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Ground Surface Temperature History in Poland in the 16th–20th Centuries Derived from the Inversion of Geothermal Profiles

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Abstract—Ground Surface Temperature (GST) history in Poland was derived from the inversion of temperature-depth profiles in over 20 wells. Temperature histories for the period 1500 A.D. through 1977 A.D. agree well with the instrumental record of the surface-air temperature available for the last two centuries. A statistical correlation of the reconstructed histories (from the well temperature data) with the instrumental record (air temperature) from the homogeneous Warsaw series is high (>0.8). Functional space inversion (FSI) of the temperature data with depth shows that beginning in the early 19th century, temperatures warmed by 0.9 ± 0.1°C following a long period of colder climate before. The last number could be a minimal as higher warming was calculated using a simple model based on surface temperature for the observational period (homogenized Warsaw surface temperature series, LORENC, 2000) and POM (pre-observational mean; HARRIS and CHAPMAN, 1998) of −1.53°C below the 1951–1980 mean temperature level.

Key words: Ground warming history, climatic change, heat flow, Poland.

1. Introduction

The climatic history in Poland for the preinstrumental period (meteorological observations in a form of time series) has been reconstructed mainly from proxy data, derived from geological, pedological, botanical, zoological, archeological, and historical data (MARUSZCZAK, 1988, 1991; RALSKA-JASIEWICZOWA and STARKEL, 1991; RALSKA-JASIEWICZOWA *et al.*, 1998; NIEWIAROWSKI, 1999). During the last few decades research has focused on the dendroclimatological data (FELIKSIK, 1972, 1990; BEDNARZ, 1976, 1984; FRITTS, 1976; ZIELSKI, 1997; BRIFFA, 2000; BRIFFA and JONES, 2000; WÓJCIK *et al.*, 2000) which uses tree growth history.

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The first direct use of geothermal profiles in thermally stabilized wells to reconstruct climatic histories was proposed by CERMÁK (1971) and LACHENBRUCH and MARSHALL (1986). Further sophistication of the inversion techniques (SHEN and BECK, 1991; SHEN *et al.*, 1995) lead to many regional and worldwide reconstructions of ground-surface temperature change (HUANG *et al.*, 2000; POLLACK and HUANG, 2000).

Inversions of temperature profiles in wells allow reconstruction of the Ground Surface Temperature (GST) history. While the time resolution of the method is less than that of proxy methods like tree-ring measurements, direct temperature inversions have the ability to determine the physical magnitude of the last warming event and of the preceding long-term level. Comprehensive analysis of the Polish temperature profiles and their interpretation in terms of climatic change reconstructions has been described in the Polish literature (MAJOROWICZ *et al.*, 2001). Such studies were previously done in neighboring countries of the Czech Republic, the Slovak Republic and Belarus (ŠAFANDA *et al.*, 1997; ZUI, 1999). Tree-ring data were also taken into consideration in Poland; however these high resolution histories are related to several factors besides the air temperature. These include precipitation and pollution (WÓJCIK *et al.*, 1999, 2000; PRZYBYLAK *et al.*, 2001). Therefore, other methods like geothermal measurements are needed to determine the physical magnitude of warming and preceding temperature levels.

In recent years long time series of mean Surface-Air Temperature (SAT) starting in Poland as early as the late 18th century have been homogenized (e.g., changes in station location, time of observation, thermometers or changes in formulas used for calculation of daily, monthly, annual etc. mean values of surface temperature were corrected for), (LORENC, 2000). These and geothermal logs in wells give us an opportunity to compare over 200 years of time series and GST histories derived from the inversions of the temperature logs.

2. Methodology

GST histories were obtained by applying the Functional Space Inversion (FSI) technique (SHEN and BECK, 1991; SHEN *et al.*, 1995). The FSI technique allows for uncertainties for both the measured temperatures and the thermo-physical parameters to be incorporated into the model in the form of *a priori* standard deviations. Due to the complexity of the problem, this technique, as well as all other available techniques, assumes that heat transfer is by conduction alone through a one-dimensional, possibly heterogeneous medium. This assumption excludes the advective component of heat transfer due to subsurface fluids or convective disturbances within the fluid-filled borehole, as well as lateral heterogeneity in thermal conductivity and uneven surface relief (SHEN *et al.*, 1995). The reconstruction of the GST history for time interval $[t_0, t_1]$ from the subsurface temperature profile $T(z, t_1)$

measured between the surface and depth z_b at time t_1 assumes that the perturbations in $T(z, t)$ caused by the GST variation before time t_0 cannot be distinguished from the steady-state field within the depth interval $[0, z_b]$ at time t_1, when the subsurface temperature is measured. This assumption can be met by considering t_0 being sufficiently distant from t_1.

The assumption of heat transfer by conduction is only well justified in areas with negligible vertical movement of the underground water. The key issue in interpretation of the GST histories in terms of long-term climatic variability is the long-term relationship between the ground surface and SATs. The general belief is that, at long time scales, mean annual GSTs track the mean annual SATs taken at screen height (1.5–2.0 m above the surface of the ground). However, at the inter-annual scale, the magnitude of the difference between the mean annual GSTs and SATs at a given site varies according to the number of days with snow cover or the content of soil moisture at the beginning of the freezing season.

The extraction of a signal from the measured *T-z* profile is impeded by the presence of noise. As shown by SHEN *et al.* (1995), the noise in this system derives from errors in the measurements of temperatures, depths and thermophysical properties of the earth's materials, as well as "representational" errors, such as departures of the mathematical representation of the problem (one-dimensional heat conduction) from the real world. Numerical experiments (SHEN *et al.*, 1995) with synthetic *T-z* profiles containing both the climatic signals over the last millennium, based on tree-ring data, and the types of noise mentioned above showed that the inverted GST history is most sensitive to two parameters of the inversion, namely to constraints (standard deviation-SD) on *a priori* thermal conductivity model and measured temperature data. The final choice of these two parameters must be a compromise between the suppression of the artifacts of noise, which can be achieved by choosing large SDs, and the recovery of the details of the GST history, which requires small *a priori* SDs.

Estimates of average conductivity based on lithology and measured rock samples were used because of the lack of rock chip samples and therefore a lack of direct conductivity data. Average conductivity values for the main rock types were based on hundreds of measurements on available cores from other deep wells in Poland (MAJOROWICZ and PLEWA, 1979). The temperature profiles were subjected to a "loose" inversion, in which the desired GST signal is attenuated, to ensure that the noise is not amplified. This suppression of noise was achieved by increasing the SD of the *a priori* thermal conductivity model and the SD of the measured temperatures. For this study, *a priori* conductivity and temperature SD are 0.5 $W \cdot m^{-1} K^{-1}$ and 0.1–0.2°C, respectively. These values are close to those suggested by SHEN *et al.* (1995) as a reasonable compromise in inverting realistic synthetic profiles.

The null hypothesis for the inversion was conservatively framed, and assumes no climate changes prior to data acquisition. The statistical properties of the GST variations were constrained by *a priori* SDs, which increase linearly from 0.5°C at year 1000 to 2.0°C at year 1990, and by the characteristic time of correlation decreasing linearly from 500 years to 100 years since the year 1000 to the year 1990 (SHEN *et al.*, 1995). The *a priori* model assumes that the estimated thermal conductivity of most clastics varies between 1.8–2.3 $W{\cdot}m^{-1}\,K^{-1}$ (± 0.5W/m K), diffusivity is $1.0 * 10^{-6} m^2 s^{-1}$ which is typical of diffusivity values assumed for rocks of Canada (JESSOP, 1990), Scandinavia (KUKKONEN *et al.*, 1998) and Bohemia (Šafanda *et al.*, 1997).

SHEN *et al.* (1995) and MAJOROWICZ and ŠAFANDA (1998) have shown that there is a risk of misinterpreting the GST history by inversion of single logs with tight constraints on the borehole data. Large *a priori* SDs for conductivity and temperature in a simultaneous inversion were therefore used as an attempt to reasonably characterize GST history for such a large region.

3. Temperature Logs

There are two sources of temperature logs in wells in Poland (well location is shown in Fig 1). Temperature logs from the 12 wells in southwestern Poland were measured using portable logging equipment with a thermistor probe calibrated to approximately 0.01°C (relative change) and 0.03°C absolute accuracy. The wells were drilled between 1970 and the 1980s and have been left undisturbed by any drilling

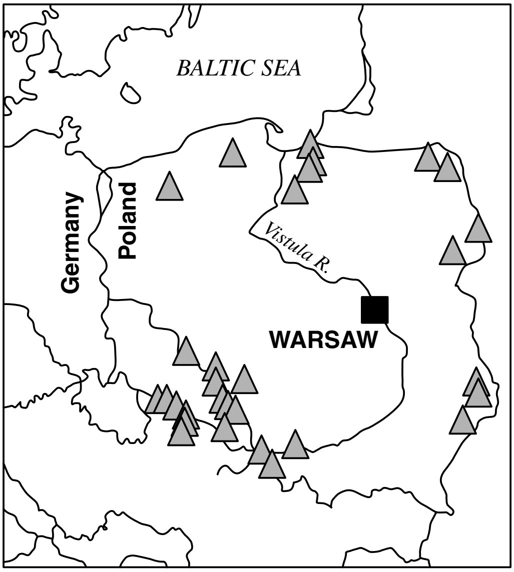

Figure 1
Location map of the boreholes with temperature logs in Poland used in this study (triangles) and of the meteorological station in Warsaw (square).

operations since that time. Measurements were made in 1996 in the upper few hundred meters in vertical wells. The tendency for the wells to slant relative to the vertical is common for deep wells but was not a problem in the data used. Some of the temperature profiles show evidence of abrupt changes in temperature gradient such as in wells Waliszów, Długopole, top part of Pełczyn, Wołczyn, Wybłyszczów, Ptakowice, Olesnica, and Janików (Fig 2). These can be a result of water flow or thermal conductivity change. Logs with evidence of water disturbance are readily apparent and were rejected from further analysis. Abrupt changes in the geothermal

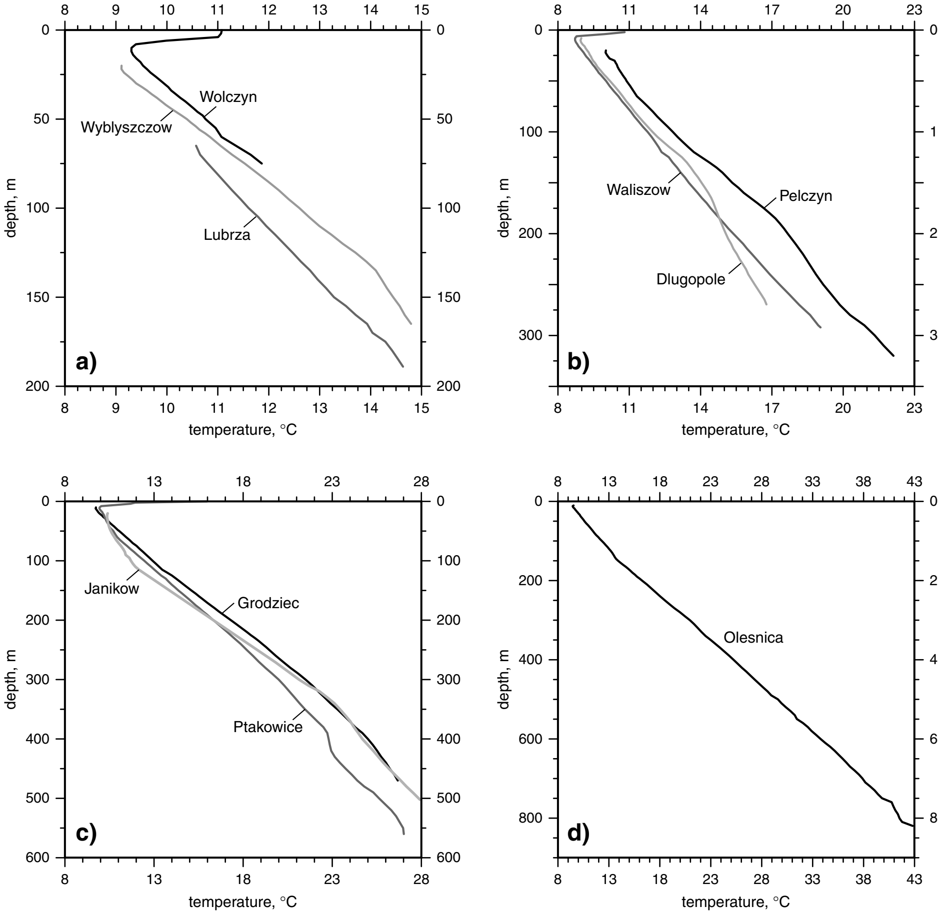

Figure 2

High precision temperature log for south-western Poland. a. Lubrza,17°38’40”E,50°20’30”N; Wolczyn, 18°02’57”E,51°01’36”N;Wyblyszczów,17°53’00”E,50°33’40”N., b. Dlugopole,16°38’45”E,50°15’43”N; Pelczyn, 16°41’05”E,51°23’52”N; Waliszów,16°42’35”E,50°18’25”N., c. Grodziec,17°41’22”E, 50°38”14”N; Janików, 17°22’45”E,50°58’20”; Ptakowice,17°33’00”E,50°44’40”N; d. Oleśnica, 17°22’33”, 51°12’56” gradient usually result from input of water behind the casing. Water seepage (either upward or downward) can cause heat flow disturbance in porous and permeable strata. The effect upon the vertical component of heat flow is only significant in the case of large differences in topography and related hydraulic head changes. Such examples are well recognized and described by JESSOP (1990). Water velocities along the bedding of the formations are commonly less than 10^{-2} m/year. The vertical component of such flow is usually 10–100 times lower. We therefore estimate that the change in heat flow is smaller than the errors due to temperature gradient accuracy and that changes in conductivity are the main reason for changes in thermal gradient. Many cases of heat flow variation with depth cannot be explained due to the lack of core samples and inferior knowledge of the conductivity. Wells from sedimentary basins of the Polish Lowland are located mostly in the flat areas. Wells in the higher topographic relief regions of the Sudetian region are therefore more vulnerable than wells from flatlands of the Polish Lowland. The small diameter of the wells relative to their length disallows any convection in the well bore significant enough to disturb the thermal regime (JESSOP, 1990).

The other temperature logs are continuous logs in a depth range from the static water level to the bottom of the well. These were selected from numerous wells across Poland. The lack of thermal equilibrium of the well was the main problem in depicted well logs. Temperature was measured with resistor thermometers calibrated to an accuracy of 0.1°C and some noise due to this factor can be seen in some of our data (Fig 3). We have rejected temperature logs for which predicted near-surface temperature is significantly different from the observational long-term mean ground temperature. In many wells in Poland temperature profiles show much higher temperature in the upper parts of the profiles than expected due to disequilibrium conditions — remaining from drilling process. Such temperature logs were rejected. We found only 11 wells which appeared to be in thermal equilibrium (Fig 3).

4. Geothermal Anomalies and Inversion

The majority of the Polish wells show significant positive anomalies of temperature with depth. These anomalies are interpreted as a result of ground warming over the last two centuries. An example of such anomalies with depth is shown in Figs 4 and 5. Figure 4 also shows evidence of an abrupt change in temperature anomaly over a short depth interval and is likely a result of water flow disturbance.

An earlier GST history (MAJOROWICZ *et al.*, 2001) was based on the upper parts of the profiles above the abrupt thermal gradient changes. The upper 95 m in Długopole, 115 m in Janików, 189 m in Lubrza, 115 m in Pełczyn, 200 m in Ptakowice, 115 m in Oleśnica, 290 m in Waliszów, 75 m in Wołczyn, and 135 m in Wybłyszczów (Fig 2) were used and showed 1°C warming in the 20th century

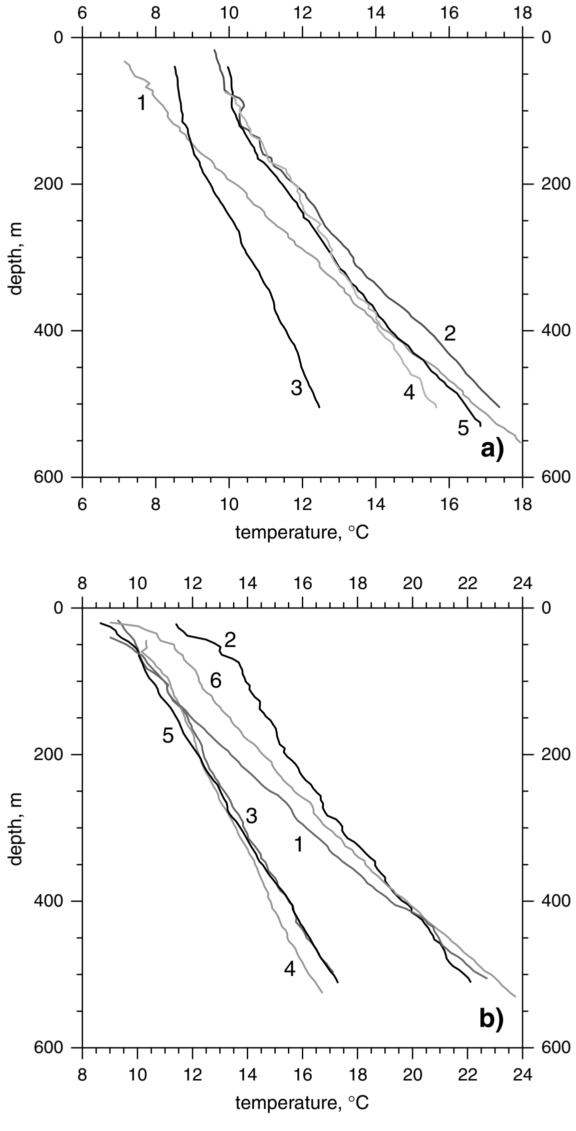

Figure 3
Selected geothermal profiles in the Polish boreholes effected with a continuous well logging technique which indicate: (a) Large climatic warming signal in the boreholes: 1—Lubawka (50°41'47"N, 16°01'17"E), 2—Marianka (54°04'36"N, 19°38'32"E, 3—Narejki (53°07'10"N, 23°50'50"E), 4—Rajsk (52°50'40"N, 23°08'52"E), 5—Boguszyn (50°27'58"N, 16°42'15"E). (b) Small climatic warming signals in the boreholes: 1—Laka (50°00'00"N,18°30"00"E), 2—Narol (50°23'06"N, 23°15'51"E), 3—Ptaszkowo (54°26'45"N,19° 37'23"E), 4—Grabowiec 2 (50°52'54"N, 23°36'05"E), 5—Grabowiec 4 (50°47'42"N, 23°40'43"E), 6—Dêbowiec (49° 49'30"N, 18°46'23"E).

(Fig 6b). The misfit of these GST histories with the homogeneous surface temperature time series is shown in Fig 6b and it can be due to too short sections of the high precision profiles used in the inversion.

New GST histories shown here are based on the FSI simultaneous inversions of deep (> 450 m) temperature profiles obtained from continuous logs (Fig 6b) and inversion of the deepest high precision temperature well in Grodziec (Fig 6a). GST histories from a group of wells showing a high warming signal (Fig 3a) and from well Grodziec (Fig 2) show very good (> 0.8) statistical correlation with the homogenized SAT time series (Figs. 6a,b). The magnitude of warming for the 19–20th century is 0.9 ± 0.1°C. This warming period is preceded by a colder period. The last number could be a minimal warming as higher warming magnitude was calculated using a simple model based on surface temperature for the observational period (homogenized Warsaw series, LORENC, 2000) and POM (pre-observational mean; HARRIS and CHAPMAN, 1998) of −1.53°C below the 1951–1980 mean temperature level (Fig 5).

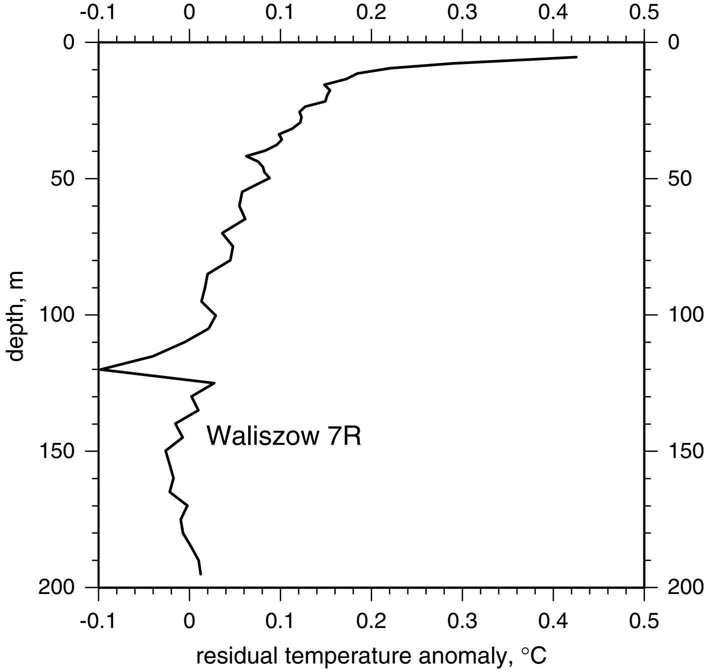

Figure 4
Example of the residual temperature anomaly due to surface warming and possible water movement (at a depth of 120 m).

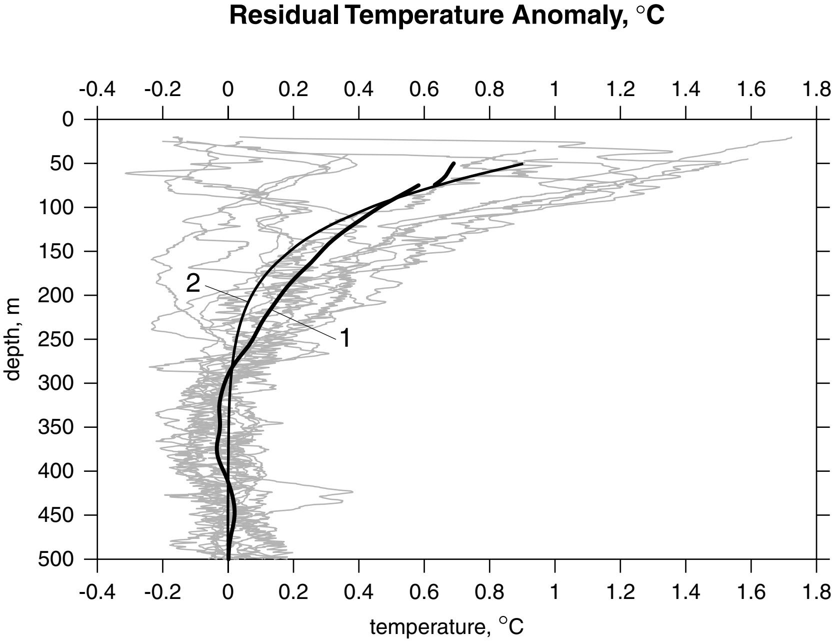

Figure 5
Calculated residual temperature for each log shown in Figure 3 based on fits to the temperature profiles below a depth of 250 m. Average residual is shown (1). Curve 2 is based on the model of surface temperature for the observational period (homogenized Warsaw series, LORENC, 2000) and POM (pre-observational mean; HARRIS and CHAPMAN, 1998) of −1.53°C below the 1951–1980 mean temperature level. RMS misfit between curves of 72 mK is lower than the measuring error of the continuous temperature log used.

5. Discussion

The relatively high noise levels of GST histories that are common from inversions of temperature logs can be due to many reasons, including poor knowledge of the conductivity variations, limited accuracy of the temperature logs, possible water percolation influence, variations in moisture, snow cover and the anthropogenic changes to the land surface between sites. Changes due to land surface changes are important factors which are supported by the results of monthly and yearly averages of the ground temperature time series in the 1–50 cm subsurface depth range done in Rezerwat Piwnicki in central Poland. Measurements made in old forest (200 years old), in the open grass area and in the area with depleted vegetation show large differences in the long-term temperature averages. Mean annual temperatures in the forest were found to be some 0.5°C lower than in the grass areas and some 1.2°C lower than in the area with depleted vegetation (MAJOROWICZ *et al.*, 2001). The effect of deforestation as well as the effect of vegetation depletion (from grass to bare land) influences (step-like) GST history. We can see such effects from the interpretation of

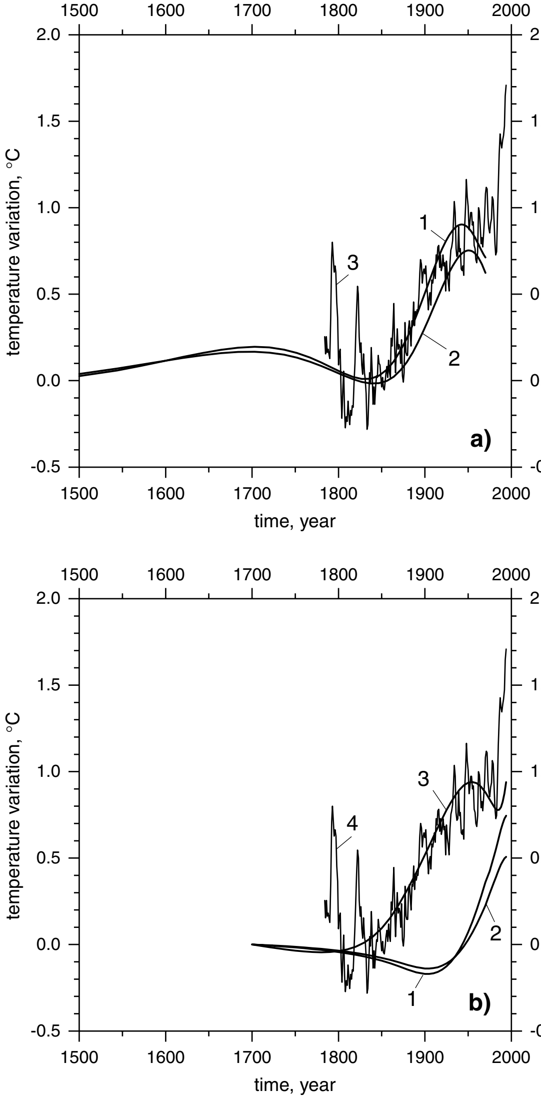

Figure 6
Reconstruction of ground surface temperature history. a. Derived from the continuous temperature profiles from wells deeper than 450 m. Curve 1 — reconstruction from the continuous temperature logs which indicate high ground surface temperature warming (shown in Fig 3a) , curve 2 — average based on all wells shown in Figs 3 a,b, curve 3 — homogeneous air temperature series from Warsaw (11–year running average) (LORENC, 2000). b. Curves 1 and 2 — reconstructions based on the upper portions of precision temperature profiles above the region of abrupt thermal gradient changes for the high and low assumed error of the *a priori* conductivity model, curve 3 — reconstruction based on the entire depth of temperature profile in well Grodziec , curve 4 — homogeneous air temperature series from Warsaw (11–year running average) (LORENC, 2000).

geothermal profiles from wells in Canada (MAJOROWICZ, 1996; MAJOROWICZ and ŠAFANDA, 2001). These show considerably higher GST warming magnitudes than the instrumental and proxy histories (OVERPECK *et al.*, 1997). GST histories from Poland signify a remarkable correlation between GST histories derived from well temperatures and the homogenized time series of SAT (Fig 6). Variations of GST are equal to or less than SAT variations which means that land surface changes are not a factor in Polish wells unlike some areas in North America (SKINNER and MAJOROWICZ, 1999). It is likely related to a difference in time of deforestation which in Poland was much older (starting in the mid-ages) than for example in western Canada (MAJOROWICZ, 1996).

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