (*Fig. 2*).

Table 3. The geochemical zones and results from core sequence of the Nádas Lake (based on *Majkut* (2009))

Zone	**cm**	**cal BP years**	**Geochemical changes**
NBC-1	340–280	15,260 – 8800 late Glacial and early Holocene	The lake basin is characterized by the deposition of non-calcareous and low-organic content sediment. This sediment was predominantly inorganic (90–95%) and contained a high amount of water soluble Fe and K
NBC-2	280–240	8800 – 6000 early Holocene	The inorganic content (80–90%) decreased and there was a gradual increase in carbonate (5%) and organic (10–15%) content. The water soluble Fe, K content decreased, while the level of water soluble Ca, Mg input prior to this increase, indicating that the transformation of the vegetation continued and deciduous forest spread around the lake basin
NBC-3	240–190	2000 – 1500 Antiquity	There is a sudden upward decrease in the inorganic content of the deposits from the depth of 240 cm upwards, with an increase of the organic matter from the previous 10–15% to 70–80%. Elements to increase the level of included water soluble Ca and Mg suggest authigenic changes within the catchment (*Dániel*, 2004).
NBC-4	190–130	1500 – 700 Dark Age and early Middle Age	There is a gradual decrease in the organic content and water soluble Ca, Mg content accompanied by an increase in the inorganic content with water soluble Na content between 190–130 cm of the core profile. Previous studies (*Dániel*, 2004) have indicated that an increase of the abundance of these elements is indicative of both physical and chemical weatherings associated with soil erosion and human impact
NBC-5	110–40	700 – 0 late Middle Age and Industrial Age	A gradual increase in the organic content indicates decreasing soil erosion and human influences around the lake catchment basin. The water soluble Na, K, Ca, Mg content increased gradually in this zone. The observed composition of these elements may refer to the development of a floating mat, or a moss blanket on the water surface
NBC-6	40–0	Last 50 years	There is a rapid increase in the amount of water soluble Ca, Mg, K, and Na, as well as the organic content in this zone with peak values in the entire profile. According to the observed chemical composition of this zone, the emergence of a closed peat layer with mosses and the formation of a small peat-bog could have been inferred for the last 50 years

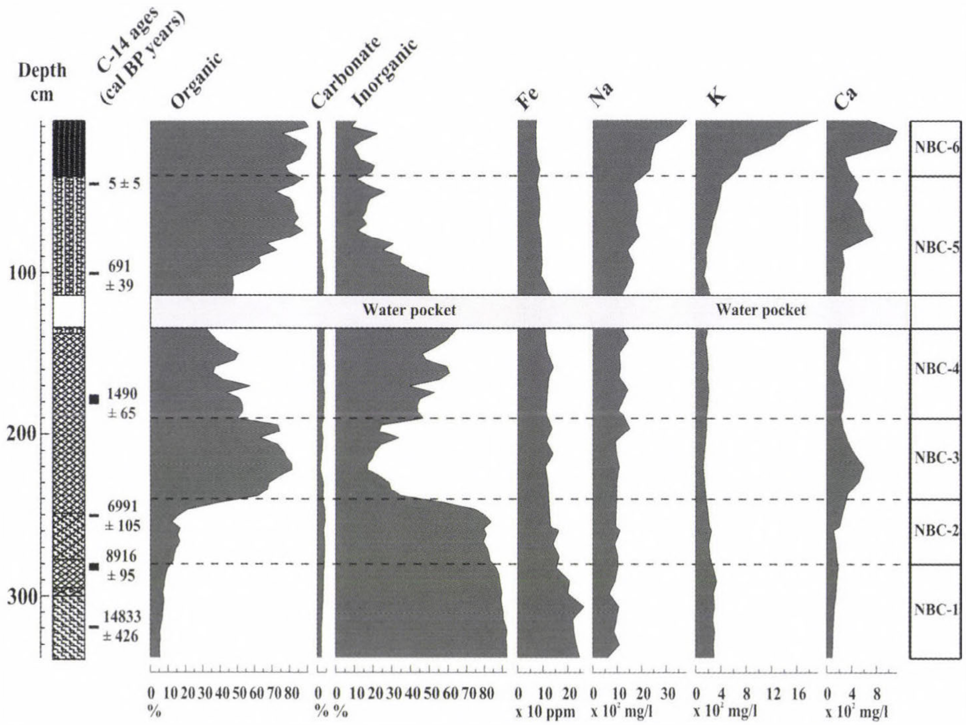


Fig. 2. Results of geochemical analyses (*Majkut,* 2009).

4.3. *Macrofossils*

The macrofossil zones are shown in *Table 4*. The profile was divided into nine zones on the basis of the analyses. The distribution of 15 most important peat components in the studied samples was evaluated using multivariate statistical methods in order to elucidate the major ecological, hydrological gradients of the individual macrofossil zones (*Jakab* and *Sümegi*, 2005). The ordination of variables (peat components) and objects (sediment samples) are depicted in *Figs. 3* and *4*.

Table 4. Macrobotanical zones and results from core sequence of Nádas Lake (based on *Jakab* and *Sümegi* (2005))

Zone	cm	cal BP years	Macrobotanical changes
NBM-1	340–288	15,260 – 10,000 late Glacial and early Holocene	The macrofossil concentration was rather low in the lower silty sediment which is poor in organic matter, suggesting high water level, oligo-mesotrophic water quality, and low vegetation cover. A narrow belt or patches of reed-beds probably lined the lakebed

Table 4 (continued)

Zone	cm	cal BP years	Macrobotanical changes
NBM-2	288–272	10,000 – 8000 early Holocene	The macrofossil concentration increased from 288 cm and reflected lower water level and mesotrophic water quality. The reed-bed at the edge of the lakebed probably formed a continuous belt by this period
NBM-3	272–247	8000 – 6000 mid-Holocene	The macrofossil concentration and the number of *Phragmites* decreased at 270 cm, marshland and bog species disappeared, suggesting a rise in the water level. In the second part of the zone, after 7000 cal BP, the macrofossil concentrations and the amount of *Phragmites* again increased, parallel to the renewed appearance of various *Sphagna* and moss species. These changes reflect another decrease in the water level and the spread of wetland vegetation
NBM-4	247–193	2000 – 1500 Antiquity	The radiocarbon measurements of the sediment samples between 187–176 cm indicated a hiatus of roughly 4400 years at the beginning of the zone. The extrapolation of the measurements suggest that this sediment hiatus developed around 2000 cal BP, during the Imperial Age, when the area was probably settled by Celtic man, who probably deepened the bog which had evolved by then
NBM-5	193 –103	1500 – 700 Dark Age and early Middle Age	The concentration of *Phragmites* rhizomes was quite high at the beginning of the zone, but declined continuously, parallel to the spread of *Typha*. The transition is marked by the lakebed's brief desiccation at 160 cm, with the significant increase of *Sphagnum squarrosum* peat-moss. The water quality was meso-eutrophic, changing to eutrophic from 160 cm. Between 130–110 cm there was a water pocket
NBM-6	103 –78	700 – 400 late Middle Age	The macrofossil concentration in this zone was extremely high. Many trees fell into the lakebed. The charcoal concentration also shows high values, reflecting the intensive exploitation of the environment. Thus, this zone represents the lake/bog transition
NBM-7	78 – 68	400 – 200 late Middle Age	A genuine floating mat phase
NBM-8	58 – 33	200 – 0 Industrial Age	A *Sphagnum* bog (*Phragmiti communis-Sphagnetum*) developed in consequence of oligotrophication in the sampling area
NBM-9	33 – 0	Last 50 years	The *Sphagnum*-bog is replaced by a *Sphagnum* willow swamp in the last zone

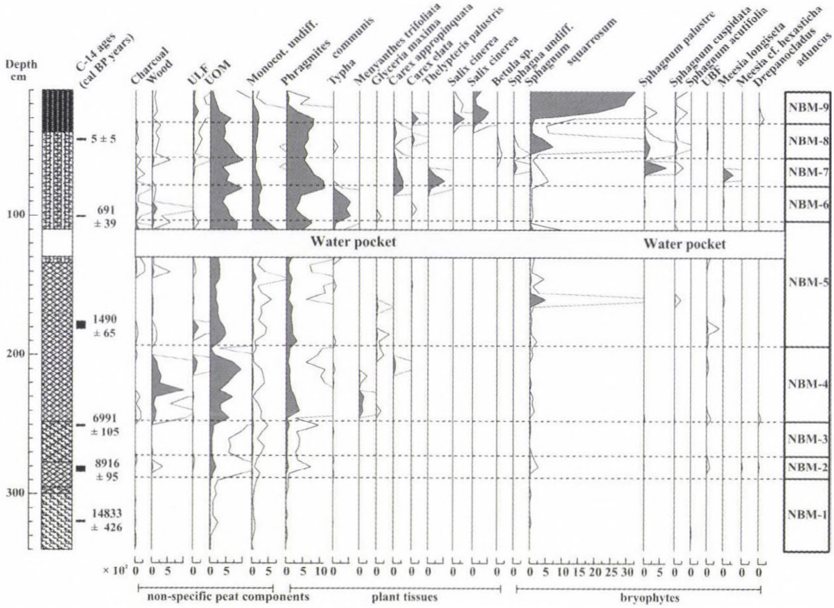


Fig. 3. Fossil plant tissues, mosses (pc cm^{-3}), and seeds (pc cm^{-3}) from Nádas Lake at Nagybárkány (*Jakab* and *Sümegi*, 2005).

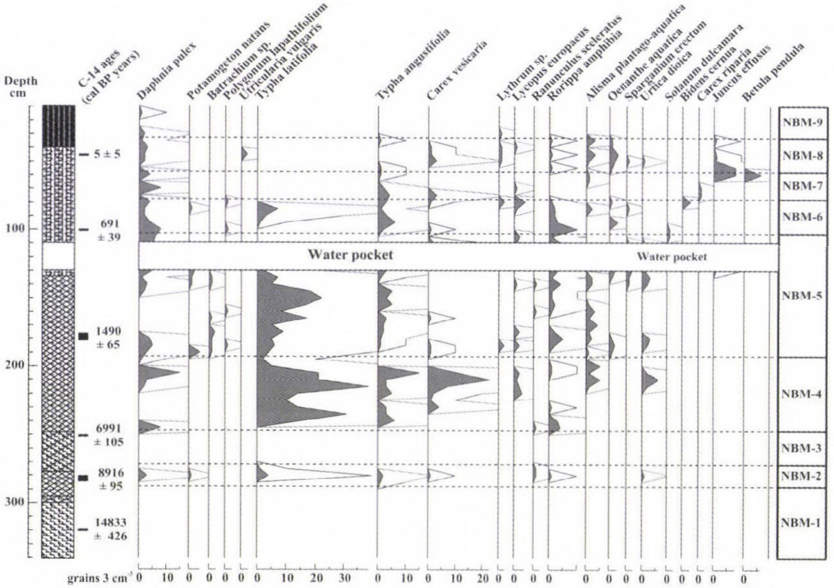


Fig. 4. Fossil plant tissues, mosses (pc cm^{-3}), and seeds (pc cm^{-3}) from the Nádas Lake at Nagybárkány (*Jakab* and *Sümegi*, 2005).

4.4. Pollen analysis

Samples taken between the depths of 340 and 0 cm yielded material suitable for evaluation. A summary of pollen analytical results is depicted in *Fig. 5*. *Table 5* shows the pollen zones of the lake Nádas.

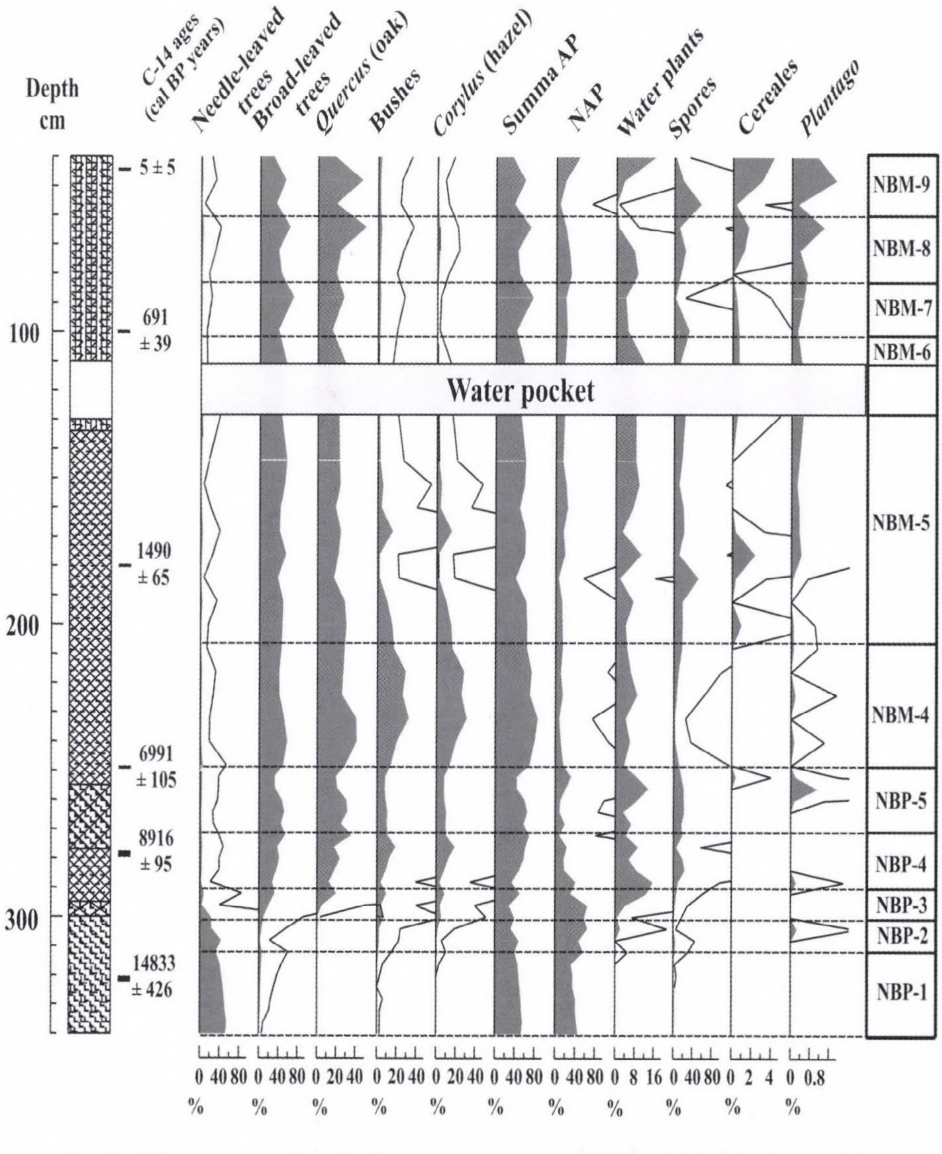


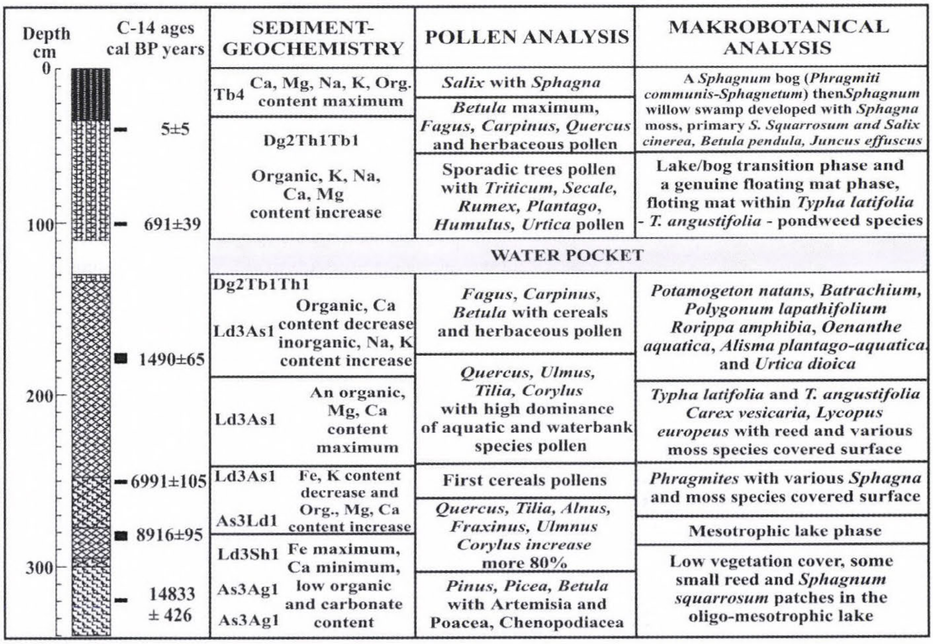
Fig. 5. Pollen zones and results from core sequence of Nádas Lake (based on *Juhász* (2005) and *Juhász et al.* (2004) (selected taxa)).

Table 5. Pollen zones and results from core sequence of Nádas Lake (based on *Juhász* (2005) and *Juhász et al.* (2004))

Zone	**cm**	**cal BP years**	**Pollen composition changes**
NBP-1	340–312	15,260 – 12,000 late Glacial	During the late Glacial, the surrounding hill slopes were covered by a mixed taiga vegetation with scattered patches of forest and steppe
NBP-2	312–304	12,000 – 10,000 transition	Open mixed taiga forest developed within *Pinus, Picea, Betula, Juniperus, Quercus* trees and *Corylus* scrub
NBP-3	304–292	10,000 – 9000 early Holocene	A species-rich mixed oak woodland appears early in this zone. There is a major decrease in the amount of pine at the beginning of the zone
NBP-4	292–272	9000 – 8000 early Holocene	A rapid spreading of *Fagus* and *Ulmus* can be traced within the newly developed mixed oak woodland accompanied by a gradual retreat of coniferous and steppe elements. The arboreal flora is dominated by oak and hazel with minor amounts of conifers and birch
NBP-5	272–248	8000 – 6000 mid-Holocene	The dominant elements of the flora in this zone are oak and hazel together with beech. Elm comprises the minor component of the flora. Evidence of the first human impacts was found in this zone. Selective logging of the woodlands is responsible for the change in the forest
NBP-6	248–192	2000 – 1600 Antiquity	In this zone, a mixed oak woodland was reestablished containing elements of hazelnut and scattered stands of *Fagus* and *Carpinus*. However, this woodland is characterized by a more closed canopy than the one present in the previous zone
NBP-7	192–136	1600 – 1000 Migration (Dark) Age	Besides the general dominance of oak, there is a sudden increase in the proportion of beech and hornbeam. The increased abundance of NAPs marks the gradual opening of the canopy from about 168 cm upwards. The presence of numerous weeds and cereals marks an intensive human activity in the analyzed area
NBP-8	104–72	900 – 300 Middle Age	The pollen profile points to the development of a closed canopy woodland with such dominant elements as *Salix* (40%) and *Quercus* (30–40%), together with *Fagus* and *Carpinus*. Other arboreal pollen (AP) types are rare. The presence of numerous weeds (*Plantago lanceolata* and *Centaurea cyanus*) and cereals marks an intensified human activity in the area
NBP-9	72–40	300 – 0 Industrial Age	The top of the pollen profile by *Juhász* (2005) is characterized by the development of an altered closed oak woodland with a presence of such AP species as beech and *Carpinus*
NBP-10	40–0	Last 50 years	Every 0.8 cm interval was analyzed for pollen. The pollen composition suggests forest regeneration process started around the peat-bog system

4.5. *Paleoecological zones*

According to the retrieved sedimentological, geochemical, pollen, and macrobotanical data, 6 paleoecological evolution phases developed in the sediment profile of the core at the lake Nádas (*Fig. 6*).



SEDIMENT-GEOCHEMISTRY	POLLEN ANALYSIS	MAKROBOTANICAL ANALYSIS
Tb4 Ca, Mg, Na, K, Org. content maximum	*Salix* with *Sphagna*	A *Sphagnum* bog (*Phragmiti communis-Sphagnetum*) then*Sphagnum* willow swamp developed with *Sphagna* moss, primary *S. Squarrosum and Salix cinerea, Betula pendula, Juncus effuscus*
Dg2Th1Tb1 Organic, K, Na, Ca, Mg content increase	*Betula* maximum, *Fagus, Carpinus, Quercus* and herbaceous pollen	
	Sporadic trees pollen with *Triticum, Secale, Rumex, Plantago, Humulus, Urtica* pollen	Lake/bog transition phase and a genuine floating mat phase, floting mat within *Typha latifolia* - *T. angustifolia* - pondweed species
WATER POCKET		
Dg2Tb1Th1 Ld3As1 Organic, Ca content decrease inorganic, Na, K content increase	*Fagus*, *Carpinus*, *Betula* with cereals and herbaceous pollen	*Potamogeton natans, Batrachium, Polygonum lapathifolium Rorippa amphibia, Oenanthe aquatica, Alisma plantago-aquatica* and *Urtica dioica*
Ld3As1 An organic, Mg, Ca content maximum	*Quercus, Ulmus, Tilia, Corylus* with high dominance of aquatic and waterbank species pollen	*Typha latifolia* and *T. angustifolia Carex vesicaria, Lycopus europeus* with reed and various moss species covered surface
Ld3As1 As3Ld1 Fe, K content decrease and Org., Mg, Ca content increase	First cereals pollens	*Phragmites* with various *Sphagna* and moss species covered surface
	Quercus, Tilia, Alnus, Fraxinus, Ulmnus Corylus increase more 80%	Mesotrophic lake phase
Ld3Sh1 As3Ag1 As3Ag1 Fe maximum, Ca minimum, low organic and carbonate content	*Pinus, Picea, Betula* with Artemisia and Poacea, Chenopodiacea	Low vegetation cover, some small reed and *Sphagnum squarrosum* patches in the oligo-mesotrophic lake

Fig. 6. Results of sedimentological, geochemical, pollen, and macrobotanical analyses.

4.5.1. *The first paleoecological phase, from late Glacial to early Holocene periods*

The lake base sediment is characterized by the deposition of non-calcareous and low-organic content sediment during the late Glacial and early Holocene periods. This sediment was predominantly inorganic (90 – 95%) and contained a high concentration of the water soluble Fe and K, and low concentration of water soluble Ca and Na.

The macrofossil concentration was rather low in the lower silty sediment which is poor in organic matter, suggesting high water level, oligo-mesotrophic water quality, and low vegetation cover. A narrow belt or patches of reed-beds probably lined the lakebed. The radiocarbon measurements indicated that this zone evolved at the time of the late Glacial up to the Pleistocene/Holocene transition. Rough peat-moss, *Sphagnum squarrosum*, a characteristic feature of the bog's recent vegetation, was already present at this time, even if in minimal amounts. The presence of peat-moss belonging to the *Acutifolia* section is noteworthy, coming from the damp soil of the surrounding coniferous forests.

During the late glacial and up until 10,000 cal BC, a coniferous forest steppe of Scots pine, spruce, and birch (*Pinus, Picea, Betula*) with several steppe elements surrounded the Nádas Lake at Nagybárkány. Pollen from the trees accounted for >50–60% of the total pollen with the remaining percentage composed of steppe elements such as the grasses (Gramineae), Chenopodiaceae, and *Artemisia.* The pollen compositions suggest that a cool climate phase developed around the catchment basin of Nádas Lake during the last phase of the Ice Age. Between 10,000 – 7000 cal BC, a dramatic change developed in the late-glacial boreal, type forest around the lake. There was a rapid decline in all dominant needle-leaved trees (*Pinus*, *Picea*) and an increase in the deciduous woodland elements. This deciduous woodland was composed of *Quercus, Tilia, Fraxinus, Alnus, Ulmus,* and *Corylus* and occurred for more 80% of the total pollen. This early postglacial diverse deciduous forest then persisted until anthropogenic activity effected the woodland at about 6000 cal BC. This pollen composition change indicates that a drastic climatic change developed during the early postglacial phase and the relative warm – rainy climatic Holocene climate was stabilized in the analyzed region.

4.5.2. The second paleoecological phase, mid-Holocene period

Up to the mid-Holocene, the inorganic content (80–90%) decreased and there was a gradual increase in carbonate (about 5%) and organic (10–15%) content. The water soluble Fe, K content decreased, while the level of water soluble Ca, Mg input prior to this increase indicates that the transformation of the vegetation continued and deciduous forest elements spread around the lake basin.

The macrofossil concentration increased from 288 cm. The number of *Phragmites communis* rhizomes and *Sphagnum squarrosum* leaves increased. *Typha angustifolia* and *Typha latifolia* made their appearance, together with the seeds of plants typical for reed-beds (*Ranunculus sceleratus, Rorippa amphibia, Alisma plantago-aquatica*) and *Daphnia* ephippiums. Bryophytes include the peatmoss *Sphagnum palustre* and other various mosses (*Drepanocladus aducus, Meesia* cf. *hexasticha*). The macrofossils reflect lower water level and mesotrophic water quality. The reed-bed at the edge of the lakebed probably formed a continuous belt by this period. The macrofossil concentration and the number of *Phragmites* decreased at 270 cm, and marshland and bog species disappeared, suggesting a rise in water level. In the second part of this zone, after 7000 cal BP, the macrofossil concentrations and the amount of *Phragmites* again increased, parallel to the renewed appearance of various *Sphagna* (*Sphagnum squarrosum, S. cuspidata, S. palustre*) and moss species

(*Drepanocladus aducus*). These changes reflect another decrease in the water level and the spread of wetland vegetation.

At approximately 5500 cal BC, the structure of the woodland altered once again with a large decline in the woodland pollen diversity, parallel with an increase of open gorund herbaceous types and an occurrence of cereal pollen. This change usually associated with anthropogenic activity. These results are consistent with archaeological data that has indicated development of Liner Pottery Culture within the Carpathian Basin at this time (*Kalicz* and *Makkay*, 1977). Some localities of this culture can be found around the analyzed region (*Bácsmegi* and *Fábián*, 2005).

4.5.3. The third paleoecological phase, Imperial Age

There is a sudden upward decrease in the inorganic content of the deposits from the depth of 240 cm upwards, with an increase of the organic matter from the previous 10–15% to 70 – 80%. Elements to increase the level of included water soluble Ca and Mg suggest authigenic changes within the catchment (*Dániel*, 2004). Probably Ca, Mg acceptor water plants, such as *Typha* and *Phragmites* colonized the analyzed catchment basin and the increase of the content water soluble Ca, Mg originated from the remains of these plants.

The macrofossil concentration suddenly increased at the beginning of the zone, with strikingly high UOM values, indicating an eutrophic marshland environment. The *Phragmites* cover expanded significantly over the lakebed. The zone contained high amounts of the leaf sheat epidermis of bogbean (*Menyanthes trifoliata*), which probably grew at the edge of the reed-bed facing the open water or in hollows. This section of the zone contained *Sphagnum squarrosum*. Reed declined in the second half of the zone, parallel to the expansion of bulrush (*Typha latifolia* and *Typha angustifolia*). This period is characterized by *Carex vesicaria* and various moss species (*Amblystegium serpens, Calliergonella cuspidata, Drepanocladus aduncus*). *Daphnia* ephippiums occurred in high numbers, and the spread of eutrophic marshland species, such as *Lycopus europaeus, Rorippa amphibia, Alisma plantago-aquatica*, and *Urtica dioica* could be noted. The macrofossils indicate lower water level and meso-eutrophic conditions at the beginning of the zone, and eutrophic conditions from ca. 1700 cal BP.

The radiocarbon measurements of the sediment samples between 187–176 cm indicated a hiatus of roughly 5000 years at the beginning of the zone. The extrapolation of the measurements suggest that this sediment hiatus developed around 1700 cal BP, during the Imperial Age, when the area was probably settled by Celtic or/and German groups, who probably deepened the peat-bog, which had evolved by then.

The closing of the forest canopy can be linked to the sudden increase of hazel (*Corylus*) from 15 to 30% and to the constantly high values of oak

(*Quercus*) in the first part of the zone. This is followed by the decline of hazel, while lime (*Tilia*) and elm (*Ulmus*) maintain a continuous presence, parallel to the re-appearance of *Fagus* and *Carpinus* at the end of the zone. The herbaceous vegetation has very low values, with a low amount of pollen grains. However, almost all taxa of the previous zone are present, even if only sporadically, but only grasses (Poaceae) and mugwort (*Artemisia*) have a continuous curve. Typical species of the wet zones, such as *Ranunculus*, *Lysimachia*, Apiaceae, can also be noted. The most important change in the local vegetation is the disappearance of *Sphagnum* moss with a very sharp decrease in the species of the earlier bogland vegetation, such as *Typha/Sparganium*, the Pteridophytes with Monolete spores (*Thelyptheris palustris*) and aquatic species (*Nuphar*, *Butomus*, *Potamogeton*).

4.5.4. The forth paleoecological phase, Migration Age

There is a gradual decrease in the organic content and water soluble Ca, Mg content accompanied by an increase in the inorganic content with water soluble Na content between 190–130 cm of the core profile. Previous studies (*Mackereth*, 1966; *Engström* and *Whright*, 1984; *Dániel*, 2004) have indicated that an increase of the abundance of these elements is indicative of both physical and chemical weatherings associated with soil erosion and human impact. The increase of the water soluble Na may indicate a drop in lake level as well during this phase.

The macrofossil concentration declined slightly in this zone. The concentration of *Phragmites* rhizomes was relatively low. Various pondweed species (*Potamogeton natans, Batrachium sp., Polygonum lapathifolium*) made their appearance, suggesting a relatively higher water level. *Sparganium erectum* became typical. The reed-bed was quite species rich, with species such as *Lycopus europaeus*, *Lythrum* sp., *Ranunculus sceleratus*, *Rorippa amphibia*, *Alisma plantago-aquatica*, *Oenanthe aquatica*, and *Urtica dioica*.

The concentration of *Phragmites* rhizomes was quite high at the beginning of the zone, but declined continuously, parallel to the spread of *Typha*. The transition is marked by the lakebed's brief desiccation at 160 cm, with the significant increase of *Sphagnum squarrosum* peat-moss. The water quality was meso-eutrophic, changing to eutrophic from 160 cm. Between 130–110 cm there was a water pocket. Between 110–100 cm, the number of *Phragmites* rhizomes increased significantly, suggesting that the extent of the open water diminished and that reed-beds also covered the sampling location. *Typha* (rhizome) appeared at the sampling location, although to a lesser degree only. The peak of *Rorippa amphibia* similarly indicates the decrease of the water level.

This zone is characterized by the opening up of the forest canopy and the increase of herbaceous elements. *Quercus* shows relatively constant values throughout the zone, while *Tilia* and *Ulmus* decline to very low values, parallel to the sudden rise of beech (*Fagus*) and hornbeam (*Carpinus*) at the beginning of the zone. *Betula* develops again in the forest with a constant level, except for a temporary minimum at 168 cm, while *Corylus* has a temporary maximum, followed by a decline to its previous level. *Alnus*, the typical taxa for the marginal zone of the peat-bog, is continuously present with low values, while *Fraxinus* shows a sporadic presence. Agricultural activity is reflected by the presence of cereals, *Plantago lanceolata*, *Centaurea cyanus*, and some nitrophilous taxa (*Urtica*) in this zone.

4.5.5. The fifth paleoecological phase, from Middle Age until 20th century AD

A gradual increase in the organic content indicates decreasing soil erosion and human influences around the lake catchment basin. The water soluble Na, K, Ca, Mg content increased gradually in this zone. The observed composition of these elements may refer to the development of a floating mat, or a moss blanket on the water surface.

The macrofossil concentration in this zone was extremely high. Many trees fell into the lakebed. The charcoal concentration also shows high values, reflecting the intensive exploitation of the environment. The expansion of bulrush at the sampling location can be noted (increase of *Typha* rhizomes), and the proportion of *Typha angustifolia* was higher than previously. *Typha angustifolia* gradually replaces *Typha latifolia*, indicating paludification and higher water level. This zone can be regarded as the first stage in the development of the present-day bog, when its central part was covered by floating bulrush mat at the expense of pondweed communities. It seems that the reed-bed broke loose from the sediment in consequence of rising water levels, leading to the formation of a floating mat. As a result of intensive oligotrophication, a floating reed swamp (*Phragmitetum communis thelypteridetosum*), then a *Sphagnum* bog (*Phragmiti communis-Sphagnetum*) developed in the sampling location with *Carex riparia* and *Carex appropinquata*. The zone is characterized by abrupt changes, reflecting further oligotrophication. There is a large-scale increase in marsh fern (*Thelypteris palustris*), which later decreases, parallel to the expansion of a rare moss, *Meesia longiseta*. Following the decline of the latter, the values of peat-mosses, especially of *Sphagnum palustris*, *Sphagnum squarrosum* increases. The high values of *Juncus effusus* are also characteristic for this zone.

According to the pollen composition (*Juhász*, 2005), this zone is characterized by a relatively closed vegetation cover. *Salix* is the dominant taxon, accounting for 40% of the total pollens. *Quercus* has high values too and shows a rise parallel to the decline of willow. Other tree taxa show a sporadic presence, except for beech (*Fagus*) and hornbeam (*Carpinus*), which are present with minor, but continuous curves, together with *Betula* and *Corylus*. Anthropogenic taxa are also present: the pollen grains of *Plantago lanceolata*, *Rumex*, and cereals (*Triticum* and also *Secale*) were identified. Cyperaceae, *Typha/Sparganium*, and aquatic species (*Lemna*, *Potamogeton*, *Butomus*) are present sporadically. The closing up of the forest canopy can be noted, with a dominance of *Quercus* and *Betula*.

4.5.6. The sixth paleoecological phase, 20th century

There is a rapid increase in the amount of water soluble Ca, Mg, K, and Na, as well as the organic content in this zone with peak values in the entire profile. According to the observed chemical composition of this zone, the emergence of a closed peat layer with mosses and the formation of a small peat-bog could have been inferred for the last 50 years.

The uppermost section of the pollen sequence is also dominated by oak, with some beech and hornbeam. Willow (*Salix*) is present and rises towards the end of the zone; the herbaceous vegetation (Poaceae and anthropogenic taxa) increases and dominates the landscape. The *Sphagnum*-bog is replaced by a *Sphagnum* willow swamp in the last zone. The recent expansion of *Salix cinerea* could be noted in the area (see *Fig. 1*). The number of reed species and reed-beds decreases, parallel to the increase of wood remains (wood, ULF). *Salix cinerea* remains (leaves, roots) are quite frequent. The values of *Sphagnum squarrosum* increase significantly.

Plantago lanceolata, Cerealia, *Urtica*, and *Rumex* have relatively high values. *Phragmites*, *Typha/Sparganium* are present in the local vegetation, together with *Thelypteris palustris*, although *Sphagnum* moss has lower values than in the previous zones. The very end of the pollen sequence was dated to 0 ± 60 uncalBP (1955 +/– 5 calAD), indicating a strong human impact on the vegetation cover, with high proportions of cereals, *Rumex*, and *Plantago lanceolata* among the herbaceous taxa. The size of the oak forest decreases and willow re-appears.

5. Discussion

5.1. Initial pond phase (late Glacial to mid-Holocene: 15,000 – 5000 cal BC yr)

The first phase of the analyzed region development, lasting until the mid-Holocene, was determined by relatively stable trophic conditions and smaller fluctuations in the water level. The water level somewhat decreased at ca. 6800 cal BC and the start of peat-bog initiation can be noted, probably in consequence of the onset of a warmer and drier climate. Species referring to paludification like *Sphagnum squarrosum* and *S. palustre* also turn up here. On the testimony of the pollen profiles (*Juhász et al.* 2004), this phase coincided with the appearance of thermophilous species rich oak forests. The water level again rose at 6000 cal BC and decreased after 5000 cal BC, enabling the expansion of reed-beds.

Between 15,000 – 5000 cal BC, inputs of K and Mg into the basin suggest that erosion of the slopes surrounding the lake basin was occurring and trophic conditions of the formed lake was oligotrophic (*Mackereth*, 1966; *Engström* and *Whright*, 1984; *Engström* and *Hansen*, 1985). The high content of water soluble Fe suggests that a combination of acidic silicate rich bedrock, coniferous trees and cool late Glacial climatic conditions resulted in podzol soil formation around the catchment basin. The deposited lacustrine sediments embedded minor pebbles as well till around 6000 cal BP in varying quantities. These must indicate abrasion of the shore in the lack of a closed reed belt.

According to the findings of geochemical analysis, the early Holocene lacustrine phase differed significantly from the previous pond stage in sedimentary, chemical composition and temperature conditions. While the earlier, late Glacial and lateglacial/postglacial transition lake environment can be characterized by sedimentation in a cold and oligotrophic water lacking Ca content and low vegetation cover, the early Holocene paleohydrological stage can be described as being relatively rich in Ca, with high carbonate and organic content and with a vegetation typical of easily warming water. The amount of Ca increased from about 100 to 200 ppm. Changes in the chemical composition refer to intensified erosion around the catchment basin and the transformation of the late Glacial oligotrophic lake into an open mesotropic lake phase. The increasing level of overland soil erosion into the catchment basin must have developed under increasing human impacts (e.g., woodland grazing). As shown by archeological data (*Bácsmegi*, 2005; *Bácsmegi* and *Fábián*, 2005), Neolithic Age communities settled around the analyzed region between 5500 – 5000 cal BC. These prehistoric human communities transformed their forested environment to open surface for arables and pasturelands. This type of human disturbance might trigger intensified soil erosion into the catchment basin.

5.2. Climate-driven mire phase (late Holocene: 0 – 1300 cal AD)

Abrupt geochemical changes indicate the emergence of a sedimentary hiatus in the catchment basin. It seems to us that this geological layer discordance formed by human impact. Results of the radiocarbon measurements are presented in *Table 1*, from which a sedimentary hiatus is apparent between 187–176 cm. This hiatus associated with a thin layer of burnt macrocharcoals. This, and a subsequent change in lacustrine stratigraphy from mesotrophic lake to reed peat show ca. 4000 years difference in age between adjacent samples. According to radiocarbon and sedimentological data of the core profile, this event coincides with a peat cutting in the Imperial Age when Barbarian groups (Celts, German tribes) occurred around the lake catchment basin (*Vaday,* 2005). Probably, one of these antique tribes cleaned the analyzed pond around 20-30 cal AD (*Figs. 5* and *6*). Then, after this cleaning procedure, a mass of water plants covered the artificially transformed pond surface (*Fig. 6*).

The *Phragmites* concentration in the sediment decreased during warmer periods in the Imperial Age and Middle Ages, parallel with an increase of *Typha* seeds and *Daphnia ephippia*. This reflects a competitive situation, characterized by alternating dominances of reed and bulrush in the lakebed. Reed and bulrush are both competitive species under favorable conditions.

In the pollen record, this phase is characterized by the opening up of the forest canopy and the increase of herbaceous elements (*Juhász*, 2005). It would appear that during periods of greater solar activity, the lake received more light, in part owing to the retreat of species forming higher and more closed forest canopy, like *Fagus* or *Carpinus*.

In order to shed light onto the interrelations of vegetation changes and climate change, the model of *Davis et al.* (2001, 2003) was adopted in our work. According to this model, some climatic changes, drier, wetter and warmer (*Table 6*), and cooler phases developed during last 2000 years (*Figs. 7* and *8*). One of the most important warmer climatic phases formed in the Imperial Age, then in the late Migration Age, and early Middle Age. The lake is fringed by high, steep slopes in the south and south-east, from where the high trees cast a shadow over the greater part of the lake. The expansion of phyto-planktons at the time of greater solar activity is indicated by an increase of *Daphnia* feeding on them. The expansion of phytoplankton leads to the development of looser sediments, encouraging the spread of *Typha*. The beginning and close of the Medieval Warm Period saw the maximum of solar activity (*Bradley et al.*, 2003). The end of this warm period at about 1250 AD was marked by the so-called medieval solar activity maximum, which caused serious droughts in Europe and North America. The sudden expansion of *Sphagnum squarrosum* can be noted at the time of the two maximums. *Phragmites* and *Typha* both declined at around 800 AD, suggesting the brief desiccation of the bed, when peat-moss temporarily covered the entire lakebed .

In the pollen record at ca. 600 cal AD, *Cyperaceae* and aquatic species (*Nuphar*, *Nymphea*, *Lemna*, *Butomus*) have a temporary minimum as well (*Juhász*, 2005). The water level decreased for a longer period of time around 1200–1300 cal AD, enabling the expansion of the reed-bed over the lake's entire surface and causing the reduction of open water. According to the geochemical data between 500–1300 cal AD, a drier and maybe a warmer phase formed (*Fig. 4*). The increase of the water soluble Na content shows that a decrease of the pond water level might have developed during this phase.

The referred period was coeval with one of the major crisis periods of medieval Hungary, the invasion of Mongolian tribes dated between 1241 and 1242. From the written record we do know that some chronicle writers blamed the Mongolian invasion of the country on the severe cold weather, while others related it to the unusual droughts hampering Europe during the summers of the 13th century. *Barber et al.* (2000) declared this period as the driest of the past 2000 years in the history of Europe. In Hungary, the extremely cold winter of

1241 was devastating regarding the political and economic fate of the country, when the river Danube was completely frozen enabling the Mongol tribes to safely cross the river and destroy the settlements of Transdanubia as well. As *Kiss* (2000, 2003) clearly stated, the controversies lying in the contrast of the extremely cold winters and summer droughts can easily be resolved. A complete freezing of the river Danube was not an unusual event in Hungary preceding the river regulations on the one hand. On the other hand, the summer droughts which might have struck Hungary as well at the time must have reinforced the devastating effects of famine attributable to the war itself as well. This warm and dry weather must have contributed to a complete desiccation of the Nádas Lake of Nagybárkány, when reed coverage must have extended to the entire lacustrine basin.

Table 6. Climatic parameters changes according to the pollen-based paleoclimatic reconstruction (used by pollen data based paleoclimatic reconstruciton methods of *Davis et al.* (2001))

Climatic parameters/Age AD	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**	**1000-1100**
MTCO (°C) The mean temperature of the coldest month	–2.0	–1.8	–2.1	–2.7	–3.0	–2.2	–1.9	–1.8	–1.9	–1.8
MTWA (°C) The mean temperature of the warmest month	+19.5	+19.7	+19.6	+19.5	+19.2	+19.7	+19.6	+19.8	+19.7	+19.7
TANN (°C) Annual temperature	+ 9.0	+ 9.2	+ 9.1	+ 8.9	+ 8.9	+ 9.2	+9.3	+9.4	+9.2	+ 9.5
PANN (mm) Annula precipitation	610	620	650	600	680	660	620	630	620	550
Continentality (°C) MTCO - MTWA	21.5	21.5	21.6	22.0	22.2	21.9	21.5	21.6	21.6	21.5
Water level of the pound based on macrobotanical data	low	low	rel. high	lowest	high	high	rel. low	rel. high	low	lowest
Climatic parameters/Age AD	**1100-1200**	**1200-1300**	**1300-1400**	**1400-1500**	**1500-1600**	**1600-1700**	**1700-1800**	**1800-1900**	**1900-2000**	**today**
MTCO (°C) The mean temperature of the coldest month	–2.5	–1.8	–2.2	–3.0	–2.2	–3.3	–3.5	–3.9	–3.6	–3.5
MTWA (°C) The mean temperature of the warmest month	+19.2	+19.9	+19.4	+18.5	+19.7	+18.2	+18.5	+19.0	+19.1	+ 19.0
TANN (°C) Annual temperature	+ 9.2	+ 9.6	+ 9.2	+ 8.8	+ 9.2	+8.3	+8.5	+8.2	+ 8.7	+ 8.8
PANN (mm) Annula precipitation	570	550	600	620	600	650	650	650	660	620
Continentality (°C) MTCO – MTWA	21.7	21.7	21.6	21.5	21.9	21.5	22.0	22.9	22.7	22.5
Water level of the pound based on macrobotanical data	low	lowest	low	rel. high	low	high	high	high	highest	**regu-lated**

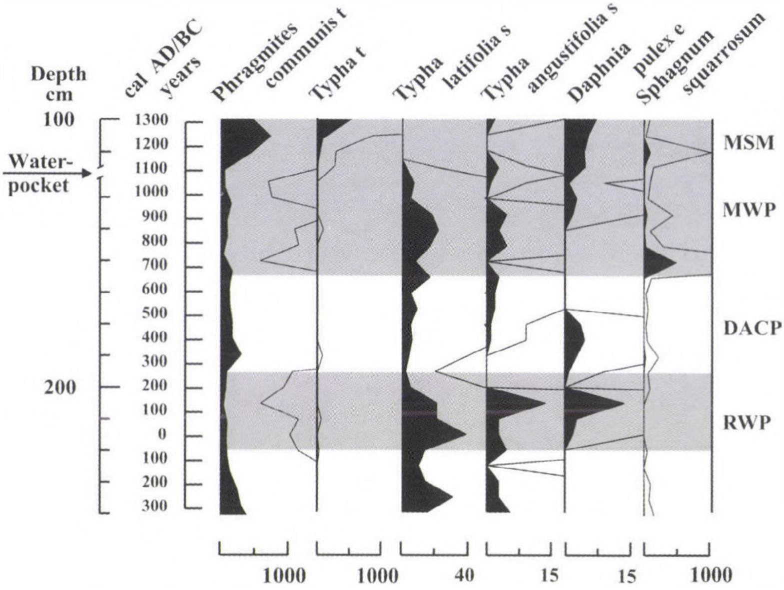


Fig. 7. Trophic fluctuations at the Nádas Lake between 330 BC and 1300 AD. The grey areas indicate periods with a warmer climate (MSM: medieval solar activity maximum; MWP: medieval warm period; DACP: Dark Ages cold period; RWP: Roman Age warm period; the interbedded water layer between 130–110 cm has been omitted).

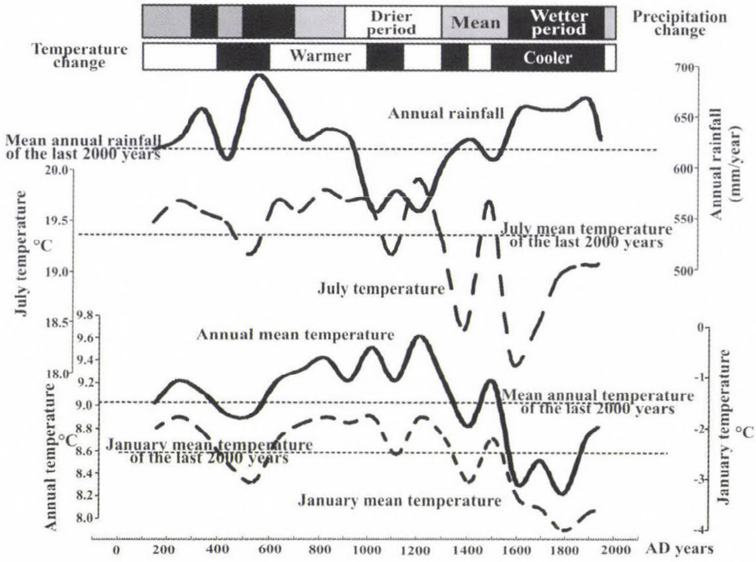


Fig. 8. Paleoclimatic changes of the last 2000 years at the Nádas Lake region reconstructed from pollen data using the method of *Davis et al.* (2001, 2003).

In the next part of the profile, there is major depositional hiatus spanning about 4400 – 4700 years. This must have emerged during the terminal part of the Iron Age, beginning of the Imperial Age around 20 –30 AD, preserving the signs of immense human impact. According to the available archeological record from the wider surroundings of the site, the area must have been controlled by Celtic herds at the time. The remains of Late Iron Age fortresses near Mátraszőlős and Kerekbikk are clear proof (*Vaday*, 2005). The area of Nádas Lake at Nagybárkány, which was a peatland at the time of the referred period, must have been systematically exploited by Celtic tribes. Peat must have been utilized in various forms ranging from fuel to litter, similarly to modern day utilizations observable in many parts of rural Ireland or Scotland (*Seymour*, 1984). An additional alternative might have been the use of the newly created ditches, which were the side-effects of peat mining, as water cisterns or reservoirs. Signs of similar activities could have been attested by Celtic tribes in the case of the Mohos Marshland at Kelemér and the Nyíres marshland of Csaroda for the periods of the late Iron Age – early Imperial Age (*Willis et al.*, 1998; *Sümegi*, 1999).

Some proxies from the referred period indicate a warming climate with perhaps a slight aridification, as seen by a concomitant increase in the amount of hazel, elm, and oak pollen grains accompanied by a retreat of lime (*Fig. 5*). In the light of this paleoenvironmental information one may assume, that the initiating peat exploitation and the artificial creation of cisterns must have been a feedback for this climatic change. Nevertheless, these activities might have been triggered by other factors as well, like a significant population growth or the foundation of a new settlement in the vicinity, not to mention a serious increase in livestock. The large proportions of macro- and micro-charcoal particles identified in the profile refer to intentional deforestation via burning, resulting in new open areas suitable for animal farming. These impacts can generally be connected to foundations of new settlements or the initiating construction of fortified settlements, around which woodland clearance was inevitable for defensive reasons (*Figs. 5* and *6*).

In the following part of the profile corresponding to the terminal part of Antiquity and the opening of the Age of Great Migrations, there is a gradual deceleration in the accumulation of organic matter in a continuously increasing trend, which was followed by alternating sudden increases and drops (*Fig. 2*). The growth period is characterized by an increase in Ca, followed by similar rises in Fe and Na. Nevertheless, when there is an increase in Fe and Na in the deposits, the ratio of Ca reaches a low. In the first part of the referred zone, there is an extremely rapid increase in the proportion of hazel pollen grains parallel with high values for oak pollen grains. Conversely, this is accompanied by a decrease in the amount of elm pollen grains and reed fragments preserved in the sediments. Afterwards, there is a very rapid decrease in the amount of oak pollen grains, reaching about two-third of their original value. Parallel with this phenomenon, large amounts of arboreal organic matter and unidentifiable organic matter appear in the deposits, accompanied by an increase in dissolved Ca as well. In the following part, oak seems to witness a slow recovery with a sudden increase in hazel pollen grains displaying a slow decrease afterwards till the end of the referred zone. All these biotic and chemical proxies seem to refer to rapid and very intensive human activities in the area. The large-scale rapid drop in oak pollen grains accompanied by an advent of lime and elm in the profile refers to selective deforestation, which must have been targeted the wood raw material itself as an ideal construction material and was not focusing on creating open areas for livestock primarily.

If the amount of available wood is proportional to changes seen in the pollen record, then one must assume a one-third decrease in the natural oak woodlands as a result of selective deforestation during the referred period, which is a very high number. Former environmental historical works speculated about the use of exploited wood in creating artificial objects within the lakebed or the exploited peatland area. This model assumes the construction of wood walls within the lakebed itself to give support to the newly formed cisterns, which seems plausible. Nevertheless, as it is seen from hard data depicted on the diagrams of *Figs. 5* and *6*, the majority of the oak stands logged down were 150-year-old at least, with a predicted volume of 800 m^3/hectar, assuming an annual growth of 8 m^3, which is a standard in forest management. This much log following the removal of branches and slicing by saw must have provided about 360 m^3 timber. The relatively small size and large proportion of retrieved timber remains call for the use of saw. If the logs were sawed into 10 cm thick, 30 cm wide and 1.5 m long timber pieces, ideal for construction of supporting walls, then for this purpose in case of a lakebed with a perimeter of 300 m, a volume of 45 m^3 timber must have been sufficient. As seen from the archeological record saw was known and utilized by late Iron Age Celtic tribes as well (*Caselli*, 1981).

The referred amount of timber could have been retrieved from an area of 1/8 hectars alone. Making predictions about the spatial extension of areas affected by logging is not an easy task. Nevertheless, the small size of the studied catchment basin (less than 100 m) and the origin of the preserved pollen grains in the deposits may help us to solve this conundrum. According to the findings of modern palynological studies in catchment basins, when the size of the basin is below 100 meters, 90% of the preserved pollen grains are of local origin with a small proportion of extralocal pollen grains (*Fig. 5*). As the largest radius of the studied catchment basin of Nádas Lake is well below this limit value, this might be rather promising in solving the above mentioned question. According to our model, the areas affected by deforestation during the referred period must have covered a radius of 300 m around the lake, reaching a maximum area of 20–30 hectars. This would suit both the spatial needs and the raw material demands of a smaller settlement with log houses and orchards, meadows, etc. As it is seen in the archeological record (*Bácsmegi* and *Guba*, 2007), people of the settlement must have been composed of Celtic groups surviving German, Dacian, and Roman attacks showing affinities to newly arriving German tribes as well. Moreover, based on the available absolute dates, the emerging settlement at the terminal part of the 4th and beginning of the 5th centuries AD might have been linked to the first appearance of Hun tribes in Central Europe, triggering the movement of lowland people to highland areas offering more safety.

After the formation of the settlement, the early period of the Age of Great Migrations (between the turn of the 4th–5th centuries AD and the terminal part of the 6th century AD) was characterized by a slow increase in the amount of oak pollen grains accompanied by the uniform accumulation of wood remains and a slow decrease in dissolved Ca in the deposits. All these imply the emergence of planned woodland management and the influences of a human group with a well-established economy for about two centuries. The use of oak woodlands in animal fodder and husbandry was a well-known established agricultural method offering efficient, cost-effective, and risk-free solutions in contrast to growing plants in arables used as fodder. Acorn has a relatively high nutrition value, with a high annual production rate of 15 tons/hectar, enabling efficient and cost-effective animal husbandry without the need of fodder plant production. As it can be seen in the pollen diagram (*Fig.5*), there is a minor peak of cereals at 200 cm corresponding to the opening of the 5th century AD, which further corroborates the permanent presence of human settlements and activities in the study area.

The next prominent change in the profile is observable at the depths of 190 and 130 cm corresponding to the period between the 6th and 9th centuries AD (*Fig. 6*). This zone is characterized by a decrease in organic and increase in inorganic components of the deposits (*Fig. 6*). The geochemical parameters also tend to be constant lacking any sudden transformations or outliers. These changes must have been triggered by a gradual retreat of reed fringing the lakebed. Nevertheless, the large amounts of wood remains as well as flue-ash in the initial part of the zone, as well as the inferred decrease in the amount of oak, hazel, lime, and elm pollen grains may indicate a smaller deforestation activity.

The presence of buttercups, known to carry toxics, can be clearly attested during the second half of the Age of Great Migrations. An increase of these plants may indicate the appearance of large livestock grazing meadows besides the survival of woodland grazing. The peak in the pollen ration of buttercups was noticed at a depth of 160 cm, followed by a gradual decrease, which must be attributed to an aridification of the climate on the one hand. On the other hand, a decrease in the importance of animal husbandry may be assumed as well. Based on the available plant macrofossils, this period is characterized by a decrease in the area of the peatland, which must be attributed to drier climatic endowments (*Figs. 7*, *8*). This transformation, however, was by no means drastic, as peat-mosses managed to survive in the area, suffering only a minor decrease. Peat-mosses are capable to thrive in areas of the Carpathian Basin, where the rate of average annual rainfall is above 550 mm. So we may assume a similar value for the referred period in our study area, corroborated by results of pollen analysis as well (*Fig. 8*), assuming a rainfall value of 630–650 mm for the period between the 6th and 9th centuries. This value is well above the average of the past two millennia (620 mm).

Conversely, as it is clearly observable in the paleoclimate diagram based on pollen data (*Fig. 5*), the referred period is characterized by elevated mean annual, January, and July temperatures. Thus, as a result of higher temperatures, evaporation must have been higher as well during the second half of the Age of Great Migrations, between the 6th and 9th centuries. As a result of the elevated evaporation rate, drier conditions must have emerged with varying intensities related to micro-morphological and geographical setting. Conversely, the higher 100-year-long environmental historical data do not refer to such a drastic climatic change during the collapse of the Avar Empire, which might be blamed for its fall, e.g., famine following an extremely dry period. This question becomes even more exciting, when our data from the referred period of the Late Age of Great Migrations is compared with those for the periods of the Hungarian Conquest, the Arpadian Age, the late Middle Ages, or the New Age.

At a depth of 144 cm there is a rapid and considerable increase in the amount of willow pollen grains, overlain by layers embedding large proportions of wood remains, flue-ash, and burnt peatland mud. This overlying horizon is characterized by a drop in willow pollen grains implying a rapid burnt-down of the area of the peatland. The advent of acidic, toxic plants and those tolerating treading as seen in the pollen record during this horizon refers to an increasing importance of animal husbandry, implying human origin of the transformation. This horizon was dated to the 10th century, possibly marking a large demand for meat produce as a result of higher population densities following the foundation of the Hungarian state. In the zone between 130 and 110 cm there is an aquatic horizon implying the emergence of floating mats in the area (*Fig. 6*). The hollow stem of reed leaning over the lakebed must have served as a natural raft for successive plant generations, providing them habitat and sufficient nutrition, enabling the emergence of floating mats. The thickness of this layered plant complex may reach such proportions, which enables the advent of trees onto the mats as well as time passes, as was the case of Nádas Lake as well.

Based on chronometric data, the emergence of floating mats must be dated between the 11th and 16th centuries, seen in the continuous and steady increase in organic components and the advent of reed, willow, and bulrush to the area connected to the natural succession of the marshland. Nevertheless, two ash and wood remain peaks in this part of the profile can clearly be correlated with a significant drop in the amount of oak pollen grains. The ash peaks correspond to drops in reed fragments implying the development of natural or artificial fires in the reed zone fringing the lakebed. The second ash peak at 96 cm with a parallel increase in the ratio of weed and cereal pollen grains indicate a larger deforestation again attributable to mixed agriculture of crop cultivation and animal husbandry in the area. As shown by the archeological record (*Zatykó*, 2005), this period was characterized by multiple periods of plot shifts, deserting population, and revivals.

The first written record of the settlement of Nagybárkány can be dated to this period at around 1220, when it was the property of the Zách clade. The climate is characterized by natural cycles with a temperature maximum and a precipitation minimum during the 13th century. This climatic transformation resulted in real dry conditions yielding the extermination of peat-mosses from the area of the lake. Peat-mosses managed to conquer the lakebed only during the 16th century. When pollen-based paleoclimatic data for the 8th and 13th centuries are compared, it becomes clear that the 13th century transformations are much more pronounced. The aridity index must have been 4 times of that inferred for the 8th century as a result of the elevated temperatures and a drastic drop of annual rainfall. Yet as it was recorded in the written historical documents, the 13th century collapse of the Hungarian Kingdom were by no means the outcome of environmental changes, but rather political ones; the military defeat of the Hungarian troops by the Mongol tribes. The inland political fights and restructuring of the feudal social and political system is explained by historians by not the extreme dry conditions characterizing the period, but rather the loss of royal power, financial problems, and the collapse of the traditional latifundium system.

Conversely, several authors emphasize the role of extreme dry climate in the collapse of the Avar Empire and the resulting inland political tensions in a period, when the aridity index was much lower, relatively negligible compared to the 13th century conditions. Some papers postulated a „*devastating drought*" accompanied by famine waves which must have affected „*the warrior nation of the half-nomadic Avars*" (*Rácz*, 2008, pp. 54–55). Conversely, the statement according to which „*the more drought tolerant Slavic tribes could have been better suited to eliminate the hardships of draughts by withdrawing near oak woodlands and using acorn as fodder in the hard times*" (*Rácz*, 2008), was turned down by our paleoenvironmental data from the Nádas Lake, as this type of landscape use was present since the Age of Great Migrations in the area. Thus, this type of landscape economy must have emerged preceding the arrival of the Slavs to the area. Our paleoenvironmental data also calls for the re-evaluation of postulations made regarding the collapse of the Avar Empire. Since social processes and disturbances can only be linked to natural catastrophes if and only if there were such catastrophes in the referred area during the referred period. Based on our data, this problem must be treated with great caution, as highly different climatic conditions must have emerged in the area than stated by numerous recent paleoenvironmental studies (*Magny et al.*, 2008).

In contrast to the previous periods, the one starting from the 16th century till today is characterized by intensified rainfall and cooler conditions, resulting in a thriving of peatland conditions in the area of the Nádas Lake at Nagybárkány. The floating mats were turned into peatmossy reeds and willow peatland. This is the period when the highest organic content (around 80 – 85%) was recorded. Nevertheless, several inorganic peaks are observable as well reflecting soil erosion from the neighboring areas as a result of recurring deforestation activities. These transformations are observable at a regular centennial scale, which can be tracked to intentional forest management. Numerous ash peaks are observable in the lower part of the zone coinciding with a halt in the expansion of reed-beds. The continuous presence of weed, buttercup, and plantain pollen grains in the record refer to permanent human activities in the area and continuous disturbances. The most dynamic advent of peat-mosses is observable in the most recent periods attributable to a deserting population in the area.

5.3. Autogenous peat-bog phase (after 1300 cal BP)

The development of the present-day bog and the commencement of peat accumulation can be dated to the end of the early Middle Age. At around 1300 AD, the number of *Typha* rhizomes increases significantly, indicating a rise in the water level and the formation of a floating mat. The hydroseries of the bog was from this point on characterized by autogenic processes, with a tendency towards a gradual oligotrophication.

Based on detailed phytogeographical studies, floating mats of *Phragmites* and *Typha* are frequent components of lake shore vegetation in Hungary. The first signs of peat-bog formation from these floating mats can be seen in a massive expansion of *Thelypteris palustris*. As time goes by, peat-mosses also turn up on the mats (*Borhidi* and *Balogh*, 1970; *Balogh*, 2000a, b). Based on the paleobotanical investigations, the bog development passed through phases characterized by *Typha* → *Thelypteris palustris* → *Meesia longiseta* → *Sphagnum* spp.. This development shares numerous similarities with the formation of two other *Sphagnum*-bogs at the Csaroda–Báb Lake (*Jakab* and *Magyari*, 2000) and Kelemér-Nagy-Mohos (*Magyari et al.*, 2001), suggesting some sort of regularity in the formation of Hungarian *Sphagnum*-bogs. *Meesia longiseta* preceding the expansion of *Sphagna* is highly interesting. The taxon *Meesia longiseta* is a unique component of the flora of the Carpathian Basin with a single occurrence recorded in Hungary from 1885 (*Boros*, 1968). According to *Hall* (1979), the appearance of *Meesia longiseta* can be linked to a distinct phase of wetland succession, characterized by the transformation of the brown moss sedge floating mat into acidic *Sphagnum*-bog. This species was observed during the secondary succession of abandoned lakes used for retting hemp. *Odgaard* (1988) reported the same for *Meesia triquetra*.

Representatives of *Sphagna* seemed to have appeared in similar quantities during the middle part of the 17th century as today, followed by a complete drop till 0 BP. Surprisingly, the taxon *Sphagnum palustre*, indicating mesotrophic conditions, was present in the largest numbers. In the pollen record *Sphagnum* reaches a maximum peak at 70%, at the same time (*Juhász*, 2005). This expansion of *Sphagnum* coincides with the coldest period of the Little Ice Age (*Rácz*, 2001), which was also the coldest time of the past 2000 years (*Fig. 7*). The Little Ice Age dates from the middle part of the 16th till the middle part of the 19th centuries (*Bradley et al.*, 2003). The most significant cooling is put to the terminal part of the 16th century, when a major drop in the average temperatures is traceable across entire Europe (*Pfister*, 1999; *Pfister* and *Brázdil*, 1999).

As shown by archeological data (*Zatykó*, 2005), the traditional Medieval Age settlement system collapsed followed by the emergence of unpopulated areas in the analyzed region during the Ottoman occupation and scattered farmstead-like settlements from the 16th century onwards. The geochemical composition and the increasing amount of charcoal indicate that the human disturbance decreased around the analyzed catchment basin in the 18th century. According to the pollen analytical data, human impact on the vegetation became more intensive (*Juhász*, 2005). There was a rapid decrease in the amount of *Sphagnum palustre* preferring mesotrophic conditions (*Daniels* and *Eddy*, 1985). A rapid expansion of *Juncus effusus* indicates eutrophication, and the quick spread of weeds. Forest management, accompanied by increased soil erosion in the study area resulted in an enrichment of plant type nutrients on the marsh. The steady expansion of *Sphagnum squarrosum* refers to the emergence of an acidophil but eutrophic peatland in the area. *Sphagnum squarrosum* relatively tolerant to high Ca, bicarbonate levels, and pH (*Clymo*, 1973), and in mineral rich habitat with a high nutrient supply grow very fast (*Kooijman*, 1993). The expanding beds of *Sphagnum squarrosum* are capable of capturing and accumulating Ca via ion exchange (*Anschutz* and *Gessner*, 1954; *Clymo*, 1963; *Kooijman*, 1993). The recorded Ca content of the embedding sediments seems to display a strong correlation with the amount of peat-moss, which is a clear sign of the excellent Ca ion bonding capacity of peat-moss. Reed is also capable of accumulating Ca in its rhizomes similarly to peat-mosses (*Kovács et al.*, 1978; *Penksza et al.*, 1994; *Podani et al.*, 1979; *Tóth* and *Szabó*, 1958).

A smaller drop in the water-level can be dated to the turn of the 15th–16th centuries, reflected by the expansion of green algae and the retreat of alder, and the rise of aquatic species and reed. A secondary reforestation following forest clearance is reflected by the expansion of hornbeam around 1500. A slight rise in the water-level and a gradual reforestation can be noted during the Ottoman period. The warmer and drier climate observed at the paleoecological sites from 9th to 14th centuries coincides with the so-called Medieval Warm Period (MWP) in Europe, which is supposed to have been characterized by a warmer and wetter climate (*Lamb*, 1977). The opening of this period can be placed between the 9th and 11th centuries with differences regarding the applied analytical methods, sources of dating, and regions (*Bradley et al.*, 2003). On the contrary to the widely accepted idea of the warmer and wetter climate of MWP, in the cases of 14 Hungarian paleoecological sites, drier climate can be noted, in spite of high amount of precipitation. It appears that the increasing evapotranspiration, following the higher temperature led to a drier climate and a drop in the water-level of the lakes. These results concerning medieval (pre-15th-century) climatic processes are among the first data derived from the medieval layer of a sediment core extracted at the Hungarian sites and call the attention to the great importance of regional studies in order to refine further the local variations of climate conditions.

6. Conclusions

The development of the bog can be divided into three main phases in the light of macrofossil analysis. The first phase spanned the late Glacial to the mid-Holocene layers. The trophic conditions in this phase were oligo-mesotrophic and mesotrophic. The water level was high, although with minor fluctuations. A hiatus of roughly 4400 years can be noted in the sediment after this phase, owing to peat-cutting during the Imperial Age. The water level decreased slightly, the trophic conditions became eutrophic, and the lake was fringed by macrophyte vegetation. This period was characterized by the fluctuation of the lake's trophic conditions. This phase can be dated to the late Holocene, lasting until the end of the early Middle Age, at the beginning of the 14th century. The last phase, spanning the period up to the present, saw the paludification of the lake and the cessation of the open water surface.

The hydroseries was characterized by autogenic processes, with taxa *Thelypteris palusris* and *Meesia longiseta* playing a key role. Peat-mosses appeared in the same quantities during the coldest period of the Little Ice Age dated to the middle part of the 17th century as today. The subsequent periods saw a temporary decrease in their amounts. Forest management, accompanied by increased soil erosion in the study area resulted in an enrichment of plant type nutrients on the marsh during the past 200 years. The steady expansion of *Sphagnum squarrosum* refers to the emergence of an acidophil but eutrophic peatland in the area. Based on our findings, changes in the paleohydrology and aquatic vegetation of the bog were mainly driven by climatic changes and autogenic processes. Recurring human influences have also significantly modified the natural path of succession in the studied area.

7. Summary

The profile of the Nádas Lake at Nagybárkány speaks about continuous sedimentation from the Paleolithic till the opening of the Copper Age. Then during the opening of the Imperial Period, a major depositional hiatus emerged in the deposits attributable to the creation of a water reservoir system by Celtic tribes in the lakebed. This initiated a secondary succession which enabled us to make inferences about the environmental historical evolution of the area for the past two millennia at a scale of centuries alone. With the help of paleoecological and geological data, a better reconstruction of climatic fluctuations was made from the Imperial Age up to modern times. As it was shown by our data, one must exercise caution in interpreting the correlations of environmental and social crises, e.g., in the case of the fall of the Avar Empire. An objective and correct approach is the careful and most elaborate utilization of available paleoenvironmental data from the area of the Carpathian Basin.

Acknowledgements—Authors would like to express their gratitude to the Headquaters of the Bükk National Park for granting access to the study area and to *Sándor Molnár* for his kind help in the fieldwork. This work was supported by grants OTKA T-034 392 and NKFP 5/0063/2002.

References

Anschutz, I. and *Gessner, F.*, 1954: Der Ionenaustausch bei Torfmoosen (*Sphagnum*). *Flora 141*, 178-236.

Bácsmegi, G., 2005: The Copper Age in the Nagybárkány area. In *Environmental archaeology in North-Eastern Hungary* (eds.: *E. Gál, I. Juhász* and *P. Sümegi*). Varia Archaeologica Hungarica, XIX. Budapest, 243-245.

Bácsmegi, G. and *Fábián, Sz.*, 2005: The Neolithic of Nagybárkány and its environs. In *Environmental archaeology in North-Eastern Hungary* (eds.: *E. Gál, I. Juhász* and *P. Sümegi*). Varia Archaeologica Hungarica, XIX. Budapest, 237-242.

Bácsmegi, G. and *Guba, Sz.*, 2007: *Mind of past ages* (in Hungarian). Szurdokpüspöki Önkormányzat Kiadványa, Szurdokpüspöki.

Balogh, M., 2000a: Classification of peatbogs (in Hungarian). In *Tőzegmohás élőhelyek Magyarországon: kutatás, kezelés, védelem* (Sphagnum-bogs in Hungary: research, conservation and management) (ed.: *E. Szurdoki*). CEEWEB Munkacsoport, Miskolc, 57-65.

Balogh, M., 2000b: On the succession of floating mat I. (in Hungarian). *Kitaibelia 5*, 9-16.

Barber, K.E. and *Charman, D.*, 2005: Holocene palaeoclimate records from peatlands. In *Global Change in the Holocene* (eds.: *A. Mackay, R. Battarbee, J. Birks* and *F. Oldfield*). Hodder Arnold, London, 210-226.

Barber, K.E. and *Langdon, P.G.*, 2001: Peat stratigraphy and climate change. In *Handbook of Archaeological Sciences* (eds.: *D.R. Brothwell,* and *A.M. Pollard*). Wiley, Chichester, 155-166.

Barber, K.E., Chambers, F.M., Maddy, D. and *Brew, J.*, 1994: A sensitive high resolution record of the Holocene climatic change from a raised bog in northern England. *The Holocene 4*, 198-205.

Barber, K.E., Maddy, D., Rose, N., Stevenson, A.C., Stoneman, R. and *Thompson, R.*, 2000: Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: new evidence for regional palaeoclimate teleconnections. *Quaternary Sci Rev 19*, 481-487.

Bennett, K.D., 1992: PSIMPOLL – A quickBasic program that generates PostScript page description of pollen diagrams. INQUA Commission for the study of the Holocene: working group on data handling methods. *Newsletter 8*, 11-12.

Bennett, K.D., 1994: Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences. *The Holocene 4*, 337-348.

Borhidi, A. and *Balogh, M.*, 1970: Die Enstehung von dystrophen Schaukelmooren in einem alkalischen See. *Acta Bot Hung 16*, 13-31.

Boros, Á., 1968: *Bryogeographie und Bryoflora Ungarns*. Akadémiai Kiadó, Budapest.

Bradley, R.S., Hughes, M. K. and *Diaz, H.F.*, 2003: Climate in medieval time. *Science 302*, 404-405.

Bronk Ramsey C., 2001: Development of the Radiocarbon Program OxCal. *Radiocarbon 43*, 355-363.

Caselli, G., 1981: *History of Everyday Things. The Roman Empire and the Dark Ages.* Macdonald and Company Publishers Ltd, London.

Clymo, R.S., 1963: Ion exchange in *Sphagnum* and its relation to bog ecology. *Ann Bot-London 27*, 309-324.

Clymo, R.S., 1973: The grows of *Sphagnum*: some effects of environment. *J Ecol 61*, 849-869.

Dániel, P., 2004: Geochemical analysis. In *The Geohistory of Bátorliget Marshland* (eds.: *P. Sümegi* and *S.* Gulyás). Archaeolingua Press, Budapest, 52-57.

Daniels, R.E. and *Eddy, A.*, 1985: *Handbook of European Sphagna.* Institute of Terrestrial Ecology, Hundtingdon.

Davis, B., Brewer, S., Stevenson, T. and *Juggins, S.*, 2001: *High resolution from low resolution; a new method for time-series pollen-climate reconstruction and its application in investigating abrupt Holocene climate change in Southern Europe/Mediterranean.* Abstracts of PAGES-PEPIII: Past Climate Variability Through Europe and Africa, Aix-en-Provence, France.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., 2003: The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Sci Rev 22*, 1701–1716.

Dean, W.E., 1974: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *J Sediment Petrol 44*, 242-248.

Dowdeswell, J.A., 1982: Relative dating of Late Quaternary deposits using cluster and discriminant analysis, Audubon Cirque, Colorado Front Range. *Boreas 11*, 151-161.

Engström, D.R. and *Hansen, B.C.S.*, 1985: Postglacial vegetation change and soil development in southeastern Labrador as inferred from pollen and chemical stratigraphy. *Can J Bot 63*, 543-561.

Engström, D.R. and *Wright Jr., H.E.*, 1984: Chemical stratigraphy of lake sediments as a record of environmental change. In (eds.: *E.Y. Haworth* and *J.W.G. Lund*). *Lake Sediments and Environmental History.* University of Minnesota Press, Minneapolis, 11-68.

Hall, A.R., 1979: A note on the Quaternary history of *Meesia longiseta* Hedw. in Britain. *J Bryol 10*, 511-515.

Jakab, G. and *Magyari, E.*, 2000: New progress in the Hungarian mire succession studies: the use of palaeobryological and palynological techniques in the reconstruction of hydroseries (in Hungarian). *Kitaibelia 5*, 17–36.

Jakab, G. and *Sümegi, P.*, 2004: Identifying of herbaceous plant remains from peat on the basis of microscopic features (in Hungarian). *Kitaibelia 9*, 93–129.

Jakab, G. and *Sümegi, P.*, 2005: The evolution of Nádas-tó at Nagybárkány in the light of the macorfossil finds. In *Environmental Archaeology in North-Eastern Hungary* (eds.: *E. Gál, I. Juhász* and *P. Sümegi*). Varia Archaeologica Hungarica, XIX. Budapest, 67-77.

Jakab, G., Sümegi, P. and *Magyari, E.*, 2004: A new palaeobotanical method for the description of Late Quaternary organic sediments (Mire-development pathways and palaeoclimatic records from S Hungary). *Acta Geologica Hungarica 47*, 1–37.

Juhász, I., 2005: Preliminary palaeobotanical results from the Nádas-tó peat bog at Nagybárkány: the Late Holocene environmental history. In *Environmental Archaeology in North-Eastern Hungary* (eds.: *E. Gál, I. Juhász* and *P. Sümegi*). Varia Archaeologica Hungarica, XIX. Budapest, 79-85.

Juhász, I.E., Jakab, G. and *Sümegi, P.*, 2004: Vegetation dynamics of a small Sphagnum peat bog from North Hungary, from the Late Pleistocene until Late Holocene: palynological and macrobotanical data. *Abstracts of the 11th International Palynological Congress*, 2004, Granada.

Kalicz, N. and *Makkay, J.*, 1977: Die Linienbandkeramik in der Grossen Ungarischen Tiefebene. *Studia Archeologica, VII.* Budapest.

Kiss, A., 2000: Weather events during the first Tartar invasion in Hungary (1241-42). *Acta Geographica Szegediensis 37*, 149-156.

Kiss, A., 2003: „Ecce, in hyemis nivis et glaciei habundantia supervenit" – Weather, environmental crisis and the Mongol invasion (in Hungarian). In *Tatárjárás* (Mongol invasion) (ed.: *B. Nagy*). Osiris, Budapest, 439-452.

Kooijman, A.M., 1993: On the ecological amplitude of four mire bryophytes, a reciprocal transplant experiment. *Lindbergia 18*, 19-24.

Kovács, M., Précsényi, I. and *Podani, J.*, 1978: Anhäfung von Elementen im balatoner Schilfrohr (*Phragmites communis*). *Acta Botanica Sci. Hungarica 24*, 99-111.

Lamb, H.H., 1977: *Climate: Present, Past and Future 2*. Methuen Press, London.

Mackereth, F.J.H., 1966: Some chemical observations in post-glacial lake sediments. Proceedings *Royal Academy of Sciences 250*, 165-213.

Magny, M., Gauthier, E., Vanniere, B., Peyron, O., 2008: Palaeohydrological changes and human-impact history over the last millennium recorded at Lake Joux in the Jura Mountains, Switzerland. *Holocene 18*, 255-265.

Magyari, E., Sümegi, P., Braun, M., Jakab, G. and *Molnár, M.*, 2001: Retarded wetland succession: anthropogenic and climatic signals in a Holocene peat bog profile from north-east Hungary. *J Ecol 89*, 1019–1032.

Majkut, P., 2009: *Geoarcheological investigation on the basin of Nádas Lake at Nagybárkány* (in Hungarian). Diplomamunka, MSc, Szegedi Tudományegyetem, Földtani és Őslénytani Tanszék, Szeged.

Mauquoy, D. and *Barber, K.*, 1999: A replicated 3000 yr proxy-climate record from Coom Rigg Moss and Felicia Moss, The Border Mires, northern England. *J Quaternary Sci 14*, 263-275.

Máthé, I. and *Kovács, M.*, 1959: The Sphagnum bog of the Cserhát Mountains (in Hungarian). *Botanikai Közlemények 50*, 106–108.

Odgaard, B.V., 1988: Glacial relicts - and the moss Meesia triquetra in Central and West Europe. *Lindbergia 14*, 73-78.

Penksza, K., Turcsányi, G. and *Kovács, M.*, 1994: Element concentration cadastres of peat profiles in Nyírjes bog near Sirok in Hungary (in Hungarian). *Botanikai Közlemények 81*, 29-41.

Peyron, O., Guiot, J., Cheddadi, R., Tarasov, P., Reille, M., Beaulieu de, J.L., Bottema, S. and *Andrieu, V.*, 1998: Climatic reconstruction in Europe for 18,000 yr B.P. from pollen data. *Quaternary Res 49*, 183-196.

Pfister, C., 1999: *Wetternachhersage: 500 Jahre Klimavariationen und Naturkatastrophen (1496-1995)*. Haupt, Bern.

Pfister, C. and *Brázdil, R.*, 1999: Climatic variability in sixteenth-century Europe and its social dimension: A synthesis. *Climatic Change 43*, 5-53.

Podani, J., 1993: SYN-TAX 5.0: computer programs for multivariate data analysis in ecology and systematics. *Abstracta Botanica 17*, 289-302.

Podani, J., Kovács, M. and *Dinka, M.*, 1979: Chemical element analysis of reed from Balaton I. (in Hungarian). *Botanikai Közlemények 66*, 275-284.

Prentice, I.C., Harrison, S.P., Jolly, D. and *Guiot, J.*, 1998: The climate and biomes of Europe at 6000 yr BP: comparison of model simulations and pollen-based reconstructions. *Quaternary Sci Rev 17*, 659-668.

Rácz, L., 2001: *Magyarország éghajlattörténete az újkor idején* (Climate history of Hungary during Modern Age). JGYF Kiadó, Szeged.

Rácz, L., 2008: Environmental history of Hungary until Modern Age (in Hungarian). MTA Történeti Intézete, Budapest.

Rollinson, H., 1993: *Using Geochemical Data: Evaluation, Presentation and Interpretation*. Longman, London - Essex.

Seymour, J., 1984: *Forgotten Arts*. Dorling Kindersley Ltd., London

Stuiver, M., Reimer, P.J. and *Braziunas, T.F.*, 1998: High-precision radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon 40*, 1127-1151.

Sümegi, P., 1999: Reconstruction of flora, soil and landscape evolution, and human impact on the Bereg Plain from late-glacial up to the present, based on palaeoecological analysis. In *The Upper Tisa Valley* (eds.: *J. Hamar, A. Sárkány-Kiss*). Tiscia Monograph Series, Szeged, 173-204.

Szurdoki, E. and *Nagy, J.*, 2002: Sphagnum dominated mires and Sphagnum occurrences of North-Hungary. *Folia Historico-Naturalia Musei Matraensis 26*, 67-84.

Tóth, L. and *Szabó, E.*, 1958: Über die chemische Zusammensetzung verschieder Schilfproben vom Balaton-See. *Annales Instituti Biologici (Tihany) Hungaricae Academiae Scientiarum 25*, 363-374.

Troels-Smith, J., 1955: Characterization of unconsolidated sediments (in Danish). Danmarks Geologiske Undersogelse *4*(3), 10.

Vaday, A., 2005: The Nagybárkány area in the Iron Age and the Roman period and Migration period. In *Environmental archaeology in North-Eastern Hungary* (eds.: *E. Gál, I. Juhász* and *P. Sümegi*). Varia Archaeologica Hungarica, XIX. Budapest, 45-347.

Valanus, A., 2008: Drawing the optimal dept-age curve on the basis of calibrated radiocarbon dates. *Geochronometria 31*, 1-5.

Willis, K.J., Sümegi, P., Braun, M., Bennett, K.D., Tóth, A. 1998: Prehistoric land degradation in Hungary: who, how and why? *Antiquity 72,* 101-113.

Zatykó, Cs., 2005: The medieval environment and settlement history of the Nagybárkány area. In *Environmental archaeology in North-Eastern Hungary* (eds.: *E. Gál, I. Juhász* and *P. Sümegi*). Varia Archaeologica Hungarica, XIX. Budapest, 405-409.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 4, October–December 2009, pp. 299–314

Reconstructed precipitation for southern Bakony Mountains (Transdanubia, Hungary) back to 1746 AD based on ring widths of oak trees

Zoltán Kern[1*], **András Grynaeus**[2], and **András Morgós**[3]

[1]*Institute for Geochemical Research, Hungarian Academy of Sciences,*
Budaörsi út 45, H-1112 Budapest, Hungary; E-mail: kern@geochem.hu

[2]*Hungarian Dendrochronological Laboratory,*
Széher út 76/a, H-1021 Budapest, Hungary; E-mail: dendro@ludens.elte.hu

[3]*Tokyo University of the Arts,*
12-8 Ueno Park, Taito-ku, Tokyo, 110-8714, Japan; E-mail: andrasmorgos@gmail.com

(Manuscript received in final form September 3, 2009)

Abstract—This paper presents a 258-year long precipitation reconstruction for the Balaton Highlands and the southern Bakony Mountains region. The reconstruction based on 22 living and 32 historical tree-ring width series from oak (*Quercus* sp.). Ring width series were standardized by regional curve standardization technique to preserve the low frequency information. Precipitation from August of the year preceding the formation of tree ring to the current July positively stimulates the growth of oaks, albeit May-June precipitation emerges as main growth regulator factor. Very dry period occurred in the late 1740s. Studied region has experienced the wettest period during the late 18th century since 1746. Since that time, a steady decreasing trend prevails over the fluctuations of regional precipitation. From this overall trend, the 1840s, 1860s, and 1940s stand out as drier periods. The post-1980s dry period was placed into a ~250 years context and found to be an unprecedented drought at the Balaton Highlands and the southern Bakony Mountains region.

Key-words: dendroclimatology, tree ring, Central Europe, drought, Balaton

1. Introduction

The only way to decide whether the 20th century climate is extreme or not is to investigate long records stretching well before the anthropogenically forced instrumental period (e.g., *Bradley,* 1999; *Bradley et al.,* 2003).

---

[*] Corresponding author

Bradley et al. (1987) analyzed 1487 instrumental precipitation series covering the northern Hemispheric land areas and pointed out significant regional differences in the fluctuation of past precipitation. They have already emphasized the dire necessity of investigations of past fluctuation of moisture regime on local-to-regional spatial scale. To fill this pronounced research need, paleoclimatic studies dealing with reconstruction of precipitation regime have taken enormous headway during the past decade. Amongst main sources of information on this field like documentary evidences (e.g., *Rodrigo et al.*, 1999; *Rácz*, 1999; *Garcia et al.*, 2003; *Diodato*, 2007) and speleothems (e.g., *Proctor et al.*, 2000; *Siklósy et al.,* 2009), tree rings play a leading part (e.g., *Brázdil et al.*, 2002; *Oberhuber* and *Kofler*, 2002; *Buckley et al.*, 2004; *Linderholm* and *Chen*, 2005; *Wilson et al.*, 2005; *Touchan et al.*, 2005, 2007; *Čufar et al.*, 2008).

The earliest sporadic instrumental rainfall data were recorded at Buda (1782), but the first continuous observations launched only in the mid-1800s (Buda 1841, Nagyszeben 1851) in the Carpathian Basin (*Hegyfoky*, 1910). These confirm that proxy based precipitation reconstructions have prominent importance also in the entire area girt with the arc of the Carpathians.

In addition, future continuation of warming on a global level is expected to procure reduction of annual precipitation in Hungary (*Bartholy et al.*, 2004, *Mika*, 2004, 2007) and, especially, the lake Balaton, prime tourist resource of Hungary, will be in risk, if precipitation declines in the future over the watershed (*Bartholy et al.*, 1995). So the knowledge about natural variability of moisture over its watershed is interesting not only from scientific but also from social and economical point of view.

This paper presents secular fluctuation of precipitation at the northern hilly part of the catchment area of the Lake Balaton. Variability of precipitation is reconstructed from tree-ring width variations of oak trees between 1746 and 2003. The low-frequency variability of present reconstruction is to be verified against longer instrumental record from the boarder vicinity of the study site. In addition, the tree-ring based reconstruction was compared to two other precipitation reconstructions, which are thought to have relevancy for the past fluctuation of the precipitation regime of the studied area.

2. Materials and methods

2.1. Tree-ring data

Fifteen mature oak trees (*Quercus petrea*, *Quercus pubescens*) were sampled by increment borer in November 2003. One or two cores were extracted from each tree. Due to exclusion of low quality samples, finally fourteen living oak trees (22 series) from Balaton Highland and southern Bakony Mts. (*Fig. 1*) developed a local oak chronology (*Kern*, 2007), and 32 historical timber samples derived from old buildings completed the 309 years long tree-ring width (TRW) chronology (1694 – 2003). Old timbers were collected from four villages close to the site of living trees, namely, Vöröstó, Nagyvázsony, Vigántpetend, and Örvényes (*Fig. 1*).

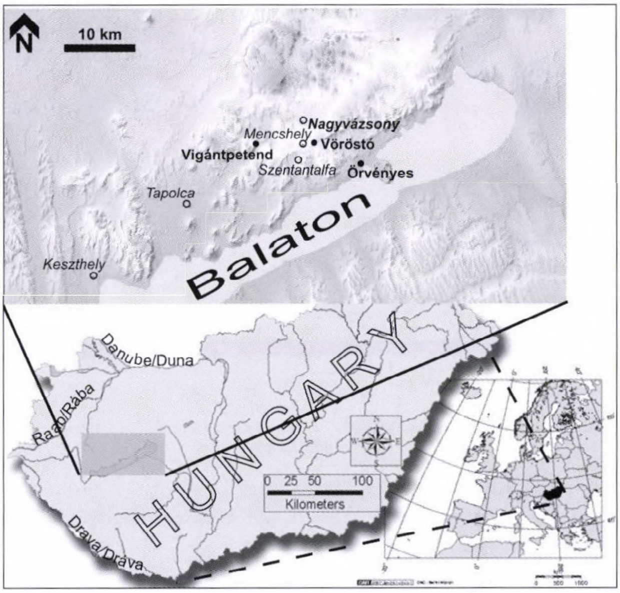


Fig. 1. Location of the study area (grey rectangle) and the precipitation gauge stations (marked by open circles and italics). Villages, from which historical wood samples originated, are marked by filled circles and bolds. From Nagyvázsony, both gauge records and historical timbers were used.

Living trees cover the 1766–2003 period, while historical samples distribute between 1694 and 1944.

Climate signal in raw ring width series are often biased by non-climatic effects (e.g., *Douglass*, 1919; *Cook*, 1985). To find the adequate method to eliminate non-climatic trends (e.g., age trend) from raw TRW series, the so-called standardization is always crucial in any dendroclimatological study.

Mean segment length (MSL) was 124 years in the data set. Applying any traditional standardization techniques (negative exponential function or digital filtering), frequencies lower than ~3/MSL could hardly be retained (*Cook et al.*, 1995). To avoid the loss of low frequency information, regional curve standardization (RCS) was applied (*Briffa et al.*, 1992; *Esper et al.*, 2003). Utilizing RCS technique, multi-centennial trends could be captured even though the mean sample length is below 50 years (*Wilson et al.*, 2004).

RCS uses the estimated biological growth curve of the studied species in the standardization. The estimated biological growth, regional curve (RC) of oak was determined as follows: first calculating the bi-weight robust mean (*Cook*,

1985) of the age-aligned series, after that fitting a cubic smoothing spline (*Cook* and *Peters*, 1981) with a 50% frequency-response cut-off at 10% of the series length (*Esper et al.*, 2003) (*Fig. 2*).

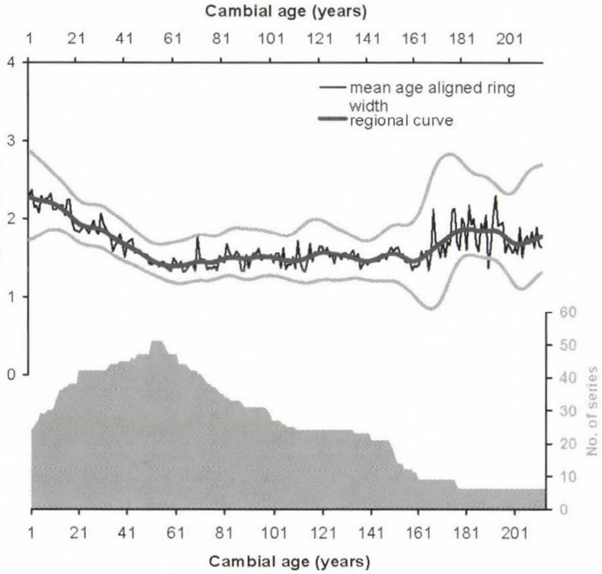


Fig. 2. Biological growth curve of oak. Upper graphics: thin black line: mean of age aligned series; thick black curve: regional curve (RC) obtained by fitting a cubic smoothing spline (50% frequency-response cut-off at 10% length); grey curves: 95% confidence intervals. Lower graph shows replication.

Twenty-five trees had the pith. In the other cases, missing rings to pith (pith offset) were estimated by the aid of graphics of concentric circles. Pith offset values for ten trees were less than 15, and the highest estimated pith offset was 50.

Indices were calculated as ratio of the measured ring width and the RC predicted value. Standardized series were rearranged by calendar date and average index was determined by bi-weight robust mean (*Cook*, 1985).

Uncertainty of the built chronology is represented by the 95% confidence interval calculated by bootstrap procedure (*Efron*, 1987). Stability of climate related signal preserved in the index series was controlled by the expressed population signal (EPS) statistic. Its widely accepted threshold is 0.85 (*Wigley et al.*, 1984). Mean interseries correlation (Rbar) and EPS were calculated for 50 years moving window with 25 years steps. Standardization and index calculation procedure was carried out using the ARSTAN software (*Cook* and *Krusic*, 2006). Variance adjustment was applied on the derived TRW chronology to minimize variance bias due to changing sample replication and the effect of fluctuating interseries correlation (*Osborn et al.*, 1997; *Frank et al.*, 2007).

2.2. Precipitation data

Monthly average precipitation totals were available from four nearby gauge-stations (Nagyvázsony 1901–2005, Tapolca 1901–2005, Mencshely 1960–1996 and 2001–2005, Szentantalfa 1900–1991 and 1998–2000) (*Fig. 1*). Since the use of averaged meteorological series yield better statistical connections in dendroclimatological analysis than individual stations (*Blasing et al.*, 1981; *Yeh et al.*, 2000), regional average precipitation series were estimated from these instrumental data. Monthly data were transformed to percentages of average monthly total of the 1961-1990 reference period (*WMO*, 1989). To accentuate the effect related to individual moisture regime of particular stations, monthly regional mean precipitation index series were calculated as non-weighted average percentage from the individual station-indices. Indices of May-June (MJ) and an annualized series were also determined. The annualized series were calculated as percentage of summarized monthly precipitation totals from the previous August to the current July.

These average percentage series were converted back to "absolute" precipitation values by multiplying each individual percentage data by the corresponding monthly, bimonthly, or annualized grand mean (mean of all stations' mean) calculated for the 1961–1990 reference period.

The longest continuous instrumental precipitation record in the region exists from the near-by Keszthely (*Fig. 1*). Early data (1861–1977) are available from Climate Explorer (*van Oldenborgh et al.*, 2005) and this series was updated to 2001.

2.3. Relationship between tree growth and precipitation, precipitation reconstruction

Relationship between annual increment of oak and precipitation was evaluated by computing Pearson's correlation coefficients from May of the previous year to October of the current year of formation of tree rings. In addition, MJ and annualized precipitation series were also involved into the correlation analysis.

To prevent the loss of natural amplitude due to the linear regression (*von Storch et al.*, 2005), rescaling technique was applied in reconstruction (*Esper et al.*, 2005). Period of instrumental precipitation data was divided into two subperiods: P1 (1901–1952) and P2 (1953–2003). Temporal stability of the reconstruction was tested in a split period calibration/verification procedure (*Fritts*, 1976). At first, mean and standard deviation of oak index for P1 were replaced by mean and standard deviation of instrumental data for P2, at second, role of subperiods was reversed.

Skill of reconstruction was tested by R^2 (explained variance), RE (reduction of error) and CE (coefficient of efficiency) statistics (*Cook et al.*, 1994). Values of R^2 are between 0 and 1. Higher value indicates more similarity, 1 means one series is the function of the others and vice versa. Potential values are $-\infty < \mathrm{RE}, \mathrm{CE} < 1$. If $\mathrm{RE} > 0$ ($\mathrm{CE} > 0$) it means that reconstruction better approximates data of the verification period than the mean of the calibration (verification) period. Obviously, CE is the more rigorous statistics.

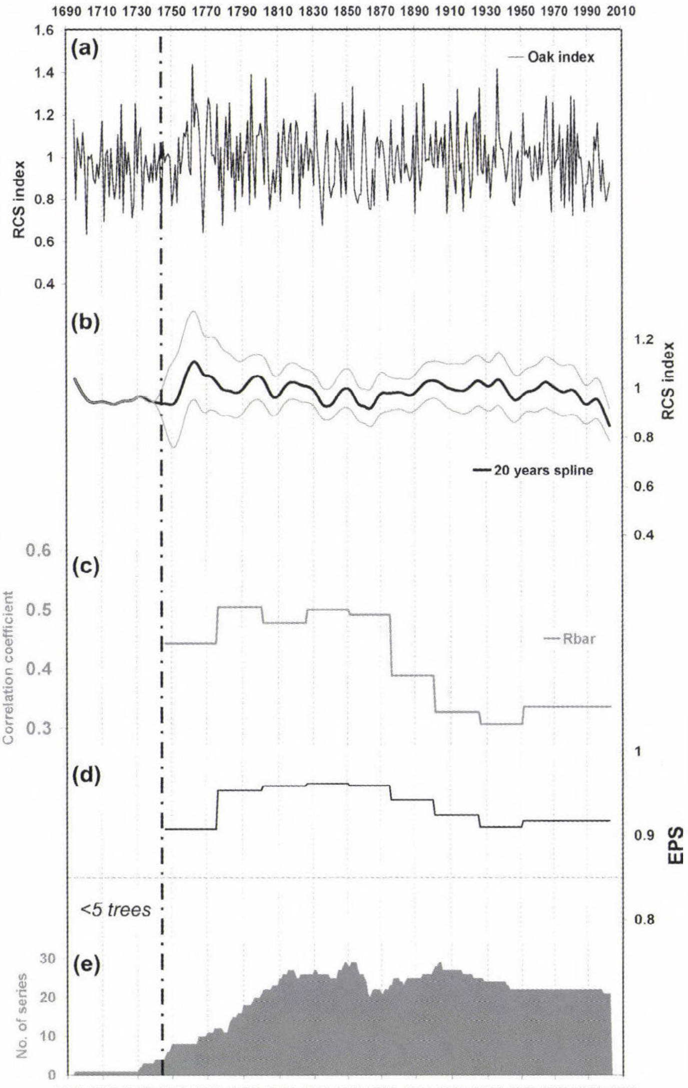


Fig. 3. Standardized oak index (a) and some signal strength statistics. (b) 20 years low pass filtered (cubic smoothing spline) indices. Light grey curves denote the bootstrapped 95% confidence interval. (c) Mean interseries correlation (Rbar). (d) Expressed population signal (EPS). Dashed horizontal grey line indicates the 0.85 level. (e) Sample depth. Dash dotted vertical line indicates 1745 AD. Before this date less than five trees build the chronology.

Two types of error were assigned as source of uncertainty (*Esper et al.*, 2007). On the one hand, chronology error was converted from the 95% confidence interval of the chronology (*Fig. 3b*). On the other hand, two standard error ranges derived from regression of 20 years smoothed reconstruction vs. instrumental data were regarded to quantify the 95% uncertainty designated as calibration error. Error terms were determined separately.

2.4. Independent precipitation reconstructions

Seven-graded monthly, seasonal, and annual precipitation indices were developed from documentary evidences for the Hungarian Kingdom (*Rácz*, 1999, hereafter R99) and available in printed form (*Rácz*, 2001). From the European gridded multi-proxy precipitation reconstruction (*Pauling et al.*, 2006, hereafter P06) seasonal totals could be extracted for the grid-cell (46.25°N; 17.25 × 46.75°N; 17.75°E) covering the studied area via internet (Climate Explorer (*van Oldenborgh et al.*, 2005)). R99 spans 1500–1850, while R06 spans 1500–2000.

3. Results

3.1. Characteristics of the TRW data

Chronology is still based on less than five trees before 1745. To avoid unreliable signal due to low replication, reconstruction is restricted to the well replicated period. Maximum replication is 29. Replication reaches its maximum level in three short periods, namely, 1903 – 04, 1852–55, and 1848 – 49 (*Fig. 3e*). Mean Rbar is 0.42 and mean EPS is 0.94 over the 1746 –2003 period. Minimum Rbar is 0.306 during the 1925 – 1960 period. A parting point (1875) appears in the Rbar statistics. Before this date, Rbar values are much higher than after. It indicates stronger common signal in the earlier part of the chronology when role of historical series is more dominant. This finding confirms the strict and excellent crossdate of the historical TRW series. EPS is steadily over the signal acceptance threshold (0.85) over the entire observation indicating robust chronology (*Fig. 3d*).

3.2. Relationship between oak index and precipitation

Correlation analysis revealed highly significant positive relationship between oak growth and May–June monthly precipitation of the year of tree-ring growth. The correlation coefficients are 0.36 and 0.41, respectively, exceeding the 99.9% significance level (*Fig. 4*). Calculating bimonthly (MJ) cumulated precipitation, the correlation coefficient reached 0.57 for the 1900–2003 period. All remaining months developed coefficients below 99% significance level. However, it is worthy to note that from August of previous year (pAug) to July, each coefficient is positive. Some of them (e.g., pDec, July) are above or (e.g., pAug, pSep) just slightly below the 90% significance level. This perception motivated the calculation of an annualized total precipitation summing monthly totals from previous August to current July. Involving this annualized precipitation into the analysis, correlation coefficient has even further improved (0.62). We can conclude that precipitation of May and June is the main growth regulator factor for oak growth in the southern Bakony Mts. and the Balaton Highlands, but moisture regime of complementary part of the previous August–current July period has also important effect. In the further steps, oak indices are to be calibrated against the annualized (i.e., previous August – current July) precipitation totals.

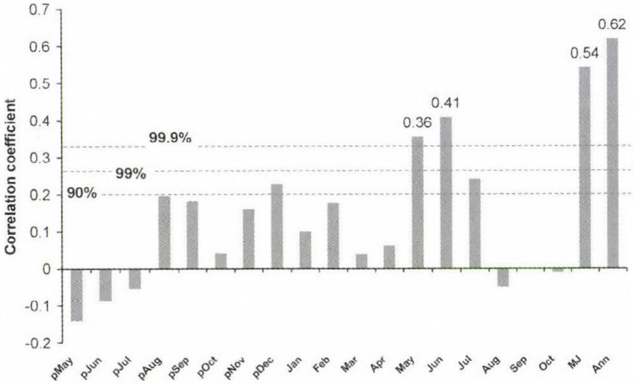


Fig. 4. Correlation coefficients computed between monthly precipitation and oak tree-ring index. Dashed horizontal lines denote 90%, 99%, and 99.9% significance levels for n=104 (1900–2003). Abbreviated months with 'p' mark months in the preceding year to formation of tree ring. 'MJ' means May–June bimonthly precipitation total. 'Ann' means annualized precipitation total summed from August of the previous year of growth to July of the current year. In the case of 'Ann' and months of previous year, comparison was restricted to 1901–2003.

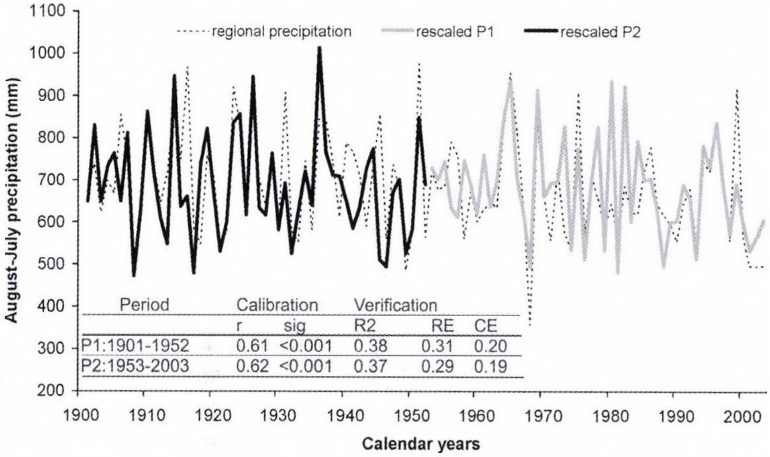
3.3. Calibration and reconstruction

Split period calibration/verification procedure ensured the stability of reconstruction utilizing the rescaling technique (*Fig. 5*). RE and CE statistics yield above zero values in each case. In addition, verification statistics are fairly high, and squared correlation (R^2) exceeds the RE value settling any doubts about spurious significance (*McIntyre* and *McKitrick*, 2005).

As rescaling technique was well verified, final reconstruction (hereafter called OAK) has been prepared as mean and variance of oak index for the entire instrumental period (1901–2003) were set equal to mean and variance of regional precipitation (*Fig. 6a*).

The wettest and driest reconstructed years are 1795 (1033 mm) and 1768 (396 mm), respectively. The wettest decade in the OAK reconstruction is 1795 – 1804 (785 mm/yr). Driest decade on record is 1746–55 (613 mm/yr) and the second one is 1855 – 64 (620 mm/yr) (*Table 1*, *Fig. 6a*).

In general, a gradual long-term decreasing trend emerges as the dominant pattern of past changes. The trend seems to accelerate since the 1970s.



Period	Calibration		Verification		
	r	sig	R2	RE	CE
P1:1901-1952	0.61	<0.001	0.38	0.31	0.20
P2:1953-2003	0.62	<0.001	0.37	0.29	0.19

Fig. 5. Temporal stability of reconstruction by rescaling technique was tested. Dotted line: regional August–July precipitation. Grey line: estimated August–July precipitation rescaled by P1 period. Black line: estimated August–July precipitation rescaled by P2 period. Inset table: Split period calibration/verification statistics. r: Pearson's correlation coefficient, sig: significance of 'r', R2: explained variance, RE: reduction of error, CE: coefficient of efficiency.

4. *Discussion*

4.1. Extreme events and trends of past precipitation

On interannual scale, weak similarity can be found in extremes between instrumental and tree ring derived record (*Table 1*). Solely the driest instrumental year (1968) appeared and ranked third among the extremes of the modern part of OAK. Much more concurrences were found in the set of extreme decades. The driest rescaled decade is practically corresponding to the second driest instrumental one. Third driest decade is the same, but the driest decade from the instrumental period has also prominent place, ranked fourth, in the rescaled record. In addition, the wettest instrumental decade agrees, within a year shift, with the second one from the modern part of the rescaled record. Finally, the wettest rescaled decade significantly overlaps the third wettest instrumental one. Same as the instrumental data, each of the three rescaled driest decades appears in the second half of the century and practically the total post-mid-1980s period, covered by two non-overlapping decades, ranked into the drought top three. These correspondences further confirm the successful preservation of low-frequency precipitation signals in the OAK.

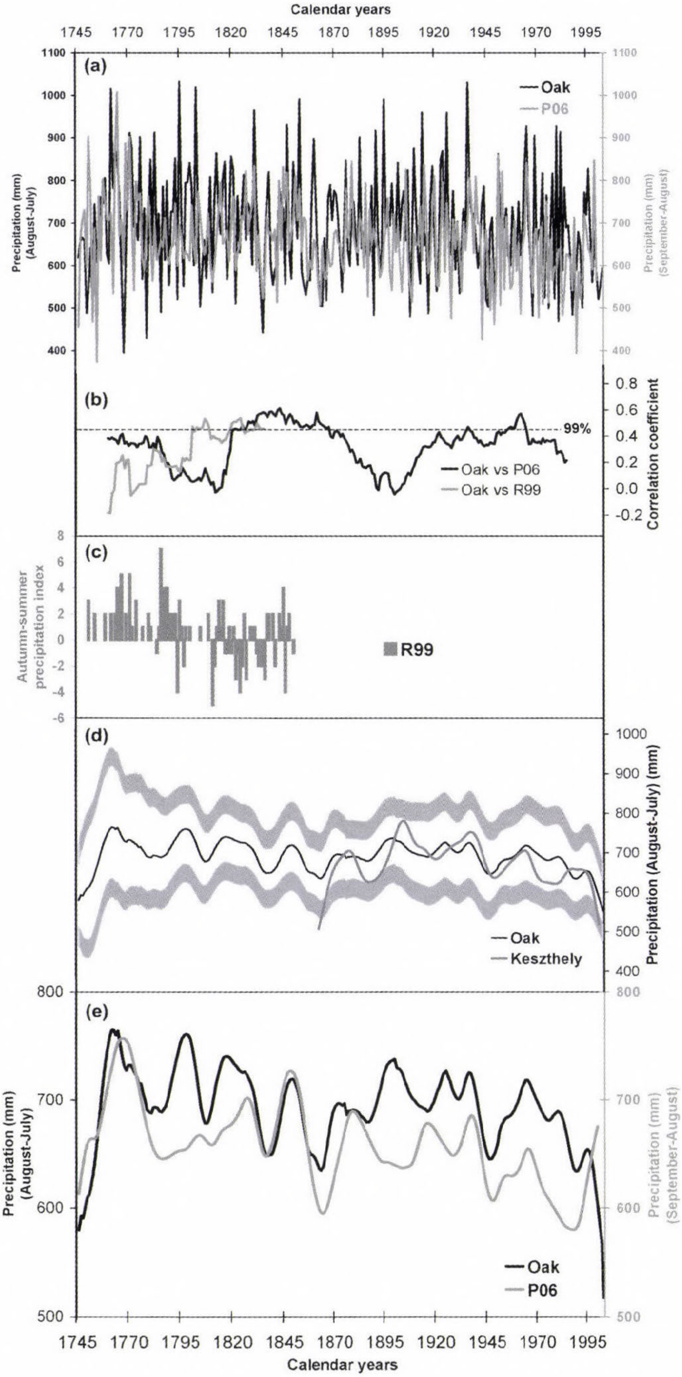


Fig. 6. (a) Reconstructed……→

Table 1. Three most extreme years and non-overlapping decades are listed from the instrumental and reconstructed era. Date in the 'year' column refers to the period from the previous August to the current July (i.e., 1968 means the period from August 1967 to July 1968). Date in the 'decade' column refers to the period from August ten years before to the current July (i.e., 1976 means the period from August 1965 to July 1976). 'Instrumental' means regional mean precipitation calculated from gauge records (see Section 2 for details)

		Instrumental (1901–2003)		**Rescaled (1901–2003)**		**Reconstruction (1746–1900)**	
		Year	**Decade**	**Year**	**Decade**	**Year**	**Decade**
Dry	1	1968	1976	1981	1994	1768	1755
	2	1949	1993	1908	1950	1779	1864
	3	2002	2003	1968	2003	1835	1842
Wet	1	1951	1945	1936	1927	1795	1804
	2	1916	1919	1914	1944	1803	1766
	3	1965	1932	1926	1973	1762	1821

Peering the extreme years in the reconstructed period, 1835 is nicely coinciding with the driest detected summer since 1800 in the eastern sector of Alps (*van der Schrier et al.*, 2006). The second driest (wettest) year was found as strong negative (positive) anomaly in reconstructed June aridity in southeast Slovenia (*Čufar et al.*, 2008).

The first studied decade was reconstructed as the driest one, but due to the larger uncertainty (mostly due to the widening chronology error (*Fig. 6d*)), absolute values are still less reliable. However, the second driest decade on record is a prominent dry period in the Alps (*Casty et al.*, 2005), especially in the eastern Alps (*Auer* and *Böhm*, 1994; *van der Schrier et al.*, 2006). Extreme Transdanubian drought from the late 1850s to the mid-1860s is nicely corroborated by documented desiccation of the lake Fertő (*Kiss*, 2001, 2004).

The wettest and the third wettest decades are in line with the statements of *van der Schrier et al.* (2006), as the first two decades of the 19th century was exceptionally wet periods also in the eastern part of the European Alps.

Fig. 6. (a) Reconstructed August–July precipitation of the Balaton Highlands and the southern Bakony Mts. over 1746–2003 based on oak ring widths (black line) and autumn-summer (previous September – current August) precipitation of the corresponding grid-cell of the P06 (*Pauling et al.*, 2006) reconstruction. (b) Coefficients of 31 years sliding window correlation computed between tree-rings based reconstruction and P06 (black) and R99 (grey). Dashed horizontal line denotes the 99% significance level. (c) Columns represent indices of the R99 reconstruction (*Rácz*, 1999). (d) Low-pass filtered (20 years cubic smoothing spline) reconstruction (black) and Keszthely gauge record (dark grey). The 95% uncertainty interval is presented as two separate bands related to chronology error (white) and to calibration error (grey). (e) Low-pass filtered (20 years cubic smoothing spline) tree-ring based reconstruction (black) and P06 (grey).

The longest continuous gauge record (Keszthely) was smoothed by a 20 years low-pass filter to verify the low-frequency signal of TRW based reconstruction (*Fig. 6d*). The independent record fits very well the fluctuation of OAK. Keszthely record excurses out from the range of uncertainty, solely, during its early decade. Though the 'low value' patterns are coherent between the records, it might be suspected that extreme low early gauge records are suffered from some negatively biasing homogeneity problem. Nevertheless, the similarity found with this independent record further confirms the fidelity of the oak ring width based precipitation reconstruction from the Balaton Highlands and the southern Bakony Mts.

4.2. Comparison with independent data

For the sake of better comparability of OAK, representing previous August–current July precipitation total as discussed above, with the seasonally resolved R99 and P06 ones were also annualized. Seasonal precipitation totals for P06 and indices for R99 were summed over the autumn-summer periods, respectively. By this way R99 and P06, in this study, differ from the original annual values of the reconstructions. Here they, indeed, represent the previous September–current August period. The one month shift in the theoretical time window of the reconstructions compared to OAK is unlikely to significantly affect their similarity or dissimilarity. Note that from 1800 to 1808 and before 1776, gaps are present in R99.

Sliding window correlation analysis revealed that OAK reconstruction and R99 shows significant similarity back to ~1800 (*Fig. 6b*). Similarity declines abruptly before. Observed worsening of relationship partially could be a consequence of gaps in R99. But we are to note that R99 gathered written evidences, practically, from the entire Carpathian Basin, so inherently and artificially reduced the ability to mirror reliably past changes on smaller spatial scales. For instance, 1786 designated as the wettest year in the observed period of R99 (*Fig. 6c*), based strongly on written evidences from the region of Miskolc and Sárospatak (northeast Hungary) (*Rácz*, 2001) and, in contrast, ranked seventh driest year by OAK during the reconstructed period in the southern Bakony Mts. (*Fig. 6a, b*).

Sliding window correlation analysis revealed that OAK reconstruction and P06 shows stable and significant similarity between ~1810 and ~1870 and quite well similarity (fluctuating around the 99% significance level) back to ~1920 (*Fig. 6b*). P06 lacks similarity in their interannual variability from the 1780s to 1810s and from the 1870s to the 1910s. Same periods present also the largest discrepancy in the low-frequency variability. In the latter case, the Keszthely gauge record verifies the fluctuation of OAK reconstruction. So we dare to conclude that P06 poorly reconstruct the fluctuation of precipitation during the above mentioned periods over the Balaton Highlands and the southern Bakony

Mts. region. After the 1910s, P06 presents similar fluctuations as OAK, but absolute values are consecutively below OAK (*Fig. 6e*). Another strange feature with P06 is that the trend for the recent decades is opponent with OAK. This sharply decreasing trend of OAK is verified by the local gauge records (*Fig. 4*, *Fig. 6d*). Since P06 also based on station data in recent century, an inadequate interpolation technique or non-representative station selection problem might be suspected.

However, the low precipitation at the earliest part of the record is coherent with P06 confirming the existence of the dry conditions during the late 1740s. In addition, the secular record of wet in the 1760s and the gradual decreasing trend since that time also agree in these independent precipitation reconstructions from the Balaton Highlands and the southern Bakony Mts. region.

5. Conclusion

We have presented a dendroclimatological reconstruction of August–July precipitation for the Balaton Highlands and the southern Bakony Mountains region since 1746. The reconstruction based on 22 living and 32 historical tree-ring width series from oak (*Quercus* sp.) samples. Ring width series were standardized by regional curve standardization technique (*Briffa et al.*, 1992; *Esper et al.*, 2003), regarding the biological character of oak's growth in the standardization procedure. By this way the low frequency climatic information was also effectively preserved in the tree-ring index.

A steady decrement has been appeared as an overall trend in the precipitation fluctuation since the mid-1700s. From this main pattern the 1840s, 1860s, and 1940s stand out as drier periods. The 1740s preceding the onset of this decreasing trend likely was also very dry. Derived precipitation reconstruction placed the late-20th century dry period into a secular context and suggests that the post-1980 drought period is unprecedented since 1746 at least. The low-frequency trend of the reconstruction from the mid-1800s century was verified by comparison with the longest nearby gauge record (Keszthely 1861–2001).

Present study pointed out weaknesses of two earlier precipitation reconstructions for the investigated region. A reconstruction developed on the base of written evidences (R99) aggregated documentary data over wide spatial distance, namely the entire Carpathian Basin, so owing to this methodological step, peculiarly in the case of precipitation, potential of R99 to detect past climate changes in local to regional scales has significantly reduced.

Data extracted from the corresponding grid from the European multi-proxy precipitation reconstruction (P06) showed poor similarity with this local reconstruction from the 1780s to the 1810s and from the 1870s to the 1910s. In addition, some problem (inadequate interpolation, non-appropriate station selection) during the instrumental era also might be suspected.

Reconstructed long-term gradual reduction of the precipitation associated with a changing seasonality (i.e., enhancing Mediterranean character (*Fogarasi*, 2004)) underlines that the climate of the Balaton Highlands and the southern Bakony Mts. significantly changed during the past centuries. Scenarios predict increasing aridity for Hungary (*Bartholy et al.*, 2004, *Gálos et al.*, 2007), especially over Transdanubia (*Szalai* and *Mika*, 2007) in future decades. Present results call the attention that agriculture and forestry have to face with this altered moisture regime by heavily depleted groundwater reservoirs.

Presented precipitation reconstruction also serves an objective basis to assess climatic conditions related to past historical events. Finally, we note that further improvements (e.g., extending the reconstructed time-span and reducing uncertainty) are possible and in progress.

Acknowledgements—The research was funded by OTKA T43666 and OTKA K67583. Budapest Tree-Ring Laboratory contribution No. 18.

References

Auer, I. and *Böhm, R.*, 1994: Combined temperature-precipitation variations in Austria during the instrumental period. *Theor Appl Climatol 49*, 161-174.

Bartholy, J.; Bogárdi, I. and *Matyasovszky, I.*, 1995: Effect of Climate Change on regional precipitation in Lake Balaton watershed. *Theor Appl Climatol 51*, 237–250.

Bartholy, J., Pongrátz, R., Matyasovszky, I. and *Schlanger, V.*, 2004: Expectable tendencies of global climate change in the Carpathian Basin (in Hungarian). In *Erdő és Klíma IV* (eds.: *Cs. Mátyás* and *P. Vig*). Nyugat-Magyarországi Egyetem, Sopron, Hungary, 57-68.

Blasing, T.J., Duvick, D.N., and *West, D.C.*, 1981: Dendroclimatic calibration and verification using regionally averaged and single station precipitation data. *Tree Ring Bull 41*, 37-43.

Bradley, R.S., 1999: Preface. *Climatic Change 43*, 1-2.

Bradley, R.S., Diaz, H.F., Eischeid, J.K., Jones, P.D., Kelly, P.M., and *Goodness, C.M.*, 1987: Precipitation fluctuations over Northern Hemisphere Land Areas since the mid–19th century. *Science 237*, 171–175.

Bradley, R.S., Hughes, M.K. and *Diaz, H.F.*, 2003: Climate in medieval time. *Science 30*, 404-405.

Brázdil, R., Štěpánková, P., Kyncl, T., and *Kyncl, J.*, 2002: Fir tree-ring reconstruction of March – July precipitation in southern Moravia (Czech Republic), 1376–1996. *Climate Res 20*, 223-239.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P., and *Eronen, M.*, 1992: Fennoscandinavian summers from AD 500: Temperature changes on short and long timescales. *Clim Dynam 7*, 111-119.

Buckley, B.M., Wilson, R.J.S., Kelly, P.E., Larson, D.W. and *Cook, E.R.*, 2004: Inferred summer precipitation for southern Ontario back to AD 610, as reconstructed from ring widths of *Thuja occidentalis*. *Canadian J Forest Res 34*, 2541-2553.

Casty, C., Wanner, H., Luterbacher, J., Esper, J. and *Böhm, R.*, 2005: Temperature and precipitation variability in the European Alps since 1500. *Int J Climatol 25*, 1855-1880. doi:10.1002/joc.1216

Cook, E.R. and *Peters, K.*, 1981: The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree Ring Bull 41*, 45-53.

Cook, E.R., 1985: A time series analysis approach to tree-ring standardization. *Ph.D. Dissertation*. The University of Arizona, Tucson.

Cook, E.R., Briffa, K.R. and *Jones, P.D.*, 1994: Spatial regression methods in dendroclimatology: a review and comparison of two techniques. *Int J Climatol 14*, 379–402.

Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A. and *Funkhouser, G.*, 1995: The 'segment length curse' in long tree-ring chronology development for paleoclimatic studies. *Holocene 5*, 229-237.

Cook, E.R. and *Krusic, P.J.*, 2006: ARSTAN4.1b_XP. http://www.ldeo.columbia.edu.

Čufar, K., De Luis, M., Eckstein, D. and *Kajfež-Bogataj, L.*, 2008: Reconstructing dry and wet summers in SE Slovenia from oak tree-ring series. *Int J Biometeorol 52*, 607-615. doi:10.1007/s00484-008-0153-8

Diodato, N., 2007: Climatic fluctuations in southern Italy since the 17th century: reconstruction with precipitation records at Benevento. *Climatic Change 80*, 411-431. doi:10.1007/s10584-006-9119-1

Douglass, A.E., 1919: *Climatic Cycles and Tree Growth. Vol. 1.* Carnegie Institution of Washington, Publication 289, Washington, DC, USA.

Efron, B., 1987: Better bootstrap confidence intervals. *J Amer Stat Assoc 82*, 171–185.

Esper, J., Cook, E.R., Krusic, P.J., Peters, K. and *Schweingruber, F.H.*, 2003: Tests of the RCS method for preserving low–frequency variability in long tree–ring chronologies. *Tree Ring Res 59/2*, 81–98.

Esper, J., Frank, D., Wilson, R.J.S. and *Briffa, K.R.*, 2005: Effect of scaling and regression on reconstructed temperature amplitude for the past millennium. *Geophys Res Lett 32,* L07711, doi: 10.1029/2004GL021236

Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J. and *Xoplaki, E.*, 2007: Long-term drought severity variations in Morocco. *Geophys Res Lett 34*, L17702, doi:10.1029/2007GL030844

Fogarasi, S., 2004: Change of Mediterranean Index on the karstic area of the Transdanubian Range and the connection with other elements of climate (in Hungarian). *Karsztfejlődés 9*, 251-268.

Frank, D., Esper, J. and *Cook, E.R.*, 2007: Adjustment for proxy number and coherence in a large-scale temperature reconstruction. *Geophys Res Lett 34*, L16709 doi:10.1029/2007GL030571

Fritts, H.C., 1976: *Tree Rings and Climate.* Academic Press, New York, p.567.

Gálos, B., Lorenz, P. and *Jacob, D.*, 2007: Climate change – drying tendency in Hungary? (in Hungarian). In *Erdő és Klíma* V (eds.: *Cs. Mátyás* and *P. Vig*). Nyugat-Magyarországi Egyetem, Sopron, Hungary, 57-67.

Garcia, R., Macias, A., Gallego, D., Hernández, L. and *Ribera, P.*, 2003: Reconstruction of the precipitation in the Canary Islands for the period 1595-1836. *Bull Am Met Soc 81,* 1037-1039.

Hegyfoky, K., 1910: Rainfall data from the 1851-1870 period (Supplementary for "The annual periodicity of precipitation in Hungary") (in Hungarian). *Meteorológiai és Földdelejességi Magyar Királyi Központi Intézet évkönyvei 37/* IV, 15-68.

Kern, Z., 2007: Tree-ring research in Balaton Highland and South Bakony Mts. (in Hungarian). In *Az erdő és a fa régészete és néprajza* (ed.: *Gömöri, J.*). MTA VEAB Soproni Tudós Társaság, Sopron, Hungary, 89-102.

Kiss, A., 2001: Die Veränderungen der natürlichen Verhältnisse des Komitates Sopron in XVIII-XIX. Jahrhundert. In *Bél Mátyás: Descriptio Comitatvs Semproniensis I.* (eds: *K. Szende* and *K. Kincses*). Quellen zur Geschichte der Stadt Ödenburg, Reihe C, Band 2. 76-89.

Kiss, A., 2004: Utilization of the Inundation Area at Lake Fertő before Regulation Works: Example of Sarród and its surroundings. *Acta Geographica Universitatis Szegediensis 38,* 39-49.

Linderholm, H.W. and *Chen, D.*, 2005: Central Scandinavian winter precipitation variability during the past five centuries reconstructed from *Pinus sylvestris* tree rings. *Boreas 34,* 43-52.

McIntyre, S. and *McKitrick, R.*, 2005: Hockey sticks, principal components, and spurious significance. *Geophys Res Lett 32*, L03710, doi:10.1029/2004GL021750

Mika, J., 2004: Regional climate scenarios: facts and doubts (in Hungarian). In *Erdő és Klíma IV* (eds.: *Cs. Mátyás* and *P. Vig*). Nyugat-Magyarországi Egyetem, Sopron, Hungary, 79-97.

Mika, J., 2007: New results and comparisons on regional features of the global warming in Hungary (in Hungarian). In *Erdő és Klíma* V (eds.: *Cs. Mátyás* and *P. Vig*), Nyugat-Magyarországi Egyetem, Sopron, Hungary, 13-30.

Oberhuber, W. and *Kofler, W.*, 2002: Dendroclimatological spring rainfall reconstruction for an inner Alpine dry valley. *Theor Appl Climatol 71,* 97-106. doi:10.1007/s704-002-8210-8

Osborn, T. J., Briffa, K.R. and *Jones, P.D.*, 1997: Adjusting variance for sample-size in tree-ring chronologies and other regional-mean time-series. *Dendrochronologia 15*, 89–99.

Pauling, A., Luterbacher, J., Casty, C. and *Wanner, H.*, 2005: Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large scale circulation. *Clim Dynam 26,* 387-405. doi 10.1007/S00382-005-0090-8

Proctor, C.J., Baker, A., Barnes, W.L. and *Gilmour, M.A.*, 2000: A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Clim Dynam 16*, 815-820. doi 10.1001/s003820000077

Rácz, L., 1999: *Climate History of Hungary Since 16th Century: Past, Present and Future.* Centre for regional studies of Hungarian Academy of Sciences discussion papers, No. 28, Pécs.

Rácz, L., 2001: *Magyarország éghajlattörténete az újkor idején* (Climate history of Hungary during Modern Age). JGYF Kiadó, Szeged, Hungary, 303 pp.

Rodrigo, F.S., Esteban-Parra, M.J., Pozo-Vazquez, D. and *Castro-Diez, Y.*, 1999: A 500-year precipitation record in Southern Spain. *Int J Climatol 19/11*, 1233-1253.

Siklósy, Z., Demény, A., Szenthe, I., Leél-Őssy, Sz., Pilet, S., Lin, Y. and *Shen, C.C.*, 2009: Reconstruction of climate variation for the last millennium in the Bükk Mts., northeast Hungary, from a stalagmite record. *Időjárás 113*, 245-263.

Szalai, S. and *Mika, J.*, 2007: Analysis and preciction of climate change and weather anomaly parameters important for forest cover (in Hungarian). In *Erdő és Klíma* V (eds.: *Cs. Mátyás* and *P. Vig*). Nyugat-Magyarországi Egyetem, Sopron, 133-143.

Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M.K., Erkan, N., Akkemik, Ü. and *Stephan, J.*, 2005: Reconstruction of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Clim Dynam 25*, 75-98.

Touchan, R., Akkemik, Ü., Hughes, M.K. and *Erkan, N.*, 2007: May-June precipitation reconstruction of southwestern Anatolia, Turkey during the last 900 years from tree-rings. *Quat Res 68*, 196-202. doi:10.1016/j.yqres.2007.07.001

van der Schrier, G., Efthymiadis, D., Briffa, K.R. and *Jones, P.D.*, 2006: European Alpine moisture variability for 1800-2003. *Int J Climatol 27*, 415-427. doi:10.1002/joc.1411

van Oldenborgh, G.J., Balmaseda M.A., Ferranti, L., Stockdale, T.N. and *Anderson, D.L.T.*, 2005: Evaluation of atmospheric fields from the ECMWF seasonal forecasts over a 15 year period. *J Climate 18*, 2970-2989.

Von Storch, H., Zorita, E., Jones, J.M., Dimitriev, Y., González-Rouco, F. and *Tett, S.F.B.*, 2004: Reconstructing past climate from noisy data. *Science 306*, 679-682. doi:10.1126/science.1096109

Wigley, T.M.L., Briffa, K.R. and *Jones, P.D.*, 1984: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J Clim Appl Meteorol 23*, 201-213.

Wilson, R.J.S., Esper, J. and *Luckman, B.H.*, 2004: Utilising historical tree-ring data for dendroclimatology: a case study from the Bavarian Forest, Germany. *Dendrochronologia 21*, 53-68.

Wilson, R.J.S., Luckman, B.H. and *Esper, J.*, 2005: A 500 year dendroclimatic reconstruction of spring-summer precipitation from the Lower Bavarian Forest, Germany. *Int J Climatol 25*, 611-630. doi:10.1002/joc.1150

WMO, 1989: *Calculation of Monthly and Annual 30-year Standard Normals.* WCDP No. 10. WMO-TD/No. 341, Geneva

Yeh, H.-Y., Wensel, L.C. and *Turnblom, E.C.*, 2000: An objective approach for classifying precipitation patterns to study climatic effects on tree growth. *Forest Ecol Manag 139*, 41-50.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 4, October–December 2009, pp. 315–339

Historical climatology in Hungary: Role of documentary evidence in the study of past climates and hydrometeorological extremes

Andrea Kiss

Department of Physical Geography and Geoinformatics, University of Szeged, Egyetem u. 2, H-6722 Szeged, Hungary; E-mail: kissandi@earth.geo.u-szeged.hu

(Manuscript received in final form October 16, 2009)

Abstract—In the present paper, an overview of studies and investigations, related to the field of historical climatology and impact of hydrometeorological extremes based on documentary evidence, is presented. In addition to this, earlier investigations as well as the present stage of historical climatology in Hungary are discussed, based on research studies of climatologists, meteorologists, historians, and geographers. Besides compilations and analyses on long-term climate change, case studies on weather-related extreme events and anomalies of the last thousand years (such as droughts and floods) are also included. As regards climate variability and change, an overview is provided on the research based on lake water-level changes.

Key-words: historical climatology, climate reconstructions, extreme weather events, hydrometeorological extremes, climate anomalies, impact studies

1. Introduction

In the last decade, recent climate change issues and global warming have elicited deeper investigation of not only short, but also long-term changes and variability of climate, with special attention paid to extreme weather events and their consequences. In this respect, studying the climate variability of the last thousand years, historical climatology has begun to play a more important role, not only in other parts of Europe (*Brázdil*, 2000, 2003; *Pfister*, 2001; for the latest overview of European literature, see *Brázdil et al.*, 2005b and *Brázdil*, 2009), but also in Hungary. While there is an obvious general interest, especially among historians, related to environmental history and climatic changes in historical periods, and also a growing demand for a better understanding of the environment where human interactions took place, the climate and climate variability of the last thousand years are still relatively underinvestigated in the

Carpathian Basin and Hungary as well. In 1986, historical climatology was already listed as a separate field of higher education (*Draskóczy*, 1986); nowadays, it is treated among historians as a part of historical ecology and environmental history (*R. Várkonyi*, 2001). Nevertheless, while in the 1980s the actual research on historical climatology related topics played a somewhat marginal role in Hungary, attention was soon drawn towards this field as a result of conference presentations and publications of L. Rácz in Hungarian and international scientific journals and textbooks (*Rácz*, 1987, 1988, 1989, 1994, 1995, 1998, 1999a, 2001a, 2003a, 2003b, 2007 etc.).

Investigations that have some connection with historical climatology and topics are quite dependent on the databases and/or source collections available. The usual practice among scientists analyzing historical evidence is to take an existing database, regardless of the source quality, translation, or copying mistakes; as such, source criticism is still of marginal importance. In fact, due to these problems, most scientists do not dare to 'touch' historical databases at all. Since the building process of a database for detecting long-term changes may take decades and bring forth less attractive results in the period in between, historians usually concentrate on a specific event or series of events, with a special emphasis on the effects of extreme events or anomalies on human society. Another area of research, mainly carried out by motivated climatologists and meteorologists, is database enlargement. Among these databases the Réthly-collection, with its four volumes (*Réthly*, 1962, 1970, 1998, 1999), doubtlessly contains the most useful information.

2. Antal Réthly and beyond: Compilations, data publishing, and reporting findings

2.1. The role of scientific journals

The positivistic 19th century was the heyday of heroic collectors, whereas in the scientific literature of the 20th century, most of the historical data-collection efforts were carried out by climatologists and meteorologists. In the quarterly journal of the Hungarian Meteorological Service (IDŐJÁRÁS), from the beginning of the 20th century up to the 1970s, there was a separate section entitled "*Régi magyar megfigyelések*" (Early Hungarian observations), intended for publishing texts on historical weather events, early meteorological observations, and measurements. Though it was mainly *Antal Réthly* who published his concrete findings, there were other authors such as *Barna* (1960) with his Sárospatak observations, and early instrumental measurements from the mid-19th century and the Slovak climatologist, *Konček* (1972) on early instrumental measurements taken in late 18th century in Bratislava. Most of the evidence was extracted from the original sources; while in many cases Latin or German texts were published in Hungarian in translated excerpts; in some cases transcriptions in the original language (e.g., in Latin) were provided as well (e.g., *Csíkmadarasi Bogáts*, 1943).

From 1952 onwards, there was another journal, called *Légkör* (Atmosphere), which published reviews and descriptions on historical weather observations that were source related, and even if most of those reports were mainly of a short, descriptive nature, they succeeded in drawing attention to the topic and the field (*Csomor*, 1988, 1991, 1992; *Justyák*, 1991, 1992; *Ambrózy*, 1995; *Simon*, 1999). Much less in quantity and better in source-quality, local historians occasionally published sources for further climatological investigation. From these efforts, the importance of the Sopron archives and publication series in the local history journal of the *Soproni Szemle*, amongst others, should be mentioned, where contemporary sources were published, mainly (*Hegyi*, 1966; *Tirnitz*, 1974) or partly for the purpose of further climatological investigations (*Csatkai*, 1940; *Heimler*, 1942).

Besides the publishing works of journals and the Réthly-series, another compilation for the Kecskemét area was published as well. Although the Kecskemét-compilation of *Szilágyi* (1993, 1999) in part contains data taken from the Réthly-series, several additional, local history pieces of evidence were also included. Concerning criticism of historical sources, *Szilágyi* followed the Réthly-style; thus, including both contemporary and non-contemporary evidence in his compilation.

2.2. Role of the Réthly-collection in climate history analysis

Early weather reports, descriptions, observations, and measurements mostly mentioned in the IDŐJÁRÁS were later included in the four volumes of Antal Réthly's well-known compilation on weather events, extremes, and natural disasters of historical Hungary, for periods before 1900 (*Réthly*, 1962, 1970, 1998, 1999). This work, without any doubt, is of the utmost importance and provides a firm basis for further studies. Although Réthly as a meteorologist clearly did ask for the help of archivists and historians for collection, transcription, and translation works in several cases, data selection was clearly his own personal choice throughout the long and fruitful decades of his life. It is a notable fact that his selection criteria, source-quality judgements primarily formed, and provided the basis of evaluation for the existing Hungarian long-term climate reconstructions, descriptions, and most of the short-term surveys as well. As a motivated meteorologist and climatologist, Antal Réthly collected and included in his series all sorts of written information concerning the weather prior to 1900, regardless of the quality of these written materials as a historical source. Thus, contemporary, non-contemporary, and secondary-literature references were all included without much source criticism and validation. As he said in the Introduction of the first volume (*Réthly*, 1962, p. 13): "I included all the old weather data collected..."

Although in some particularly problematic cases and with clear contradictions, he did give his opinion, and thus, criticized some of the sources included in his series from the viewpoint of dating mistakes or general credibility of points, the vast majority of non-contemporary evidence as well as secondary literature references were included in exactly the same way as primary sources. Furthermore, we need to make distinction between the various volumes. While the first three books mainly contain texts or text-summaries taken from contemporary and non-contemporary sources as well as from secondary literature, originally written either in Latin, German, or Hungarian (or occasionally in other languages), in the fourth volume chiefly direct transcriptions of contemporary daily weather observations and early instrumental measurements of the 19th century, originally written in Hungarian, were gathered (*Réthly*, 1999). As such, there is a source-quality difference compared to the earlier, translated extracts, which in many cases were based on non-contemporary evidence. Unfortunately, in this last volume of 19th century daily observations, no clear reference on the availability of original sources are provided for each case, which makes proper investigations in some cases quite difficult.

In conclusion, when making use of the Réthly-series in any climatological analysis, we should enumerate the following sets of problems, which largely affect and concern the complete database included in the first three volumes of the Réthly-compilation:

(1) Up to the late 18th century, significant part of evidence included in the Réthly-collection is non-contemporary, which makes the Réthly-based analysis of the period rather problematic, due to the fact that non-contemporary evidence often contains the wrong dating of events, doubling or tripling events, etc. At the level of data analysis, another crucial problem is that while filtering out the non-contemporary evidence, in periods prior to the 17th century a significant part needs to be removed, and the same goes for some of the 18th century sources. This is especially true for the Middle Ages, whose part of the first volume contains information of acceptable source quality only in exceptional cases. For example, secondary literature without source references (*Bagi*, 1896; *Szentkláray*, 1880–1882; *Tőry*, 1952, etc.), as well as foreign source compilations like the one by *Hennig* (1904) or those by *Weikinn* (1958–1963), and texts of popular journals, newspapers (*Hasznos Mulatságok*) about curiosities which happened hundreds of years earlier, were included as well. In this respect, volumes of the Réthly-collection show clear similarities to other European compilations: none of them can be properly utilized without prior source validation (*Bell* and *Ogilvie*, 1978).

(2) Regarding the majority of the 16th–18th centuries and a part of the 19th century, sources (both contemporary and non-contemporary) were originally written not in Hungarian, but mainly in Latin or German, and rarely in other languages such as Turkish. Hungarian texts are mainly well extracted and

German texts were usually well translated and well extracted too. In some cases, however, there are clear problems (misinterpretations, gaps), for example, with texts taken from Latin, which without the help of other corresponding material can affect some of the index values (e.g., monthly reports taken from the volumes of *Sydenham*, 1769; or texts taken from the Jesuit diary of Levoča (in Hungarian: Lőcse), see Hungarian National Archives p. 478).

(3) In many cases, there are clear contradictions between the intervals provided by Réthly at the beginning of the actual source entry and the duration of a period mentioned in the actual text (e.g., an unknown length of time before a wine harvest is imprecisely recorded as the whole of October); similarly, some of the often equivalent events are misdated (problems of dating winter weather; or the huge amount of misdated materials, taken from secondary literature or from recent, unpublished private compilations or text collections, such the one by Florián Holovics or Gottlieb Bruckner – without mentioning original sources).

(4) Another dating problem especially of the late 16th century is that, although in the introduction Réthly draws attention to the question of proper dating due to the switch between Julian and Gregorian calendars occurring in different years in various parts of the Carpathian Basin, he clearly did not take it into consideration when providing the dates of events or periods in the actual text entries (see parts before and around late 16th – early 17th centuries in *Réthly*, 1962).

(5) Contemporary evidence is very much scattered in space, type, and time: observations or descriptions are rarely available from one place or even one region for a period of at least several decades, and even in these cases it is rare that one type of evidence (e.g., a family diary) contains a lot of detailed (monthly level) data for longer periods (for several decades at least). Hence the available data may be quite patchy; that is, it may have a low level of homogeneity.

(6) Parallel observations and descriptions would be of special importance to specify and check the credibility and quality of indices provided. Since in the majority of cases no parallel observation of appropriate quality on monthly or seasonal level is available in the Réthly-volumes, and contemporary indirect evidence, where it exists, often does not provide enough additional information, in many cases it is not possible to provide good-quality indices. Thus, the sources allow us to provide indices (i.e., the stage of deviations from normal values) only with some uncertainty in relatively clear cases without using further control evidence (independent, reliable sources).

As regards the temperature and precipitation indices of monthly or seasonal level, a great deal of evidence included in the Réthly collection is non-contemporary. Since non-contemporary evidence cannot form the main basis of analysis for further investigations, just the contemporary evidence entries should be used. These circumstances lead us to conclude that large portions of the materials should be excluded from a primary analysis. The remaining contemporary documentary evidence, on the other hand, does not provide a source that is large and detailed enough to draw long-term conclusions in appropriate quality and detail.

In summary, based on the above-mentioned main points, the Réthly-collection by itself cannot form the basis of an adequate long-term historical climatological reconstruction of the past 500 years, or longer. Therefore, significant and systematic database enlargement based on contemporary evidence, not only for the Middle Ages and early modern times but for the 19th century as well, is required.

3. Long-term reconstructions of historical climate

3.1. Index-based climate reconstructions of the last 500–1000 years

Apart from his studies in collecting weather and weather-related data, Antal Réthly carried out some basic analyses of selected evidence, such as the series of daily observations combined with early instrumental measurements, later published in the 18th century volume of his compilations (*Réthly*, 1970). Despite this, Réthly did not provide any further, long-term analysis based on his compiled database. Instead, somewhat earlier *Berkes* (1940) carried out some investigations on the long-term fluctuations of climate, first based on instrumental measurements, and then on the early-spring temperature-related evidence of the Kőszeg Book of Vinesprouts (*Berkes*, 1942). On a local scale, for the Kecskemét area in the central part of the Great Hungarian Plain, *Szilágyi* (1987, 1988a, 1988b, 1988c), besides his catalogue of weather events, mainly described extremes and anomalies reported from 1600 to 1873, highlighting winter temperature extremes as well as extremely dry periods.

The first and still most widely known and applied (7-scale) index-based temperature and precipitation reconstruction along with a description of weather conditions, for the past five hundred years, focusing on the regions of the former Hungarian kingdom, were published and analyzed by *Rácz* (1999b). In addition to the revised indices and historical investigations, in the extended textual analysis a clear attempt towards separating major regions can be seen (see also *Rácz*, 2001a, 2003c). Another concise statistical analysis of long-term temperature and precipitation conditions as well as of the frequency of strong winds were carried out for a thousand-year period, based on the documentary data included in the Réthly-compilation by *Bartholy et al.* (2004).

In the case of both existing long-term reconstructions and investigations of written weather records, the text data of the Réthly-series formed the basis of further research. Nevertheless, while Lajos Rácz did not include the analysis of medieval parts due to the strikingly low source quality of non-contemporary evidence, in the second reconstruction the complete Réthly-database of weather events, namely documentary evidence of the entire last millennium, was included. Although authors of the second reconstruction (*Bartholy et al.*, 2004) did distinguish between quality value classes of information (based on quantity-analysis), they only provided data for 50-year intervals: in this sense they concluded that the data for the entire 16th century and partly for the first half of the 17th century was of low quality; while from the quantity aspect, only the period of 1700–1850 was regarded as highly reliable (*Bartholy et al.*, 2003, 2004).

In essence, these reconstructions were carried out for historical Hungary, hence, practically, for the entire Carpathian Basin. In the last decade, however, there has been an increasing demand for high-resolution long-term temperature and precipitation information, divided on a (sub)regional basis, in fields such as landscape research or geomorphology (e.g., *Stankoviansky*, 2003; *Kovács* and *Rakonczai*, 2003; *Kovács*, 2004; *Kiss et al.*, 2006a), and this has a potential use in other well-established or emerging research fields, in the Carpathian Basin, like borehole climatology, dendroclimatology, speleology (*Bodri* and *Dövényi*, 2004; *Kern et al.*, 2004, 2009; *Siklósy et al.*, 2006, 2009; *Popa* and *Kern*, 2009), or fields of historical science that apply the results of historical climatology (e.g., *Laszlovszky*, 1994; *Kiss* and *Paszternák*, 2000; *R. Várkonyi*, 2001; *Szabados*, 2004). Furthermore, some interest from a climatology aspect can be seen as well, which can provide a climatological background to historical climate investigations (e.g., *Mika et al.*, 2000; *Mika* and *Lakatos*, 2008).

In Romania, *Cernovodeanu* and *Binder* (1993) provided a description of historical evidence taken from the Middle Ages onwards, based partly on source materials mentioned in the Réthly-series and partly on other, mainly contemporary written evidence related to the eastern parts of historical Hungary, namely Transylvania and the historical Partium (which today make up the western Romanian lowlands). In their investigations, the historical Romanian principalities (Walachia and Moldova) were also included. In the most westerly areas of the Carpathian Basin, a historical analysis of weather-related evidence was performed by *Strömmer* (2003) for the period of 1700–1830 for eastern Austria. In his recent investigations, *Rohr* (2007) provided a detailed account and a concise historical analysis of high and late medieval as well as early modern extremes that occurred in the eastern regions of the Alps.

Climate reconstructions of shorter periods are also available in Hungary, mostly in the form of case studies. From a climatological aspect, as early as in 1918, Antal Réthly carried out some statistical analyses, for example, on the early instrumental measurements and daily weather observations of Timişoara (in Hungarian: Temesvár) for the period of 1780–1803. Tables of results of this study were later included in his compilation (*Réthly*, 1970), together with a basic statistical analysis of other observations and early instrumental measurements of the same type (e.g., for Miskolc and Kežmarok (in Hungarian: Késmárk). This work, together with the digitalization process of the complete Timişoara-manuscript, was continued by *Csernus-Molnár* and *Kiss* (2008). A detailed historical and climatological analysis of well-documented periods, based on daily observations and early instrumental measurements was carried out in certain selected cases, in the present eastern parts of Slovakia, for some periods of the late 17th and early 18th centuries (*Brázdil* and *Kiss*, 2001; *Brázdil et al.*, 2008).

3.2. Phenological evidence and harvest results: The role of indirect information

As regards documentary sources containing regular observations of phenological data of a longer duration, up to now in Hungary the information content of the Kőszeg Book of vinesprouts has without doubt gained much interest. Looking for long-term evidence of climate fluctuation and change, *Berkes* (1942) was the first who investigated the connection between early spring temperature values and the length of vinesprouts illustrated each year on April 24. His evaluation was extended by *Péczely* (1982), who also raised an awareness of the connection between the quality of wine as another possible temperature indicator. Their works on Kőszeg vinesprouts were continued and a temperature reconstruction model, based on the length of vinesprouts, was developed by *Střeštík* and *Verő* (2000). Studying 20th-century data series, the connection between wine quality, quantity and climate is the topic of a recent investigation referring to the Tokaj wine region (*Makra et al.*, 2009).

By the early 1970s, *Bendefy* (1972a) in a conference report pointed out the possible reconstruction potential of wine harvest data series in town council protocols such as those in Kőszeg, Sopron, Szombathely, and Kecskemét. In a preliminary report he considered a 36-year periodicity in Hungarian vintage dates (*Bendefy*, 1972a); no information is, however, available for a continuation of this investigation. While some dates of Kecskemét vintages from the late 17th to the early 19th centuries were already published by that time (*Szabó*, 1934), the Kőszeg vintage dates, for the period of 1649–1820 (with gaps), were published a few decades later (*Szövényi*, 1965). Nevertheless, in both cases the actual series of dates formed a relatively less-important, additional part of two local history investigations. As a result, both sets of data have never been analyzed from a climatological point of view, or the later remarks on their significance. Moreover, in both cases it can be seen that they often provide not the date of beginning but a date 2–3 days after, or only one date during the wine harvest in general; thus, they did not concentrate on providing data for the beginning of an event. Following these early investigations, based on the original sources, a new interpretation of vine- and grain-related historical evidence (see *Fig. 1*) has been initiated within the framework of the EU project called Millennium (*Kiss,* 2008; *Kiss* and *Wilson*, 2009).

By looking for possible causes of economic wealth, crises, or periods of decline, economic historians can play an important role in identifying weather extremes or climate anomalies. Based on grain tithe accounts, for the bad harvest years of the late 16th century in the Žitný ostrov (in Hungarian: Csallóköz) area, the principal causes of a rainy period and Danube floods as well as wars were highlighted by *Zimányi* (1984). Using tithe series, *Landsteiner* (1999) studied vine harvest results of selected Central European towns, including Sopron, at the end of the 16th and the beginning of the 17th centuries and demonstrated, that similarly to other wine producing areas of Central Europe, the Sopron area had to face a decline in wine production in the late 16th century, mainly caused by adverse weather conditions.

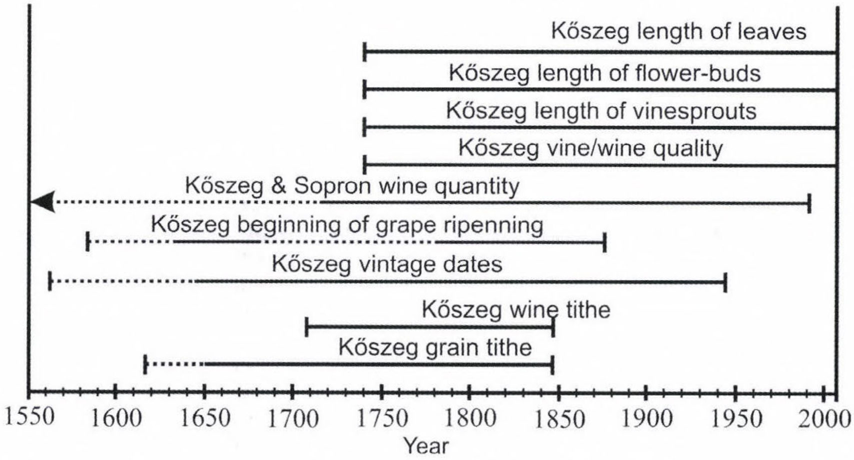


Fig. 1. Temporal coverage of recently available historical phenology evidence in Kőszeg (*Kiss*, 2008).

In the recent years, great interest has been shown in the possible agricultural consequences of climate change: based on evidence obtained from the Réthly-compilation, an analysis of phenological dates was done and phenophases information was examined (*Surányi*, 2006). However, owing to the quality and frequency of the data available in the Réthly-collection it is rather difficult to draw firm conclusions on this topic.

4. *Analysis of hydrometeorological extremes*

4.1. Causes and consequences: Impact studies based on extreme events

Series and combinations of extreme events and their consequences on the agriculture sector have, in some cases, gained more interest among agrarian and local historians. Some of the local history monographs, published in the period of the Austro-Hungarian Empire, contain particularly detailed accounts of natural disasters, induced by climate anomalies and weather extremes and their impact on local societies. Among others, a good example is the early monograph series by *Reizner* (1899–1900) about the local history of Szeged, where the great flood events of the Tisza in the Szeged area are described in an unusually detailed form, similar to the famine years, caused by a severe, prolonged drought of the late 1710s and 1720s. For instance in 1728, when the spring was particularly dry, and later this weather was combined with a great hailstorm over the plain, this caused the famous Szeged accusation case of witches. This witch-hunt, together with the historical background, was elaborated on in the first volume, together with primary sources (for a Central European context of witchcraft and weather, e.g., *Behringer*, 1999). This is of special importance, since the later monograph series of Szeged paid less attention to such issues (*Kristó*, 1985).

Droughts combined with extremely wet or cold periods caused the series of appealingly bad harvests in the Great Hungarian Plain, Transylvania, as well as in the Romanian principalities, which resulted in the great famine years of 1814–1817 in Bihar county (today, in Hungary and Romania), discussed by *Hodgyai* (1991). Also, the occurrence of the Maunder Minimum anomaly (1675–1715), as well as the cool summers of the 1830s and their adverse consequences on society in historical Hungary were discussed by *Rácz* (1994, 2001b). According to the author, as a consequence of cool summers there were bad harvests: these unfavorable conditions had an indirect influence on the decision-making policies of the contemporary Hungarian reform parliaments.

4.2. Droughts

In the central and eastern parts of the Carpathian Basin, especially in its lowland parts, mainly in the short-term but sometimes even in the long-term, severe droughts or a series of dry years probably had the most marked effects on the economy. Therefore, due to the well-known drought sensitivity of the semi-arid Great Hungarian Plain, droughts, said to be responsible for 22 known famines between 1790 and 1863 (*Érkövy*, 1863), have become a focal point of research. In historical research, the fields of local history and historical ethnography took a principal role in the study, description, and analysis of the effects of droughts on society, social relationships, economy, activities, and campaigns by the state and local authorities in finding solutions for crises which arose as a result of long dry spells. Since droughts had the greatest impact (greater than any flood event) in the aridification-endangered Great Hungarian Plain, studies usually concentrated on the most significant famines and mass extinction of cattle related to prolonged droughts of the late 18th and 19th centuries (*Györffy*, 1978; *Bellon*, 1996), but in some cases attention has also turned to the 1710s and 1720s (*Reizner*, 1899–1900).

Whereas floods caused problems in the previous decades but especially in the 1770s, the 1790s was without doubt the decade of droughts: investigating the great droughts of 1790 and 1794 (whose droughts also touched Moravia and Silesia – see *Brázdil et al.*, 2007), followed by famines, *Szabó* (1991) emphasized the significance of defence mechanisms developed by the society in 1791–1795 at both the local and regional levels in the north-central part of the Great Hungarian Plain, namely in Greater Cumania. Apart from the overwhelming importance of local history and historical ethnography research, looking for historical parallels of present drought events, to some extent environmental scientists also turned their attention towards this question (*Pálfai*, 1994). Nonetheless, without doubt great interest arose in the most influential drought of 1863, which is believed to have been primarily responsible for the fundamental and irreversible structural changes of Hungarian agriculture and as such, was widely discussed at both the regional and local level (*Reizner*, 1899; *Györffy*, 1978; *Bellon*, 1996; *Sipos*, 2001). In recent years, the possible connection between drought and the early 18th-century rise of witch accusations also became a topic of discussion among social historians (see, e.g., *Tóth*, 2008).

In two studies, mostly investigating the occurrence of famines in historical Hungary, the economic background, social consequences of droughts, and the response of the state are topics of discussion (*Gunst*, 1984a, 1984b). In his first article, the author suggests that due to the relatively low importance of crop production and consumption, and also due to the relatively low population density of the Carpathian Basin, droughts did not cause severe famines prior to the 18th century. Still, the number of famines caused by droughts increased from the early 18th century, when a great number of new settlers arrived in the country (*Gunst*, 1984a). Similar conclusions were reached in historical ethnography and local history studies, and he concluded that droughts of the Great Hungarian Plain and Transylvania in the 1850s and 1860s, and especially the well-known drought event of 1863 had probably the greatest impact on the long-term development and changes in agriculture, agricultural management, and economic development in Hungary. Moreover, this great drought event acted as a catalyst for the establishment of an independent Hungarian meteorological institute (*Gunst*, 1984b).

4.3. Floods

In Hungary another direction of historical research, which is also quite important in Central European investigations (e.g., *Brázdil et al.*, 2005a, 2007; *Glaser* and *Stangl*, 2004; concerning the Danube in Austria with emphasis on human response – see *Rohr*, 2005, 2007), focused on destructive historical floods: similar to well-known droughts, some of the especially destructive flood events were of especial interest and, as such, historians, hydrologists, as well as meteorologists studied them in great detail (in a European context, it is also reflected in the definition of historical hydrology – see *Brázdil et al.*, 2006). One of the early investigations was carried out by *Zawadovski* (1891). Apart from a detailed catalogue of data on water regulation, he listed the most destructive flood events that took place on larger rivers of the Carpathian Basin, especially from 1732 onwards, and sometimes he even gave a short overview on selected early modern floods as well. Although in most cases he did not provide clear evidence of his sources, in several cases he did refer to contemporary archival evidence. In addition, the author discussed some consequences (especially of material damage) of the greatest Danube floods in the late 18th and 19th century in the twin-town of Pest-Buda and Pest-Pilis-Solt County, like those of 1768, 1775, 1838, and 1876. Divided into small chapters, the author provided statistical information about damage in tabular form. Even if it is not completely free of errors, owing to the fact that no other comprehensive study of larger historical floods (Vol. 1) of the Carpathian Basin was carried out, this work became especially influential. Later investigations of hydrologists, usually including the obligatory short passages of a historical introduction, were largely based on the Zawadowski-catalogue.

Among the studies on individual flood events, most of the early studies were carried out on the 1838 ice flood at Pest-Buda (*Németh*, 1938; *Lászlóffy*, 1955), and the 1879 great Tisza flood at Szeged (for a concise overview of an early bibliography, see *Dégen et al.*, 1969; for a recent overview, see *Tóth*, 2009). These two events, together with their other consequences gained and still gain attention, and thus, separate chapters on several concise urban local history series, both old and new ones of Budapest and Szeged are usually devoted to the floods of great importance from the viewpoint of later urban development (*Gerevich*, 1975; *Kristó*, 1985). Furthermore, separate issues of the *Hidrológiai Közlöny* (*Hydrological Bulletin*) (1979: 59/6, 1988: 68/2) were published for the anniversaries of the great Pest-Buda and Szeged floods. In the past few decades, a new wave of analyses from both historians and environmental scientists were published for probably the most destructive flood event, namely the great 1838 Danube ice flood (*Faragó*, 1988; *Boldvay*, 1988; *Létay*, 1991 etc.), which practically destroyed the towns of Pest and Óbuda together with their suburbs. In this latter case, the meteorological conditions were also studied in detail (*Bodolainé Jakus*, 1988).

Based on data obtained from the Réthly-collection and the Zawadowski-catalogue, the connection between hard winters, ice cover, and ice floods of the Danube over a thousand year period are topics of discussion in the article by *Déri* (1989): due to the plentiful information available mostly for the period after 1820 and the impact of water regulations on ice cover, they were analyzed in more detail. Déri also emphasized the fact that, while significant efforts of water regulation works markedly reduced the chance of a looming destructive ice flood, still the danger was not over and, in the case of a hard winter, ice floods could cause significant damage even today. Mostly relying on the Zawadowski-catalogue, *P. Károlyi* (1970) studied the main periods and major consequences of significant flood events from the 18th century onwards of the Tisza valley from a hydrological viewpoint, with special emphasis on their impact on the later regulation works.

Other case studies on flood events are available in several individual articles, mainly done by local historians. Historical flood marks in Budapest were, for example, systematically described and investigated by *Rajna* (1979). Based on contemporary local history evidence, the most destructive flash floods and their impact on urban development were discussed in several local history articles (*Boronkai*, 1965; *Dobrossy* and *Veress*, 1978). In other studies, flood events of the River Maros (in Romanian: Mureş) in the 18th century (*Pálfai*, 1997; *Kiss et al.*, 2006b, 2008), those of the Drava river in the 16th–18th centuries (*Petrić*, 2007), and the main ice floods of the Danube between 1768 and 1799 together with related problems in the late 18th century development of Pest suburbs were discussed (*Kiss*, 2007). In a recent case study, the European aspects of great flood events in the winter and spring of 1784, including the Carpathian Basin, were also examined (*Brázdil et al.*, 2009).

5. Lake water-level changes: An interdisciplinary topic applying documentary evidence

As regards the lake-level variations related to climate variability, the investigations for Lake Balaton and Lake Fertő (in German: Neusiedlersee) should be emphasized.

By studying the water-level fluctuations of Lake Balaton, a great advantage can be detected in its shallowness as well as in the small, well-defined catchment situated at the west-central part of the Transdanubia in Hungary. In a book by *Bendefy* and *V. Nagy* (1969) on the water-level changes of Lake Balaton on a millennial scale, there is a clear attempt to apply contemporary medieval, early modern and modern documentary evidence. Although the book is still widely-accepted and used by scientists, the authors' interpretation of historical, cartographic, and archaeological evidence is often problematic and conclusions drawn are sometimes conceptual, and mostly related to the possible importance of human activity versus climate variability. As in some cases their results clearly contradict the other existing reconstruction, better accepted amongst historians and archaeologists (*Sági*, 1968; see also *Fig. 2*), a well-known, long-lasting debate (the so-called Balaton-debate), concerning medieval and early modern water levels, developed in the early 1970s (*Sági*, 1970; *Bendefy*, 1972b; *Sági* and *Füzes*, 1973). Another important difference was that, while in the case of the first water-level reconstruction human influence played an important role in the medieval and early-modern periods (*Bendefy* and *V. Nagy*, 1969; *Bendefy*, 1973), the other reconstruction viewed climate fluctuation as the factor primarily responsible for the historical water levels of Lake Balaton (*Sági*, 1968; *Sági* and *Füzes*, 1973).

On the other hand, in both papers there was a consensus on the fact that the average water-level of the Balaton underwent a slow rise in the high and later

Middle Ages, then this increase speeded up from the 16th century onwards. The changing human impact on the only natural outflow of the lake by itself, however, cannot be blamed for this significant increase, since the 14th century up to the mid-15th century contemporary sources show a survival of earlier utilization and management practices (mainly mills) of the waterflow (Fok/Sár river), even if in the 16th century, only the mills of the lower river sections (Sár river) were documented (*Kiss*, 2009). In the past few years, a multidisciplinary study, which included historical documentary evidence, was carried out by *Sümegi et al.* (2009a), and a comparison between the above-mentioned first water-level reconstruction and the available tree-ring evidence, connected to the 19th and 20th centuries, was published by *Kern* (2009).

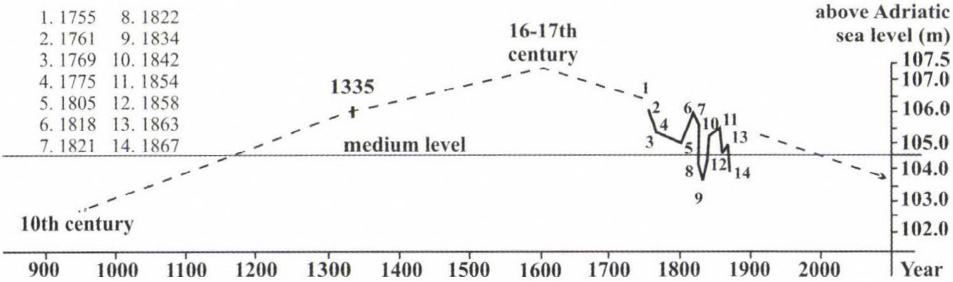


Fig. 2. The water-level changes of Lake Balaton in the past millennium, given by *Sági* and *Füzes* (1973).

Allegedly based on written evidence, the historical water-level changes of another lake, the Fertő (Neusiedlersee), which is even more sensitive to climate variability, was published by *Kopf* (1963). His extended reconstruction (*Fig. 3*), presumably based on documentary evidence, was widely accepted in the Hungarian scientific literature (*Zorkóczy*, 1975). Application possibilities are, however, strongly limited by the fact that Kopf made no mention at all of the sources used in the reconstruction (*Kiss*, 2004a).

In a similar way, although there was great interest and dozens of previous and later studies were carried out concerning the historical water-level changes of Lake Fertő (Neusiedlersee) and the Hanság (in German: Wasen) wetlands, most of the data was presented with no direct source-reference (*Nagy*, 1869; *Kövér*, 1930; *Haller*, 1941; *Károlyi*, 1955). They referred to earlier studies where, likewise, no reference concerning the source of information was provided (*Balsay et al.*, 1975; *Kováts*, 1982). As such, it is rarely possible to trace back all the original sources, based on literature entries. Other problems may occur when taking indirect written evidence into account: reconstruction attempts concerning medieval and early modern conditions often have interpretation problems of contemporary terminology (*Kiss*, 2004b). Quite similar problems have arisen in the scientific literature (*Bendefy* and *V. Nagy*, 1969) for the only natural outflow of Lake Balaton; namely the medieval Fok or Sár river (*Kiss*, 2009).

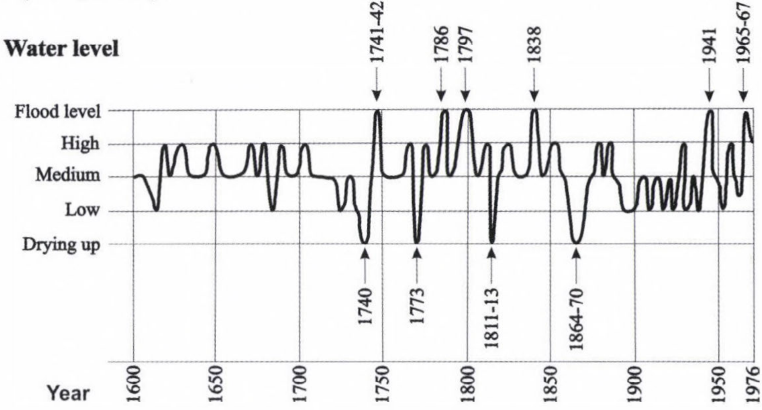


Fig. 3. Water-level changes of Lake Fertő (Neusiedlersee) in the last 400 years, elaborated by *Kopf* (1963), extended by *Zorkóczy* (1975).

6. Medieval weather and climate: Sources and analysis

From both medievalists and archaeologists, a growing interest could be seen to some extent from the 1960s (*Sági*, 1968), but especially from the 1990s onwards, with a particular emphasis on the Medieval Warm Epoch and the Little Ice Age transition (e.g., *Fügedi*, 1992; *Györffy* and *Zólyomi*, 1994, 1996; *Laszlovszky*, 1994; *Bálint*, 2003).

For the early Middle Ages, rather questionable attempts were made to relate the very scarce and problematic documentary evidence to a probable drought anomaly in the 8th century (*Györffy* and *Zólyomi*, 1994, 1996). Conversely, recent paleoenvironmental investigations suggest that droughts were more severe in the 13th century than in the 8th century (*Sümegi et al.*, 2009a; referring to 13th century conditions, see also *Sümegi et al.*, 2009b, 2009c). Concerning written sources, even much later, in the 11th–12th centuries only sporadic evidence is available (e.g., the battle of Ménfő: *Négyesi*, 1994), and these rarely provide the opportunity to draw some conclusions (*Kiss*, 2000a). Due to the growing amount of evidence, a few more detailed case studies have been occasionally carried out for particular, well-documented events of the 13th century like the hard winter conditions during the great or first Mongol invasion (*Kiss*, 2000b, 2003).

With the increasing amount of accurately dated 14th century legal evidence, in certain cases such as the 1340s, some great floods and presumed higher flood frequencies may be observed (*Kiss*, 1999). Concerning long-term changes, primarily based on archaeological and partly documentary evidence of the Visegrád royal palace and settlement, an interesting, early case study suggests that a significant increase of the average water level of the Danube began in the late medieval-early modern period (*Héjj*, 1988).

As regards the great subsistent crisis of 1315–1322 in Western Europe (*Kershaw*, 1973; *Jordan*, 1996), *Szántó* (2005, 2007) concluded that no contemporary evidence suggests that the crisis would have reached and had a significant impact in medieval Hungary. A recent investigation based on contemporary documents indicated that the European crisis of the mid-1310s reached and caused some problems in Hungary (*Vadas*, 2008).

Owing to the generally increasing amount of available medieval evidence, a review article was recently published on the medieval climate of Hungary (*Rácz*, 2007). Since very few studies have been published that directly analyze medieval weather and climate, it is a difficult task to provide any reliable conclusions on this subject. Therefore, database extension is of primary importance; up to now even key periods, like the 15th century with the most potential, have clearly been underinvestigated. Moreover, some contemporary legal documents (charters) suggest that not only direct but some indirect, landscape and hydrological evidence, for example the water-level conditions of larger lakes such as the Fertő (Neusiedlersee) in certain years, can also provide more useful information (*Kiss*, 2001; *Kiss* and *Piti*, 2005).

7. Conclusions and outlook

As we have seen, in Hungary climatologists and historians turned towards the study of climatic fluctuations and weather-related natural extremes at a relatively early period in history. This was partly due to the excellent potential arising from the immense amount of documentary evidence, largely available in present-day Hungary, but for historical reasons, for almost all of the Carpathian Basin as well. In this respect, it is clearly a positive point that the area of historical Hungary, meaning mainly Hungary, Slovakia, western Romania, northern Serbia, and the Transcarpathian region in Ukraine, is one of the areas in Central Europe with relatively early long-term historical climate reconstructions for the early-modern period (*Rácz*, 1999b, 2001a).

As a comparison, long-term (500-year or 1000-year) reconstructions on a monthly, seasonal basis (temperature, precipitation) are available in such areas of Central Europe as Switzerland (*Pfister*, 1988), the Czech Lands (*Brázdil* and *Kotyza*, 1995; *Dobrovolný et al.*, 2009a), and Germany (*Glaser*, 2001, 2008; *Glaser* and *Riemann*, 2009). A joint 500-year Central European seasonal temperature reconstruction, including the Czech Lands, Germany, and Switzerland, was recently carried out within the framework of the EU project called Millennium (*Dobrovolný et al.*, 2009b). Thus, an important future task will be to provide new index-based reconstructions, both for temperature and precipitation, based on an enlarged database of contemporary source evidence and a critical evaluation of sources.

Another promising direction for obtaining other long-term (mainly temperature-related) reconstructions is related to historical phenology evidence and other data series concerning agricultural activities (e.g., harvested amounts). Vine and grain phenology-based investigations, covering 500 years or more, have already been carried out in Central Europe (*Meier et al.*, 2007), which may eventually provide a good methodological background for the analysis of evidence either belonging to Hungary or other areas of the Carpathian Basin.

In spite of the good potential of contemporary documentary evidence, covering not just the early-modern period, but also the Middle Ages, in Hungary relatively little has been done on the systematic analysis of hydrometeorological extremes. This is especially true for flood evidence; even if dozens of more or less detailed case studies are available on one or another destructive drought or flood event, no systematic investigations have been carried out, unlike some other parts of Central Europe (see references in sub-chapter 4.3). Hence, another possible future direction of research is the systematic collection and analysis (e.g., frequency, classification, seasonality, causes, impact) of hydrometeorological extremes. Short- and long-term effects of extremes and anomalies on society had a further importance and have gained increasing interest in the past decade: impact studies and the role of human response have become a significant issue for environmental historians in Central Europe (e.g., *Behringer et al.*, 2005; *Pfister*, 1999, 2002; *Pfister* and *Brázdil*, 2006). As we saw earlier, in the form of individual events, in Hungary historical ethnographers and local historians played an important role in analyses, especially on droughts, and also on other hydrometeorological events like floods. As regards other types of impact, studies on the relationship between climatic fluctuations, frequency of extremes and landscape development might also be an interesting direction of further research (for Central European parallels, see, e.g., *Bork et al.*, 1998).

While no systematic collection and analysis of events have been carried out yet, after the source validation process the vast amount of contemporary evidence included in the Réthly-compilation could form a good starting point for systematic investigations covering a period of four hundred years or more. In this respect, the Middle Ages need to be treated differently: a completely new documentary source collection process has to be launched.

Acknowledgements—The present study was supported by the FP6 EU project Millennium No. 017008. The author would like to express her special thanks to *Rudolf Brázdil* (Masaryk University, Czech Republic) for his help and careful corrections. The author is also grateful to *Sheila Hicks* (University of Oulu, Finland), *József Laszlovszky* (Central European University, Hungary), *János Mika* (Hungarian Meteorological Service, Hungary), *Pál Sümegi* (University of Szeged, Hungary), and *Ágnes R. Várkonyi* (Eötvös Loránd University, Hungary) for their useful suggestions, and to *David P. Curley* (University of Szeged, Hungary) for proof-reading this article.

References

Ambrózy, P., 1995: Meteorological observations of David Frőhlich (in Hungarian). *Légkör 40*, No. 4, 23-24.

Bagi, L. (ed.), 1896: *Kecskemét múltja és jelene* (Past and present of Kecskemét). Tóth László Nyomdája, Kecskemét, 214 pp.

Balsay, L., *Halupa, L.* and *Komjáthy, F.*, 1975: Data on the history of forests in the Hanság area (in Hungarian). In *Az erdőgazdálkodás története Magyarországon* (History of Forestry in Hungary) (ed.: *Kolossváry, Sz.*). Akadémiai Kiadó, Budapest, 394-465.

Barna, U., 1960: Weather reports in Sárospatak between 1847-1853 (in Hungarian). *Időjárás 64*, 115-118.

Bartholy, J., *Pongrácz, R.* and *Molnár, Zs.*, 2003: Extremes and millennial trends in the Carpathian Basin using the Réthly documentary collection. American Meteorological Society, *17th Conference on Probability and Statistics in the Atmospheric Sciences*, Extended Abstracts, 1-12.

Bartholy, J., *Pongrácz, R.* and *Molnár, Zs.*, 2004: Classification and analysis of past climate information based on historical documentary sources for the Carpathian Basin. *Int J Climatol 24*, 1759-1776.

Bálint, M., 2003: Landscape development and soil formation in the Danube-Tisza Interfluve. In *People and Nature in Historical Perspective* (eds.: *J. Laszlovszky* and *P. Szabó*). Archaeolingua, Budapest, 157-174.

Behringer, W., 1999: Climatic change and witch-hunting: The impact of the Little Ice Age on mentalities. *Climatic Change 43*, 335-351.

Behringer, W., *Lehmann, H.* and *Pfister, Ch.* (eds.), 2005: *Kulturelle Konsequenzen der "Kleinen Eiszeit*". Vandenhoeck&Ruprecht, Göttingen, 510 pp.

Bell, W.T. and *Ogilvie, A.E.J.*, 1978: Weather compilations as a source of data for the reconstruction of European climate during the medieval period. *Climatic Change 1*, 331-348.

Bellon, T., 1996: *Beklen. A nagykunsági mezővárosok állattartó gazdálkodása a XVIII-XIX. században* (Beklen. Animal husbandry of the towns in Greater Cumania in the 18-19th centuries). Karcag Város Önkormányzata, Karcag, 31-38.

Bendefy, L., 1972a: A 400-year phenological curve based on the ripening of Hungarian grapevines (in Hungarian). In *Anyag- és energiaáramlási ankét* (Meeting on material and energy flux) (eds.: *E. Szádeczky-Kardoss* and *É. Pécsiné Donáth*). Akadémiai Kiadó, Budapest, 31-33.

Bendefy, L., 1972b: The influence of natural and anthropogenic factors on the water-level changes of Lake Balaton (in Hungarian). *Földrajzi Értesítő 2-3*, 335-358.

Bendefy, L., 1973: Dykes at Jut and the high water-level conditions of Lake Balaton in the Turkish Period (in Hungarian). *Somogy megye múltjából 4*, 113-128.

Bendefy, L. and *V. Nagy, I.*, 1969: *A Balaton évszázados partvonalváltozásai* (Millennial shoreline changes of Lake Balaton). Műszaki Kiadó, Budapest, 215 pp.

Berkes, Z., 1940: Changes in climate or variability of climate? (in Hungarian) *Időjárás 44*, 155.

Berkes, Z., 1942: Éghajlatingadozások tükröződése a kőszegi szőlőhajtások hosszában / Spiegelung der Klimaschwankungen in dem Längenwachstum der Weinreben-Triebe in Kőszeg. *A M. Kir. Orsz. Meteorológiai és Földmágnességi Intézet Kisebb kiadványai, Új sorozat 15*, Budapest, 17 pp.

Bodolainé Jakus, E., 1988: Weather conditions of the 1838 ice flood of the Danube (in Hungarian). *Hidrológiai Közlöny 68*, 72-77.

Bodri, L. and *Dövényi, P.*, 2004: Climate change of the last 2000 years inferred from borehole temperatures: data from Hungary. *Global and Planetary Change 41*, 121-133.

Boldvai, F., 1988: About the ice flood of Pest 150 years ago (in Hungarian). *Légkör 33*, No. 2, 32-37.

Bork, H-R., *Bork, H.*, *Dalchow, C.*, *Faust, B.*, *Piorr, H-P.* and *Schatz, T.*, 1998: *Landschaftsentwicklung in Mitteleuropa: Wirkungen des Menschen auf Landschaften*. Klett-Perthes, Stuttgart, 328 pp.

Boronkai, P., 1965: Floods in Sopron (in Hungarian). *Soproni Szemle 19*, 339-346.

Brázdil, R., 2000: Historical climatology: definition, data, methods, results. *Geografický časopis 52*, 99-121.

Brázdil, R., 2003: Historical climatology and its progress after 1990. In *People and Nature in Historical Perspective* (eds.: *J. Laszlovszky* and *P. Szabó*). Central European University, Department of Medieval Studies & Archaeolingua, Budapest, 197-227.

Brázdil, R., 2009: Historical climatology and its contribution to climate reconstruction in Europe. In *Nachhaltige Geschichte. Festschrift für Christian Pfister* (eds.: *A. Kirchhofer, D. Krämer, C.M. Merki, G. Poliwoda, M. Stuber* and *S. Summermatter*). Chronos Verlag, Zürich, 65-89.

Brázdil, R. and *Kotyza, O.*, 1995: *History of Weather and Climate in the Czech Lands I (Period 1000-1500).* Zürcher Geographische Schriften 62, Zürich, 260 pp.

Brázdil, R. and *Kiss, A.*, 2001: Daily weather observations at Košice, Slovakia, in the period 1677-1681. *Meteorologický časopis 4*, 3-14.

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Macková, J., Müller, M., Štekl, J., Tolasz, R. and *Valášek, H.*, 2005a: *Historical and Recent Floods in the Czech Republic* (in Czech). Masaryk University, Czech Hydrometeorological Institute, Brno, Praha, 370 pp.

Brázdil, R., Pfister, Ch., Wanner, H., von Storch, H. and *Luterbacher, J.*, 2005b: Historical climatology in Europe – the state of the art. *Climatic Change 70*, 363-430.

Brázdil, R., Kundzewicz, Z. W. and *Benito, G.*, 2006: Historical hydrology for studying flood risk in Europe. *Hydrolog Sci J 51*, 739-764.

Brázdil, R., Kirchner, K. Březina, L, Dobrovolný, P., Dubrovský, M., Halásová, O., Hostýnek, J., Chromá, K., Janderková, J., Kaláb, Z., Keprtová, K., Kotyza, O., Krejčí, O., Kunc, J., Lacina, J., Lepka, Z., Létal, A., Macková, J., Máčka, Z., Mulíček, O., Roštínský, P., Řehánek, T., Seidenglanz, D., Semerádová, D., Sokol, Z., Soukalová, E., Štekl, J., Trnka, M., Valášek, H., Věžník, A., Voženílek, V. and *Žalud, Z.*, 2007: *Selected Natural Extremes and Their Impacts in Moravia and Silesia* (in Czech). Masaryk University–Czech Hydrometeorological Institute and Institute of Geonics–Academy of Sciences of the Czech Republic, Brno, Praha, Ostrava, 432 pp.

Brázdil, R., Kiss, A., Luterbacher, J. and *Valášek, H.*, 2008: Weather patterns in eastern Slovakia 1717-1730, based on records from the Breslau meteorological network. *Int J Climatol 28*, 1639-1651.

Brázdil, R., Demarée, G.R., Deutsch, M., Garnier, E., Kiss, A., Luterbacher, J., MacDonald, N., Rohr, Ch., Dobrovolný, P., Kolář, P. and *Chromá, K.*, 2009: European floods during the winter 1783/1784: scenarios of an extreme event during the 'Little Ice Age'. *Theor Appl Climatol,* doi 10.1007/s00704-009-0170-5.

Cernovodeanu, P. and *Binder, P.*, 1993: *Cavalerii Apocalipsului. Calamităţile naturale din trecutul României (până la 1800)* (Knights of the Apocalypse. Natural disasters of Romania up to 1800). SILEX–Casă de Editură S.R.L., Bucureşti, 255 pp.

Csatkai, E., 1940: Sopron chronicles I.: Chronicle of Daniel Petz senior and junior (in Hungarian and German). *Soproni Szemle 4*, 133-203.

Csernus-Molnár, I. and *Kiss, A.*, 2008: Instrumental measurements and weather reports in Temesvár [Timişoara] (in Hungarian). In *IV. Magyar Földrajzi Konferencia tanulmánykötet* (Research papers of the Fourth Conference on Geography in Hungary) (eds.: *V. Szabó, Z. Orosz, R. Nagy*, and *I. Fazekas*). Debreceni Egyetem, Debrecen, 205-211.

Csíkmadarasi Bogáts, D., 1943: Reports of János Vásárhely, Calvinist priest of Sepsiszentgyörgy [Sfântu Gheorghe] about the weather conditions of the years 1722-1764 (in Hungarian and Latin). *Időjárás 47*, 143-145, 235-236.

Csomor, M., 1988: Extreme winters in Hungary in the 19th century (in Hungarian). *Légkör 33*, No. 4, 31.

Csomor, M., 1991: Early Hungarian observations: the winter of 1791 (in Hungarian). *Légkör 36*, No. 2, 29.

Csomor M., 1992: Early Hungarian weather observations (1791/1792) 200 years ago (in Hungarian). *Légkör 37*, No. 3, 31.

Dégen, I., Lászlóffy, W. and *Károlyi, Zs.*, 1969: *A szegedi árvíz 1879* (The Great Flood of 1879 in Szeged). Vízügyi történeti füzetek 1, VIZDOK, Budapest, 80 pp.

Déri, J., 1989: Ice floods of the Danube in the last Millennium (in Hungarian). *Hidrológiai Közlöny 69*, 151-158.

Dobrossy, I. and *Veres, L.*, 1978: *Miskolci árvíz 1878-1978* (Flood in Miskolc 1878-1978). Herman Ottó Múzeum, Miskolc, 66 pp.

Dobrovolný, P., Brázdil, R., Valášek, H., Kotyza, O., Macková, J. and *Haličková, M.*, 2009a: A standard paleoclimatological approach to temperature reconstruction in historical climatology: an example from the Czech Republic, A.D. 1718–2007. *Int J Climatol 29*, 1478–1492.

Dobrovolný, P., Moberg, A., Brázdil, R., Pfister, Ch., Glaser, R., Wilson, R., van Engelen, A., Limanówka, D., Kiss, A., Haličková, M., Macková, J., Riemann, D., Luterbacher, J. and *Böhm, R.*, 2009b: Monthly and seasonal temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. *Climatic Change*, doi 10.1007/s10584-009-9724-x.

Draskóczy, I., 1986: Historical climatology (in Hungarian) In *A történelem segédtudományai* (Auxiliary sciences of history) (ed.: *I. Kállay*). Eötvös Loránd Tudományegyetem Bölcsészettudományi Kar, Budapest, 307-316.

Érkövy, A., 1863: *Az 1863. évi aszályosság a Magyar Alföldön* (Drought in 1863 on the Great Hungarian Plain). Országos magyar gazdasági egyesület, Pest, 103 pp.

Faragó, T. (ed.), 1988: *Pest-budai árvíz 1838* (Flood in Pest-Buda 1838). Főv. Szabó Ervin Könyvtár, Budapest, 515 pp.

Fügedi, E., 1992: Historical demography of medieval Hungary (in Hungarian). *Történeti demográfiai füzetek 10*, 10-60.

Gerevich, L. (ed.), 1975: *Budapest története* (History of Budapest). Akadémiai Kiadó, Budapest, 288-300.

Glaser, R., 2001: *Klimageschichte Mitteleuropas. 1000 Jahre Wetter, Klima, Katastrophen*. Primus-Verlag, Darmstadt, 227 pp.

Glaser, R., 2008: *Klimageschichte Mitteleuropas. 1200 Jahre Wetter Primus-Verlag, Klima, Katastrophen*. Wissenschaftliche Buchgesellschaft, Darmstadt, 227 pp.

Glaser, R. and *Stangl, H.*, 2004: Climate and floods in Central Europe since AD 1000: Data, methods, results and consequences. *Surv Geophys 25*, 485-510.

Glaser, R. and *Riemann, D.*, 2009: A thousand-year record of temperature variations for Germany and Central Europe based on documentary data. *J Quaternary Sci 24*, 437-449.

Gunst, P., 1984a: Hungersnöte und Agrarausfuhr im spätmittelalterlichen Ungarn (1700-1848). *Agrártörténeti Szemle 26*, 11-18.

Gunst, P., 1984b: Droughts and the Hungarian state. From the 18th century to 1945 (in Hungarian). *Agrártörténeti Szemle 26*, 438-457.

Györffy, L., 1978: Memory of the 'horrible year' and the great famine of 1863 (in Hungarian). *Szolnok megyei múzeumok közleményei 1*, 91-103.

Györffy, Gy. and *Zólyomi, B.*, 1994: Landscape of the Carpathian Basin and the 'Etelköz' thousand years ago (in Hungarian). In *Honfoglalás és régészet* (Conquest and archaeology) (ed.: *L. Kovács*). Balassi Kiadó, Budapest, 13-37.

Györffy, Gy. and *Zólyomi, B.*, 1996: The Carpathian Basin and the 'Etelköz' thousand years ago (in Hungarian). *Magyar Tudomány 96*, 899-918.

Haller, J., (1941) 1998: *Moson vármegye történelmi földrajza* (Historical geography of Moson county). Mosonmagyaróvári Helytörténeti Füzetek 9. Mosonmagyaróvári Hansági Múzeum, Mosonmagyaróvár, 318 pp.

Hegyi, F., 1966: Judgement day in the Sopron area in 1789 (in Hungarian). *Soproni Szemle 20*, 378.

Heimler, K., 1942: Sopron chronicles II: chronicle of Georg Payr and Michael Payr 1584-1700 (in Hungarian and German). *Soproni Szemle 6*, 1-94.

Hennig, R., 1904: *Katalog bemerkenswerter Witterungsereignisse von den ältesten Zeiten bis zum Jahre 1800.* Abhandlungen des Königlich Preussischen Meteorologischen Instituts. Vol. 2, No. 4. A. Asher, Berlin, 93 pp.

Héjj, M., 1988: Observations concerning settlement geography. Visegrád in the 14th-16th centuries (in Hungarian). In *Visegrád 1335. Tudományos tanácskozás a visegrádi királytalálkozó 650. évfordulóján* (Visegrád 1335. Scientific workshop on the 650th anniversary of the Visegrád royal meeting) (ed.: *J. Köblös*). Pest Megyei Levéltár, Budapest, 63-67.

Hodgyai, M., 1991: Hunger years in Bihar between 1814-1817 (in Hungarian). *Történelmi Szemle 33*, 59-69.

Jordan, W.Ch., 1996: *The Great Famine. Northern Europe in the Early Fourteenth Century.* University Press, Princeton, 316 pp.

Justyák, J., 1991: Weather reports in Széchenyi's diary (in Hungarian). *Légkör 36*, No. 2, 15-18.

Justyák, J., 1992: Weather of Debrecen based on early reports: 1820-1837 (in Hungarian). *Légkör 37*, No. 3, 19-21.

Károlyi Z., 1955: Development of water-regulation issues of the Hanság wetlands and Lake Fertő (in Hungarian). *Vízügyi Közlemények 37*, 291-332.

Kern, Z., 2009: Connection between oak tree ring width of the Balaton Uplands and the water-level changes of Lake Balaton (in Hungarian). In *Környezettörténet* (Environmental history) (ed.: *M. Kázmér*). Hantken kiadó, Budapest, 357-366.

Kern, Z., Fórizs, I., Nagy, B., Kázmér, M., Gál, A., Szántó, Z., Palcsu, L., and *Molnár, M.*, 2004: Late Holocene environmental changes recorded at Gheţarul de la Focul Viu, Bihor Mountains, Romania. *Theor Appl Karstology 17*, 51-60.

Kern, Z., Grynaeus, A. and *Morgós, A.*, 2009: Reconstructed precipitation for southern Bakony Mountains (Transdanubia, Hungary) back to 1746 AD based on ring widths of oak trees. *Időjárás 113*, 299-314.

Kershaw, I., 1973: The Great Famine. *Past and Present 59*, 3-50.

Kiss, A., 1999: Some weather events in the fourteenth century II (Angevin period: 1301-1387). *Acta Climatologica Universitatis Szegediensis 32-33*, 51-64.

Kiss, A., 2000a: Evidence on weather in 11-12th-century Hungary (in Hungarian). In *Magyaroknak eleiről* (About the ancestors of Hungarians) (eds.: *F. Piti* and *Gy. Szabados*). SzKM, Szeged, 249-263.

Kiss, A., 2000b: Weather events during the first Tatar invasion in Hungary (1241-42). *Acta Geographica Universitatis Szegediensis 37*, 149-156.

Kiss, A., 2001: Hydrology and Environment in the Southern Basin of Lake Fertő/Neusiedlersee in the Late Middle Ages. *Medium Aevum Quotidianum 44*, 61-77.

Kiss, A., 2003: „Ecce, in hyemis nivis et glaciei habundantia supervenit" – Weather, environmental crisis and the Mongol invasion (in Hungarian). In *Tatárjárás* (Mongol invasion) (ed.: *B. Nagy*). Osiris, Budapest, 439-452.

Kiss, A., 2004a: Utilization of the inundation area at Lake Fertő before the regulation works: Example of Sarród and its surroundings. *Acta Geographica Universitatis Szegediensis 38*, 39-49.

Kiss, A., 2004b: Waterflows in the basin of great lakes: Fertő and Balaton rivers? (in Hungarian). In *Víz a tájban* (Water in the landscape) (ed.: *Gy. Füleky*). Gödöllői Agrártudományi Egyetem, Gödöllő, 325-331.

Kiss, A., 2007: "Suburbia autem maxima in parte videntur esse deleta" – Danube icefloods and the pitfalls of urban planning: Pest and its suburbs in 1768–1799. In *From Villages to Cyberspace*. (ed.: *Cs. Kovács*). University Press, Szeged, 271-282.

Kiss, A., 2008: The 'Millennium' FP6 EU projekt – possible role of Hungarian documentary evidence in the European millennial climate reconstruction (in Hungarian). In *IV. Magyar Földrajzi Konferencia tanulmánykötet* (Research papers of the Fourth Conference on Geography in Hungary) (eds.: *V. Szabó, Z. Orosz, R. Nagy*, and *I. Fazekas*). Debreceni Egyetem, Debrecen, 163-169.

Kiss, A., 2009: „Rivulus namque, qui dicitur Fuk, fluens de prefatu lacu" – Fok, Sár, Foksár (in Hungarian). In *Antropogén ökológiai változások a Kárpát-medencében* (Ecological changes of anthropogenic origin in the Carpathian Basin) (eds.: *B. Andrásfalvy* and *G. Vargyas*). Studia Ethnologica Hungarica 9, L'Harmattan and PTE Néprajz–Kulturális Antropológia Tanszék. Budapest, 49-63.

Kiss, A. and *Paszternák, I.*, 2000: Where was Urkony located? Historical geographical and archaeological evidence for studying the topography of a medieval village (in Hungarian). *Soproni Szemle 52*, 402-419.

Kiss, A. and *Piti, F.*, 2005: The 'fok' of the Fertő (in Hungarian). *Soproni Szemle 59*, 164-184.

Kiss, A. and *Wilson, R.*, 2009: Analysis of late spring-summer temperatures for Western Hungary based on vine, grain tithes and harvest records. European Geosciences Union, *Geophysical Research Abstracts*, Vol. 11, 10945.

Kiss, A., Sümeghy, Z. and *Danku, Gy.*, 2006: The severe winter of 1783-1784 and the ice flood of the Maros river (in Hungarian). In *Táj, környezet és társadalom* / Landscape, Environment and Society (bilingual Hungarian and English volume, with English abstracts) (eds.: *A. Kiss, G. Mezősi* and *Z. Sümeghy*). Szegedi Tudományegyetem, Szeged, 353-362.

Kiss, A., Sümeghy, Z. and *Fehér, Z. Zs.*, 2008: 18th-century floods of the Maros river and the regional consequences of a typical winter flood event (in Hungarian). In *Tájváltozások a Kárpát-medencében: Az erdélyi táj változásai* (Landscape changes in the Carpathian Basin: Changes of the Transylvanian landscape) (ed.: *Gy. Füleky*). Környezetkímélő Agrokémiáért Alapítvány, Szent István Egyetem, Gödöllő, 94-100.

Kiss, T., Nyári, D. and *Sipos, Gy.*, 2006a: Blown sand movement in historical times in the region of Csengele (in Hungarian). In *Táj, környezet és társadalom* / Landscape, Environment and Society (bilingual Hungarian and English volume, with English abstracts) (eds.: *A. Kiss, G. Mezősi* and *Z. Sümeghy*). SzTE, Szeged, 373-382.

Končec, M., 1972: Über die ersten meteorologischen Aufzeichnungen in Bratislava (Pressburg) aus dem Ende des 18. Jahrhunderts. *Időjárás 76*, 51-53.

Kopf, F., 1963: Wasserwirtschaftliche Probleme des Neusiedler Sees und des Seewinkels. *Österreichische Wasserwirtschaft 15*, 190-203.

Kovács, F., 2004: Evaluation of environmental changes in the Danube Tisza Interfluve, with special emphasis on drought problems (in Hungarian). In *II. Magyar Földrajzi Konferencia tanulmánykötet* (Research papers of the Second Conference on Geography in Hungary) (eds.: *G. Barton* and *G. Dormány*). Szegedi Tudományegyetem TFGT, Szeged, 1046-1072.

Kovács, F. and *Rakonczai, J.*, 2003: Analysis of the 200-year environmental changes of a strictly protected area in the Kiskunság National Park, Hungary. In *Dealing with Diversity. Proc. of the 2nd International Conference of European Society for Environmental History*. Charles University, Prague, 263-268.

Kováts, Z., 1982: A Fertő tó mederviszonyai / Bettverhältnisse des Neusiedlersees. In *A Fertő-tó természeti adottságai* / Naturverhältnisse des Neusiedlersees (in Hungarian with German abstracts) (eds.: *Z. Kováts* and *E. Kozmáné Tóth*). Országos Meteorológiai Szolgálat, Budapest, 13-40.

Kövér, F.J., 1930: *A Hanság földrajza* (Geography of the Hanság area). Szeged városi nyomda és könyvkiadó Rt., Szeged, 99 pp.

Kristó, Gy. (ed.), 1985: *Szeged története* (History of Szeged). Vol. 2, Somogyi Könyvtár, Szeged, 846 pp.

Landsteiner, E., 1999: The crisis of wine production in late sixteenth-century Central Europe: Climatic causes and its economic consequences. *Climatic Change 43*, 323-334.

Laszlovszky, J., 1994: „Per tot discrimina rerum" Zur Interpretation von Umweltveränderungen im mittelalterlichen Ungarn. In *Umweltbewältigung. Die historische Perspektive* (eds.: G. *Jaritz* and *V. Winiwarter*). Verlag für Regionalgeschichte, Bielefeld, 37-55.

Lászlóffy, W., 1955: Flood of 1838 and the water regulation works of the Danube (in Hungarian). *Vízügyi Közlemények 20*, 39-44.

Létay, M., 1991: Flood in Óbuda in 1838: for the 150th anniversary of the catastrophy (in Hungarian). *Tanulmányok Budapest múltjából 24*, 17-26.

Meier, N., Rutishauser, Th., Pfister, Ch., Wanner, H. and *Luterbacher, J.*, 2007: Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. *Geophysical Research Letters 34*, L20705, doi 10.1029/2007GL031381.

Makra, L., Vitányi, B., Gál, A., Mika, J., Matyasovszky, I. and *Hirsch, T.* 2009: Wine quantity and quality varioations in relation to climatic factors in the Tokaj winegrowing region (Hungary). *Am J Enol Viticult 60*, 312-321.

Mika, J. and *Lakatos, M.*, 2008: Extreme weather tendencies in Hungary based on empirical and model approaches. *J Environ Geography 1*, 57-66.

Mika, J., Domonkos, P. and *Lakatos M.*, 2000: Meteorological revision of indirect temperature series (in Hungarian). In *Erdő és Klíma* (Forest and climate) (ed.: *K. Tar*). Debreceni Egyetem, Debrecen, 171-184.

Nagy, I., 1869: Early floods of the Fertő (in Hungarian). *Századok 3*, 690-709.

Négyesi, L., 1994: Battle of Ménfő (in Hungarian). *Hadtörténeti Közlemények 3*, 136-146.

Németh, K., 1938: *A pest-budai árvíz 1838-ban* (Flood of Pest-Buda in 1838). Budapest Székesfőváros Közönsége, Budapest, 387 pp.

Pálfai, I., 1994: Memory of the extraordinary drought of 1794 (in Hungarian). *Hidrológiai Tájékoztató 34*, 16-17.

Pálfai, I. 1997: Floods of the Maros in the 18th century (in Hungarian). *Hidrológiai Tájékoztató 37*, 34-35.

Petrić, H., 2007: Drava river flooding in Varaždin and Koprivnica parts of Podravina (Drava river region – between Croatia and Hungary) in the period of 17th-19th centuries. *Podravina 12*, 136-147.

Péczely, Gy., 1982: The Kőszeg 'Book of Vinesprouts' (in Hungarian) *Légkör 27*, No. 3, 24-27.

Pfister, C., 1988: *Klimageschichte der Schweiz: 1525-1860: das Klima der Schweiz von 1525-1860 und seine Bedeutung in der Geschichte von Bevölkerung und Landwirtschaft.* Haupt Verlag, Bern, Stuttgart, 394 pp.

Pfister, C., 1999: *Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen (1496-1995).* Paul Haupt, Bern, 304 pp.

Pfister, C., 2001: Klimawandel in der Geschichte Europas. Zur Entwicklung und zum Potenzial der Historischen Klimatologie. *Österreichische Zeitschrift für Geschichtswissenschaften 12*, 7-43.

Pfister, C. (ed.), 2002: *Am Tag danach. Zur Bewältigung von Naturkatastrophen in der Schweiz 1500-2000.* Paul Haupt, Bern, 263 pp.

Pfister, C. and *Brázdil, R.*, 2006: Social vulnerability to climate in the "Little Ice Age": an example from Central Europe in the early 1770s. *Climate of the Past* 2, 115-129.

P. Károlyi, Zs., 1970: Data to the flood-history of the Tisza-valley (in Hungarian). *Vízgazdálkodás 10*, 150-152, 191-192.

Popa, I. and *Kern, Z.*, 2009: Long-term summer temperature reconstruction inferred from tree-ring records from the Eastern Carpathians. *Climate Dynamics 32*, 1107-1117.

Rajna, Gy., 1979: Flood marks in Budapest (in Hungarian). *Tanulmányok Budapest múltjából 21*, 361-392.

Rácz, L., 1987: Climate variabilities in the Carpathian Basin between 1490-1700 (in Hungarian). *Légkör 32*, No. 4, 29-31.

Rácz, L., 1988: Changes in the climate of the Great Hungarian Plain between 1490-1779 based on historical sources (in Hungarian). *Alföldi Tanulmányok 12*, 34-47.

Rácz, L., 1989: About the climate history of the Little Ice Age (in Hungarian). *Agrártörténeti Szemle 31*, 185-190.

Rácz, L., 1994: The climate of Hungary during the Maunder Minimum Period. In *Climatic Trends and Anomalies in Europe 1675-1715* (eds.: *B. Frenzel, C. Pfister* and *B. Gläser*). *Palaeoclimate Research 13*, Fischer, Stuttgart, 95-108.

Rácz, L., 1995: Climate history of the Carpathian Basin in the early modern period (in Hungarian). *Történelmi Szemle 37*, 487-508.

Rácz, L., 1998: Climate history source collections of Antal Réthly and the reconstruction of climate changes (in Hungarian). *Légkör 43*, No. 4, 2-6.

Rácz, L., 1999a: Climate history of Hungary from the 16th century to the present day (in Hungarian). *Magyar Tudomány 44*, 1127-1139.

Rácz, L., 1999b: *Climate History of Hungary Since 16th Century: Past, Present and Future.* Centre for Regional Studies of Hungarian Academy of Sciences, Pécs, 158 pp.

Rácz, L., 2001a: *Magyarország éghajlattörténete az újkor idején* (Climate history of Hungary during Modern Age). JGYF Kiadó, Szeged, 303 pp.

Rácz, L., 2001b: "... rains made harvests impossible..." Weather anomalies in the 1830s (in Hungarian). In *Ezredforduló-századforduló-hetvenedik évforduló* (Millennium–hundred years anniversary–seventieth anniversary) (ed.: *Zs. Újváry*). PPKE BTK, Piliscsaba, 367-379.

Rácz, L., 2003a: Environmental crisis in Hungary during the Modern Epoch. In *Exploitation and Overexploitation in Societies Past and Present* (eds.: *B. Benzing* and *H. Bernd*). LIT Verlag, Münster, 107-114.

Rácz, L., 2003b: The Climate History of Central Europe in the Modern Age. In *People and Nature* (eds.: *J. Laszlovszky* and *P. Szabó*). CEU Press, Budapest, 229-246.

Rácz, L., 2003c: Long-term trends of climate changes in the Great Hungarian Plain (in Hungarian). In *A fenntartható fejlődés és az Alföld* (Sustainable development and the Great Hungarian Plain) (eds.: *T. Baukó* and *I. Nagy*). MTA Társadalomkutató Központ, Budapest, 9-28.

Rácz, L., 2007: Climate changes in the Carpathian Basin during the medieval period (in Hungarian). In *Dixit et salvavi animam meam* (eds.: *Cs. Jancsák, G.F. Kiss, P. Zakar* and *A. Döbör*). Belvedere Meridionale, Szeged, 57-78.

Reizner, J., 1899-1990: *Szeged története* (History of Szeged). Vols. 1-2, 4, Szeged Szab. Kir. Város Közönsége, Szeged, 388, 358, 577 pp.

Réthly, A., 1962: *Időjárási események és elemi csapások Magyarországon 1700-ig* (Weather events and natural disasters in Hungary until 1700). Akadémiai Kiadó, Budapest, 450 pp.

Réthly, A., 1970: *Időjárási események és elemi csapások Magyarországon 1701-1800* (Weather events and natural disasters in Hungary 1701-1800). Akadémiai Kiadó, Budapest, 622 pp.

Réthly, A., 1998: *Időjárási események és elemi csapások Magyarországon 1801-1900-ig* (Weather events and natural disasters in Hungary 1801-1900). Vol. 1, Országos Meteorológiai Szolgálat, Budapest, 616 pp.

Réthly, A., 1999: *Időjárási események és elemi csapások Magyarországon 1801-1900-ig* (Weather events and natural disasters in Hungary 1801-1900). Vol. 2, Országos Meteorológiai Szolgálat, Budapest, 1369 pp.

Rohr, Ch., 2005: The Danube floods and their human response and perception (14th to 17th C). *History of Meteorology 2*, 71-86.

Rohr, Ch., 2007: *Extreme Naturereignisse im Ostalpenraum. Naturerfahrung im Spätmittelalter und am Beginn der Neuzeit*. Böhlau Verlag, Köln, Weimar, Wien, 640 pp.

R. Várkonyi, Á., 2001: Historical ecology (in Hungarian). In *A történelem segédtudományai* (Auxiliary sciences of history) (ed.: *I. Bertényi*). Osiris, Budapest, 307-316.

Sági, K., 1968: Water-level tendencies of Lake Balaton in the light of historical and cartographical data (in Hungarian). *Veszprém megyei múzeumok közleményei 7*, 441-468.

Sági, K., 1970: Natural scientific sides of a historical debate (in Hungarian). *Földrajzi Értesítő 19*, 200-207.

Sági, K. and *Füzes, M.*, 1973: Recent data to the question of the water-level tendencies of the Balaton before 1863 (in Hungarian). *Somogyi múzeumok közleményei 1*, 247-261.

Siklósy, Z., Demény, A., Vennemann, T. W., Kramers, J., and *Leél-Őssy, Sz.*, 2006: Stable isotope compositions of speleothems from Hungary: climate conditions and local variations. European Geosciences Union, *Geophysical Research Abstracts*, Vol. 8, 06905.

Siklósy, Z., Demény, A., Szenthe, I., Leél-Őssy, Sz., Pilet, S., Lin, Y. and *Shen, C.-C.*, 2009: Reconstruction of climate variation for the last millennium in the Bükk Mountains, northeast Hungary, from a stalagmite record. *Időjárás 113*, 245-263.

Simon, A., 1999: Some climate extremes of the 19th-century, based on the source collection of Antal Réthly (in Hungarian). *Légkör 44*, No. 3, 29-33.

Sipos, I., 2001: *Makó és az 1863. évi országos aszály* (Makó and the regional drought of 1863). *Szirbik Miklós Társaság füzetei 14*, Makó Város Önkormányzata, Makó, 28 pp.

Stankoviansky, M., 2003: Gully evolution in the Myjava Hill Land in the second half of the last millennium. *Geographia Polonica 76*, 89-107.

Střeštík, J. and *Verő, J.*, 2000: Reconstruction of the spring temperatures in the 18th century based on the measured lengths of grapevine sprouts. *Időjárás 104*, 123-136.

Strömmer, E., 2003: *Klima-Geschichte. Methoden der Rekonstruktion und historische Perspektive. Ostösterreich 1700 bis 1830.* Franz Deuticke, Wien, 325 pp.

Surányi, D., 2006: Phenological extremes on fruit-types in the Carpathian Basin between the 6th and 19th centuries (in Hungarian). *Agro-21 füzetek 47*, 70-84.

Sümegi, P., Majkut, P., Páll, D.G., Persaits, G., Pomázi, P., Bodor, E., Jakab, G. and *Törőcsik, T.*, 2009a: Environmental reconstruction for Fenékpuszta in the Migration period (in Hungarian). In *A hadak útján 9. Konferenciakötet* (On the military route 9. Conference papers) (eds.: *A. Nagy* and *Sz. Bíró*). Xantus János Múzeum, Győr, 79-88.

Sümegi, P., Majkut, P., Jakab, G., Persaits, G. and *Törőcsik, T.*, 2009b: Environmental reconstruction for Nagybárkány (Cserhát-hills) (in Hungarian). In *A hadak útján 9. Konferenciakötet* (On the military route 9. Conference papers) (eds.: *A. Nagy* and *Sz. Bíró*). Xantus János Múzeum, Győr, 89-99.

Sümegi, P., Jakab, G., Majkut, P., Törőcsik, T. and *Zatykó, Cs.*, 2009c: Middle Age palaeoecological and palaeoclimatological reconstruction in the Carpathian Basin. *Időjárás 113*, 265-298.

Sydenham, T., 1769: *Opera Medica. Editio Novissima, aliis omnibus quae praecesserunt multo emaculatior, et novis Additamentis ditior.* Tomus Secundus. Apud Fratres de Tournes, Genevae [Genève], 288-339.

Szabados, Gy., 2004: Country defence during the German wars 1030–1052 (in Hungarian). In *Gyepűk, várak, erődítmények és egyéb honvédelmi létesítmények a Kárpát-medencében (895-1920)* (Barriers, castles, fortresses and other objects of national defence in the Carpathian Basin 895-1920) (eds.: *S. Frisnyák* and *Gy. Csihák*). Nyíregyházi Főiskola Földrajz Tanszéke, Nyíregyháza, Zürich, 35-45.

Szabó, K., 1934: *Kecskemét szőlő- és gyümölcstermelésének múltja* (Vine and fruit production of Kecskemét in the past). Katona József Társaság, Kecskemét, 84 pp.

Szabó, L., 1991: Drought in Greater Cumania at the end of the 18th century (in Hungarian). *Zounuk 6*, 99-112.

Szántó, R., 2005: Natural catastrophy and hunger in 1315-1317 (in Hungarian). *Világtörténet 27*, 50-64.

Szántó, R., 2007: Environmental changes in Europe in the first decades of the 14th century (in Hungarian). *Középkortörténeti tanulmányok 5*, 159-164.

Szentkláray, J., 1880-1882: *Száz év Dél-Magyarország ujabb történetéből: 1779-től napjainkig* (Hundred years from the recent history of South-Hungary: from 1779 to the present). Csanád Egyházmegyei Ny., Temesvár [Timişoara], 520 pp.

Szilágyi, T., 1987: Very cold, snowy winters in Kecskemét 1 (in Hungarian). *Légkör 32*, No. 4, 2-6.

Szilágyi, T., 1988a: Very cold, snowy winters in Kecskemét 2 (in Hungarian). *Légkör 33*, No. 1, 2-7.

Szilágyi, T., 1988b: Very dry, drought years in Kecskemét 1 (in Hungarian). *Légkör 33*, No. 3, 20-25.

Szilágyi, T., 1988c: Very dry, drought years in Kecskemét 2 (in Hungarian). *Légkör 33*, No. 4, 18-20.

Szilágyi, T., 1993: *Szélsőségek Kecskemét időjárásában* (Extremes in the weather of Kecskemét). *Bács-Kiskun megyei Levéltári Füzetek 10*, Bács-Kiskun Megyei Önkormányzat Levéltárának kiadványai, Kecskemét, 155 pp.

Szilágyi, T., 1999: *Időjárási események Kecskeméten a XVII-XIX. században. Forráskiadvány* (Weather events in Kecskemét in the 17-19th centuries. Source collection). Kaloprint, Kecskemét, 473 pp.

Szövényi, I., 1965: The importance of vine harvest in the economy of old Kőszeg (in Hungarian). *Savaria 3*, 259-281.

Tirnitz, J., 1974: 18th century reports on the climatic conditions of Sopron and the natural disasters affecting the town: 1725-1800 (in Hungarian). *Soproni Szemle 28*, 165-178.

Tóth, B., 2009: *A szegedi nagyárvíz képeskönyve* (Picture book of the great flood in Szeged). 3rd edition, Bába Kiadó, Szeged, 285 pp.

Tóth, G.P., 2008: Trial by water – swimming of witches: procedures of ordeal in witch trials. In *Witchcraft Mythologies and Persecutions. Demons, Witches, Spirits*. Vol. 3, (eds.: *G. Klaniczay* and *É. Pócs*). Central European University Press, Budapest, 129-163.

Tőry, K., 1952: *A Duna és szabályozása* (Water regulation of the Danube). Akadémiai Kiadó, Budapest, 454 pp.

Vadas, A., 2008: Documentary evidence on weather conditions and an environmental crisis in 1315-1317: Case study from the Carpathian Basin. *J Environ Geography 1*, 67-76.

Weikinn, C., 1958-1963: *Quellentexte zur Witterungsgeschichte Europas von der Zeitwende bis zum Jahre 1850. Hydrographie.* Vols. 1-4, Akademie-Verlag, Berlin, 531, 486, 586, 381 pp.

Zawadowski, A., 1891: *Magyarország vizeinek statisztikája* (Statistics concerning the waters in Hungary). Vol. 1, Orsz. Magy. Kir. Statisztikai Hivatal, Budapest, 450 pp.

Zimányi, V., 1984: Grain yields in the villages of the Csallóköz [Žitny ostrov] area, based on tithe accounts (in Hungarian). *Agrártörténeti Szemle 26*, 458-505.

Zorkóczy, Z., 1975: Data of the lake basin, catchment area and water economy (in Hungarian). In *A Fertő-táj Monográfiáját előkészítő adatgyűjtemény. 2. kötet: Természeti adottságok: A Fertő-táj hidroszférája és vízgazdálkodása* (Data collection for the preparation of the Monography of the Fertő. Vol. 2: Natural conditions: Hydrosphere and the water economy of the Fertő area) (eds.: *L. Aujeszky, F. Schilling* and *S. Somogyi*). Vízgazdálkodási Kutató Intézet, Budapest, 5-43.

IDŐJÁRÁS

VOLUME 113 * 2009

Editor-in-Chief
LÁSZLÓ BOZÓ

Executive Editor
MARGIT ANTAL

BUDAPEST, HUNGARY

AUTHOR INDEX

TABLE OF CONTENTS

Papers

SUBJECT INDEX

GUIDE FOR AUTHORS OF *IDŐJÁRÁS*

The purpose of the journal is to publish papers in any field of meteorology and atmosphere related scientific areas. These may be

- research papers on new results of scientific investigations,
- critical review articles summarizing the current state of art of a certain topic,
- short contributions dealing with a particular question.

Some issues contain "News" and "Book review", therefore, such contributions are also welcome. The papers must be in American English and should be checked by a native speaker if necessary.

Authors are requested to send their manuscripts to

Editor-in Chief of IDŐJÁRÁS
P.O. Box 39, H-1675 Budapest, Hungary
E-mail: antal.e@met.hu

including all illustrations. MS Word format is preferred in electronic submission. Papers will then be reviewed normally by two independent referees, who remain unidentified for the author(s). The Editor-in-Chief will inform the author(s) whether or not the paper is acceptable for publication, and what modifications, if any, are necessary.

Please, follow the order given below when typing manuscripts.

Title page: should consist of the title, the name(s) of the author(s), their affiliation(s) including full postal and e-mail address(es). In case of more than one author, the corresponding author must be identified.

Abstract: should contain the purpose, the applied data and methods as well as the basic conclusion(s) of the paper.

Key-words: must be included (from 5 to 10) to help to classify the topic.

Text: has to be typed in single spacing on an A4 size paper using 14 pt Times New Roman font if possible. Use of S.I. units are expected, and the use of negative exponent is preferred to fractional sign. Mathematical formulae are expected to be as simple as possible and numbered in parentheses at the right margin.

All publications cited in the text should be presented in the *list of references*, arranged in alphabetical order. For an article: name(s) of author(s) in Italics, year, title of article, name of journal, volume, number (the latter two in Italics) and pages. E.g., *Nathan, K.K.,* 1986: A note on the relationship between photosynthetically active radiation and cloud amount. *Időjárás 90,* 10-13. For a book: name(s) of author(s), year, title of the book (all in Italics except the year), publisher and place of publication. E.g., *Junge, C.E.,* 1963: *Air Chemistry and Radioactivity.* Academic Press, New York and London. Reference in the text should contain the name(s) of the author(s) in Italics and year of publication. E.g., in the case of one author: *Miller* (1989); in the case of two authors: *Gamov* and *Cleveland* (1973); and if there are more than two authors: *Smith et al.* (1990). If the name of the author cannot be fitted into the text: *(Miller,* 1989); etc. When referring papers published in the same year by the same author, letters a, b, c, etc. should follow the year of publication.

Tables should be marked by Arabic numbers and printed in separate sheets with their numbers and legends given below them. Avoid too lengthy or complicated tables, or tables duplicating results given in other form in the manuscript (e.g., graphs).

Figures should also be marked with Arabic numbers and printed in black and white or color (under special arrangement) in separate sheets with their numbers and captions given below them. JPG, TIF, GIF, BMP, PNG or EPS formats should be used for electronic artwork submission.

Reprints: authors receive 30 reprints free of charge. Additional reprints may be ordered at the authors' expense when sending back the proofs to the Editorial Office.

More information for authors is available: antal.e@met.hu

Published by the Hungarian Meteorological Service

Budapest, Hungary

INDEX 26 361

HU ISSN 0324-6329