CLIMATE HISTORY STORED IN THE UNDERGROUND

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Abstract

Air temperature is one of the principal characteristics of climate. Variations in the air temperature produce changes in the ground surface temperature (GST), which propagate slowly downward into the rock subsurface and modify the ambient thermal regime. Heat conduction smears the climate signal, its high frequency components are diffused out with time (and depth) and only traces of relatively robust long wavelength past events are preserved. The ground thus "remembers" the major climate (temperature) episodes of the past and the inversion of the present-day borehole temperature-depth profiles T(z) may well contribute to the paleoclimate reconstruction. This method is notably valuable to complement various temperature proxies and in the combination with the long-term meteorological series may improve our knowledge of the climate in the pre-instrumental era.

First two years of the co-operation under the IGCP 428 project "Borehole and Climate" revealed a complex climate pattern of the last millennium. Clear evidence was provided that the world climate got warmer by at least 1 K in the last five centuries, the 20th century being by far the warmest (Pollack and Huang, 1998). The detailed regional studies further enabled to assess environmental character of the observed GST warming by detecting a certain man-made component due to deforestation, changes in land use, industrialisation and urbanisation. Several years of the regular subsurface temperature monitoring confirmed the present-day warming rate of 0.02-0.03 K/yr. The application of the inversion technique and the interpretation of the obtained GST-histories is demonstrated on example of the ample T(z)-data set measured in the Czech Republic.

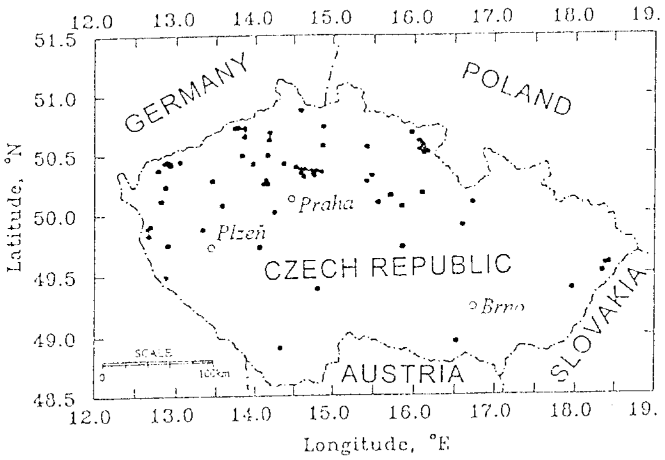

Fig.1. Map of the Czech Republic showing borehole sites, temperature logs of which were processed (near-by holes are shown as single dot).

Climate History of the Past Two Millennia

T(z)- records from 98 holes drilled on the territory of the Czech Republic (Figure 1) were inverted to assess the GST-history (Bodri and Cermak, 1995, 1997a). In general the climatic episodes over the past two millennia were identified, including a warmer period around 400 A.D., followed by colder times between 700-1000 A.D., the Little Climatic Optimum with its culmination around 1250±50 A.D., and the Little Ice Age with a temperature minimum at 1650±30 A.D. (Bodri and Cermak, 1997a,b). Since the beginning of the 19th century a warming has dominated the climate pattern interrupted by several short-term oscillations. For the most recent 30-40 years, there exists a strong geographical pattern of regions where the warming rate has been particularly intense or where it has been relatively weaker.

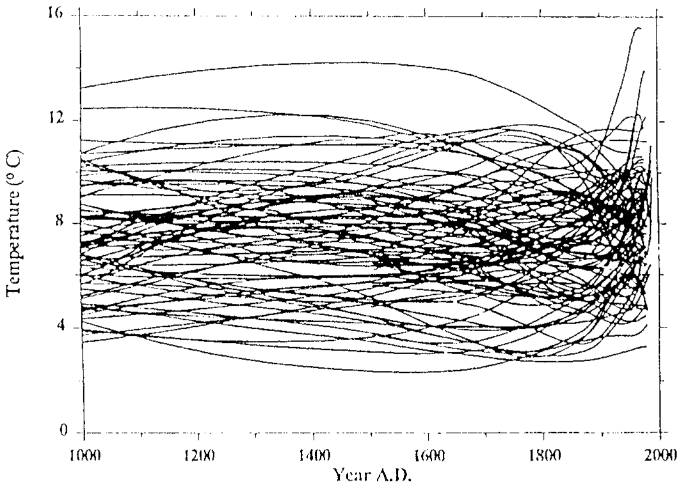

Fig.2. GST-histories inferred from 98 T(z) profiles in the Czech Republic

Reconstructed GST variations are damped towards the past due to progressively increasing smoothing character of the inversion method and the magnitudes of reconstructed GST-histories for different boreholes and at different time intervals are not thus always comparable. The realistic amplitude of the climate change can be estimated only for the most recent warming. For practical purpose each searched individual GST-history was approximated by a series of individual time intervals of constant temperature, the mean value of temperature in each such interval being an unknown parameter. When demonstrating the results graphically, the calculated temperature-values were ascribed to the mid-point of the corresponding time interval and then approximated by cubic spline technique (Bodri and Cermak, 1997a). Figure 2 presents all „spaghetti-type" GST-histories obtained from 98 T(z)-records. Such representation is definitely not easy to survey and the times of the individual onsets and the characteristic trends of the climate excursions are difficult to be distinguished, however the culmination times of the individual excursions can be better detected on the derivative scale (Bodri and Cermak, 1997b).

The inversion method only rarely permits to resolve more than 3-4 climatic events from one borehole. To describe the climate trend characteristic for the whole region investigated; calculated occurrence times for all 98 holes were summarised in Figure 3. Regardless of the magnitude, all GST minima were considered as "cold" and all maxims as "warm" unit events, to further credit such illustration and to avoid overcomplicated picture due to potentially unrepresentative single isolated data, only events indicated by at least two boreholes were used for further interpretation. The characteristic times of the minimum (min) and maximum (max) alternating extremes are: max 1730±20, min 1780±10, max 1820±10, min 1880±10, max 1935±7, min 1943±5, max 1976±3 A.D.

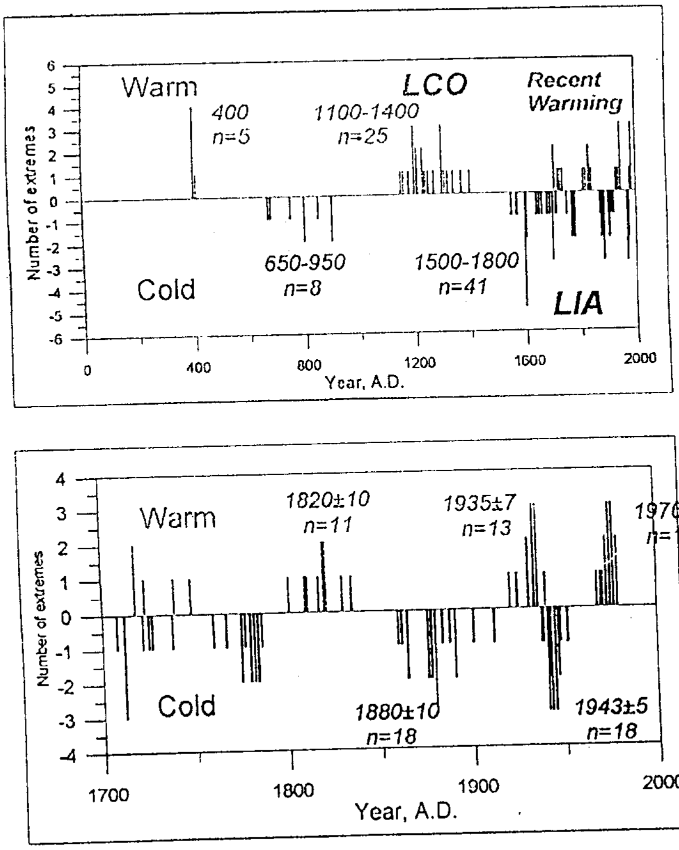

Fig.3. Occurrences of the climatic extremes (see text) of the past two millennia (top) and detail of the last three centuries (bottom).

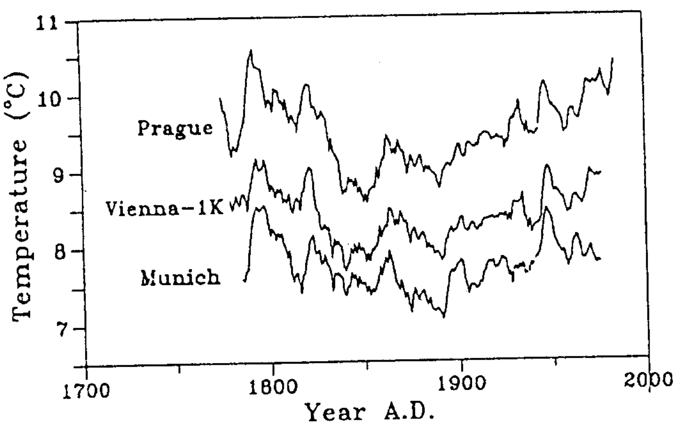

Fig.4. Ten-year running means of the annual air temperature at meteorological stations Prague, Vienna and Munich.

The whole 17th and 18th centuries were clearly characterised by severe climate of the Little Ice Age, however since the beginning of the 19th century, climate in Europe has been one-way story (Lamb, 1977) with probably several shorter, not more than decade-long, fluctuations (Flohn and Fantechi, 1984).

For comparison Figure 4 presents the meteorological records of mean annual air temperature recorded in Prague, Vienna and Munich. The relatively warmer period around 1820 with a subsequent cooling appears in all these records; also the 1880's were the coldest decade. Similarly the warmer 30's and colder 40's of the 20th century seem to be well confirmed. On the other hand, certain short setbacks of warmer conditions in the meteorological series of the last 40 years may be regarded as a high-frequency noise in the dominating warming rather than individual climate events.

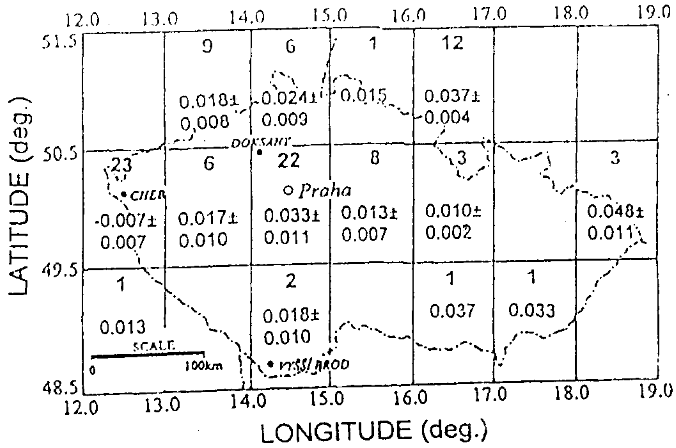

Fig.5. Grid values of the calculated GST warming rate. Upper figure – number of holes, lower figures – warming rate +/- s.d.

Most Recent Climate History (Since 1960)

Practically all boreholes yielded GST histories that exhibit a significant recent warming that started only a few decades ago. To assess the geographical distribution and evaluate a possible man-made post-industrial contribution, the rate of temperature change since 1950-60 has been calculated individually for each borehole and the obtained values averaged in a regular latitude-longitude 1 by 1 degree grid network (Figure 5). Most of the warming rates exceed their standard deviation. Generally, the magnitude of warming in the last 30 years amounts from less than 0.5 to more than 1.2 K (which corresponds to the warming rate of 0.01-0.04 K/yr), which by far exceeded the range of earlier climatic excursions (Bodri and Cermak, 1999). Such values are in relatively good agreement with the warming trends of the mean annual air temperature observed at the meteorological stations (for comparison see two examples in Figure 6).

Figure 7 presents the tentative regional map of the GST change rate since 1960 (Bodri and Cermak, 1999), constructed for the grid data of Fig.5. Warming has been most pronounced around Prague and its vicinity and decreased to the south and south-west. Another area of significant warming is located in the eastern part of the country. Only one single sub-area around Cheb in the westernmost part of the Czech Republic shows an inexpressive cooling which agrees with the results published by Clauser and Mareschal (1995) and by Safanda *et al.*(1997), however has not been satisfactorily explained yet. In addition of the vicinity of Prague the highest amounts of warming of over 0.03 K/yr were obtained also for the industrial regions of the Sudety and Ostrava coal basins, while the lowest warming rates of 0.01-0.02 K/yr correspond to the south western and south-eastern slopes of the Bohemian massif, areas generally forested. The obtained results are in good agreement with long-term meteorological observations and conventional climatic records.

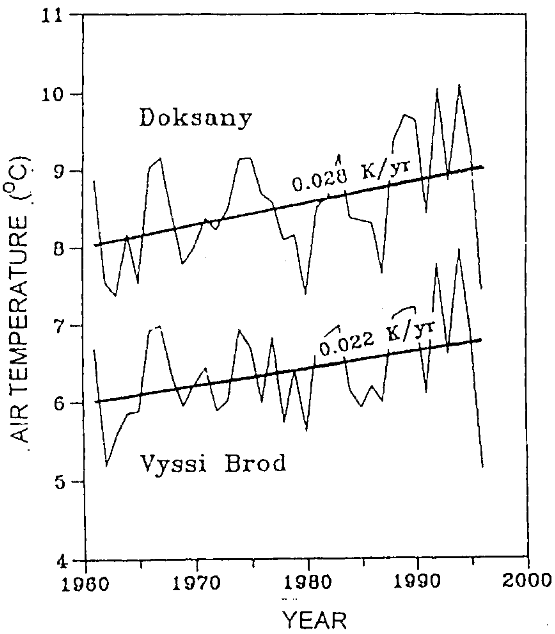

Fig.6. Mean annual air temperature trends in two meteorological stations for period 1961-1997 (for location see Fig.4)

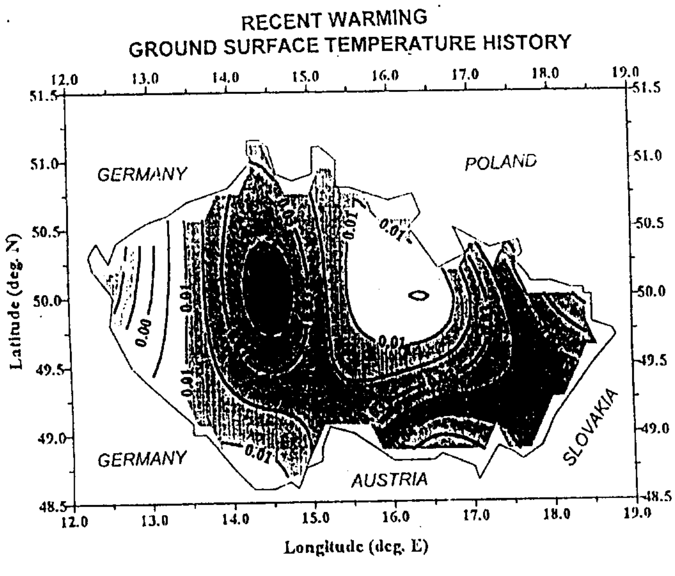

Fig.7. Tentative attempt to construct the regional pattern of the last 35 year warming rate based on inversion of geothermal data.

Long-term Temperature Monitoring in Shallow Holes

Earth's surface effectively filters out high frequency variations and the annual variations are generally negligible at the depth below 20 m. To complete the above inversion results by experimental data two 40 m deep boreholes were specially drilled to monitor long-term subsurface temperature changes and to compare the potentially different conditions in urban and countryside environments with view to assess the potential anthropogenic contribution to the present-day warming rate.

Sporilov hole - 50°02'27" N, 14°28'39" E, (drilled in the campus of the Geophysical Institute in Prague, October 1992). Upper ten meters present soil and loose material of low thermal conductivity, underlain by Ordovician silty to clayey shales of mean conductivity of 3.2±0.2 W/mK (Safanda, 1994, Stulc, 1995).

Kocelovice hole - 49°28'2.2" N, 13°50'18.7" E, (drilled near local meteorological station in south central Bohemia in 1997) located on a mild grassy slope. Hole penetrates compact granite body of mean conductivity of 3.1±0.1 W/mK, covered by about 1-2 m soil layer.

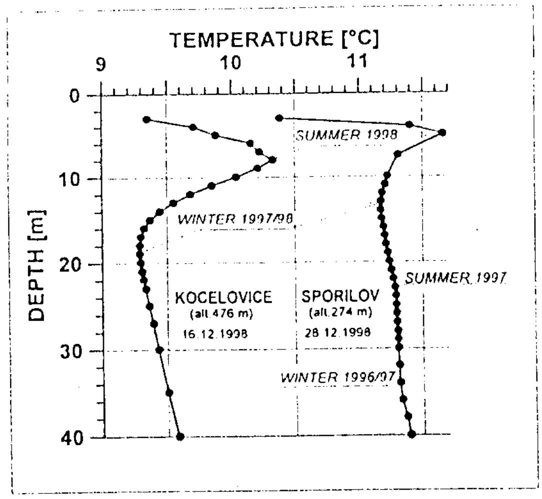

Fig.8. Temperature-versus-depth profiles in Sporilov and Kocelovice holes

Both holes are equipped with a chain of measuring thermistor elements at a number of selected depth levels covering all 0-40 m depth interval, accompanied by a set of thermometers at three elevations of 0.1, 1, 2 meters to record air temperatures. At the Kocelovice-site geothermal parameters are completed with meteorological data, namely precipitation, wind speed/direction, direct and reflected solar radiation, snow layer thickness, air humidity, soil moisture and water vapour tension.

According to the theory of heat conduction in a semi-infinite body, temperature changes at the surface propagate into the subsurface with the amplitude attenuation and time delay that increases with depth. Figure 8 demonstrates the case, showing the Sporilov and Kocelovice temperature profiles, both measured in December 1998. Due to a different altitude of the boreholes the mean annual surface temperatures are different, different thermal conductivity in the uppermost 10-metre section controls the penetration rate of surface signal to depth On the Kocelovice T(z)-profile the summer/winter peak is observed deeper than in Sporilov-hole. For illustration Figure 9 shows several T(z) logs (Sporilov-hole) taken in different seasons to show the penetration of the surface signal to the depth. Slight excursions from the „ideal" smooth shape are due to 3D thermal conductivity structure.

Below approx. 25-30 metre the response to the annual temperature variations on the surface is not measurable (being less than 0.01 K). Five-year (1994-1998) record of temperature at approx. 40-m depth in the Sporilov hole clearly demonstrates the present long-term warming rate of 0.0264 K/yr characteristic for the last five years (Figure 10). It can be seen that the warming may even slightly increase from less to 0.025 to present 0.03 K/yr. The experiment proved that the magnitude of the climate warming is extractable by long-term precise temperature monitoring in holes.

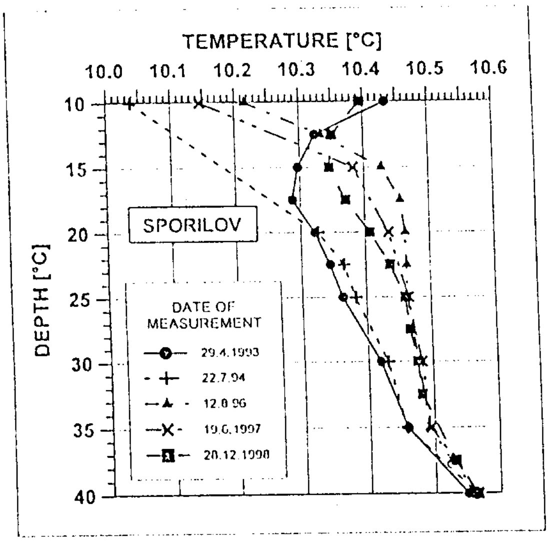

Fig.9. Penetration of the surface signal to depth, demonstrated on the T(z) records measured in the Sprilov hole

Acknowledgements

Most of the work was done under the research projects of the Grant Agency of the Czech Republic Nos. 205/93/0413 and 205/96/0969 and completed under the UNESCO programme of the International Geological Correlation Programme, IGCP 428."Borehole and Climate".

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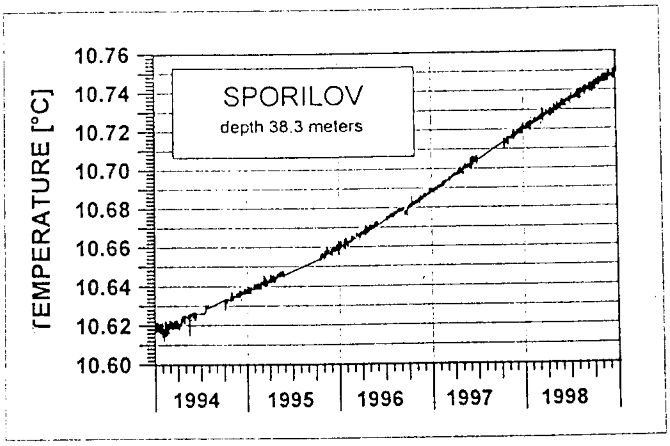

Fig.10. Five-year record of temperature at 38.3 m depth in the Sporilov hole

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