Chapter 11
Climate Warming in the Czech Republic: Evidence Stored in Shallow Subsurface

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11.1 Introduction

There is clear evidence that the world climate has been undergoing a general warming. This warming was typical for the most of the last century, following the previous relatively colder nineteenth century. An important question to answer is whether this warming is just a manifestation of natural climate variability and a certain "return" to previous conditions or an indication of a new (and permanent) trend. What is alarming, is the matter of fact, that the warming rate has been accelerating in the last 3 or 4 decades. The 1990s was the warmest decade of the last century (IPCC 2001) and global mean surface temperature deviations (related to the 1961–1990 average) were in 1998 and in 2002–2007 the absolutely warmest since the world data have been collected in 1861 (NASA 2008, WMO 2005). Also the Czech meteorological records confirmed the growth of the mean annual air temperatures (Kalvová 2001, see also http://www.chmi.cz). The increase of the global mean temperature is accompanied by changes of many climatic and environmental variables (Hansen and Lebedeff 1987; Jones et al. 1999). The observed climate change does not only mean a change of average values, but may present additional changes in climate variability leading to the increasing occurrences of extreme phenomena such as floods or droughts. If the warming is to continue in the future, serious environmental changes present a risk for the population of many countries, see plentiful recent reports presented during the Paris (February 2007) and Brussels (April 2007) IPCC assemblies. The Czech Hydrometeorological Institute published Climate Atlas of Czechia with a detailed description of climate evolution in the Czech Republic for 1961–2000 (Tolasz et al. 2007).

The nonlinear climate system is under effects of many forcing agents – natural (solar and volcanic activity, natural aerosols) as well as anthropogenic (massive deforestation, industrial pollution and emissions of greenhouse gases, land-use).

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In order to describe the climate evolution and to attribute it to the individual forcing factors, a robust record of the past climatic changes is required. Equally important is to improve the knowledge of the spatial distribution of the present-day warming rate and its environmental confidence. Direct evidence of climate change and its variability based on instrumental measurements covers only a relatively short period. The longest European temperature records started at the beginning of the eighteenth century (Camuffo and Jones 2002). The Czech longest continuous temperature series covers more than two centuries (Prague-Klementinum), see e.g. Hlaváč (1937) or Brázdil and Budíková (1999). More detailed database of measurements based on a dense station network is available for the last 4 or 5 decades. From all these records, it is possible to detect a significant evidence of gradually changing conditions.

There is an alternative, relatively new, but powerful method (so called borehole climatology), which relies on the inversion of the present-day subsurface temperature-depth profiles into the ground surface temperature history (GSTH) (Čermák, 1971; Lachenbruch and Mareschall, 1986; Pollack and Chapman 1993). For a comprehensive summary of this method see e.g. Pollack and Huang (2000), Majorowicz et al. (2004) or Bodri and Čermak (2007). Inverting almost one hundred borehole temperature logs from the Czech territory into the GST-history revealed a past climate scenario of the last millennium (Bodri and Čermak, 1995, 1997, 1999). Numerous shorter meteorological surface air temperature (SAT) series completed by shallow subsurface temperature monitoring offered a quantitative estimate of the present day warming rate of 0.02–0.04 K/year (Čermak et al. 2000). There is no doubt that combining several approaches, namely the instrumental and proxy data analysis, can enable better understanding of the Earth's climate history and that the knowledge of the past will facilitate a more reliable assessment of the future of the climate system (Harris and Chapman 1998; Huang et al. 2000).

11.2 Rationale

The observed increase of air temperature is linked to the increase of the surface (soil) temperature. The response to changes in the surface conditions slowly penetrates downwards into the shallow subsurface (Fig. 11.1). Subsurface temperature field at depth of several tens to several hundreds of meters contains a record of what has happened on the surface in the past, i.e. the long-term ground surface (soil) temperature history (GSTH). This information can be recovered from present-day borehole temperature-depth profiles and used to reconstruct the GSTH of several past centuries (see e.g. Lewis 1992). Amplitude of the surface temperature changes is attenuated and time delay increases with depth (Čermak et al. 1993). The high-frequency component of the transient temperature signal from the surface is progressively filtered out as it propagates to depth (Pollack and Chapman 1993). Seasonal temperature variations, in dependence on the thermal conductivity and diffusivity of the near surface rock, practically fade out below the depth of 20–30 m. As the (meteorological) air temperature series exhibit certain variability and the relatively

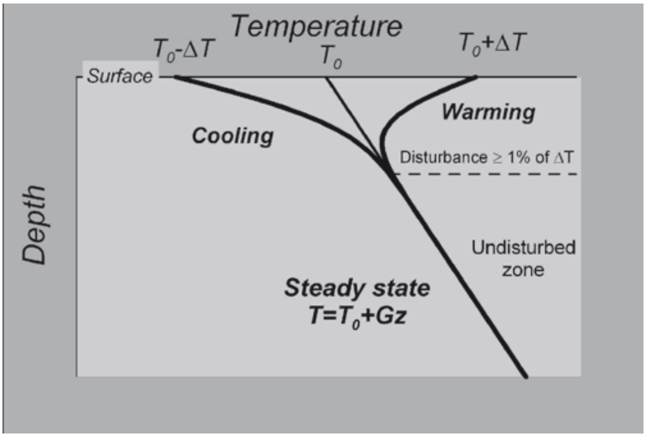

Fig. 11.1 Response of the subsurface temperature field to the change on the surface. Temperature-depth profile measured in a borehole indicates the surface warming/cooling signal as a departure from the (undisturbed) steady-state geotherm

"warmer" and "colder" years may occur irregularly, a relatively long time span is generally needed to provide reliable statistical results. Since the ground smoothes the temperature extremes, the magnitude of the present day climate warming, as the reflection of the long-term climate evolution, can be more easily obtained by the temperature monitoring at shallow depths just below the penetration reach of the seasonal temperature variations and in a considerably shorter time interval.

The geothermal method to reconstruct past climate history addresses the analysis of the downward diffusion of variation of the subsurface temperature field with time. While this method has a low time resolution (being diffusion controlled), it is directly related to the past temperature on the surface (unlike all other proxies). It is an advantage that the time span of most GST-histories extracted from borehole data exceeds that of meteorological SAT data, so they can be used to "extend" the SAT time series back into the pre-instrumental period. This can be done only in case that ground and air temperatures track each other on a long-term scale. Although there are papers suggesting that the climatic temperature record in the Earth is compatible with measured SAT series (e.g. Harris and Chapman 1995), the air and ground temperature coupling is governed by the energy and mass fluxes at the Earth's surface which represent a complex system of competing physical and biological processes (Beltrami and Mareschal 1995). Therefore the effect of other climate variables, such as precipitation and evaporation, transpiration, moisture, soil freezing, snow and vegetation cover changes need to be taken into account (Harris and Chapman 1995; Možný and Kott, 2003). While this fact somehow limits the practical use of the routine inversion procedure, at the same time it offers interesting applications such as detecting long-term changes in the vegetation cover (Čermak and Bodri 2001) and also the possibility to distinguish between the natural and potential anthropogenic components of the present-day warming (Čermak et al. 2000).

11.3 Subsurface Temperature Monitoring

As a part of the "Borehole and Climate" program of the International Geological Correlation Program (IGCP 428), two experimental shallow holes were drilled in two different environments to monitor the depth response to the downwards penetrating signal of the changing surface temperatures. The first 40 m deep hole was drilled in October 1992 on the campus of the Geophysical Institute in Praha Sporilov (50º02'27" N, 14º28'39" E, 275 m a.s.l.). The hole is located on a low E-W trending ridge. The upper four meters of the lithological column represent soil and a man-made loose material backfill of low conductivity (1.7–2.0 W/mK), underlain by silt to clayey shale of gradually increasing conductivity, below 10 m the conductivity is practically constant (3.2 ± 0.2 W/mK) (Šafanda 1994; Štulc, 1995). The corresponding diffusivity of the upper strata is only 0.4×10^{-6} m^2s^{-1}, lower strata is characterized by values of $0.73–0.9 \times 10^{-6}$ m^2s^{-1}.

While the Sporilov hole is located on the rim of a large urban area, the site for the second hole was selected at Kocelovice in south-central Bohemia at a distance of about 70 km SSW of Praha in a typical farming area . The 40 m deep Kocelovice hole (49º28'02.2" N, 13º50'18.7" E, 519 m a.s.l.) was drilled in 1997. The borehole site is near one of the main Czech meteorological stations on a gently grassy slope in slightly undulating terrain. The hole penetrates a compact granite body with a mean conductivity of 3.1 ± 0.1 W/mK, covered by about 1–2 m thick soil layer. The diffusivity was not measured, but can be estimated as $1.2–1.3 \times 10^{-6}$ m^2s^{-1}.

Both holes were equipped with a measuring chain of temperature sensors (thermistors) spaced at selected depth levels covering the whole 0–40 m depth section. Both holes are filled with water, the depth of which slightly varies between 4 and 5 m in Kocelovice hole and is stable at 9 m depth in the Sporilov hole. In addition to the subsurface temperatures, air (SAT) temperatures are monitored at 0.05 m, 1 and 2 m above surface. At Sporilov also precipitation is recorded and at the Kocelovice meteorological station a complete set of various information is completed (wind speed and direction, direct and reflected solar radiation, snow layer thickness, air humidity, soil moisture and vapor tension).

11.4 Monitoring Temperatures

Regular temperature variations at the surface occur at temporal scales, such as diurnal or seasonal/annual. The typical magnitude of the daily variations amounts 10–15ºC, the amplitude of the seasonal variations may amount to 20–30ºC and more. Inter-annual and long-term temperature change patterns are irregular. As the surface, temperature signal propagates downward, its amplitude decreases exponentially with depth due to the diffusive process of heat conduction, each variation vanishes over a vertical distance related to the period of change and to the thermal diffusivity of the ground. The shorter period fluctuations attenuate more rapidly.

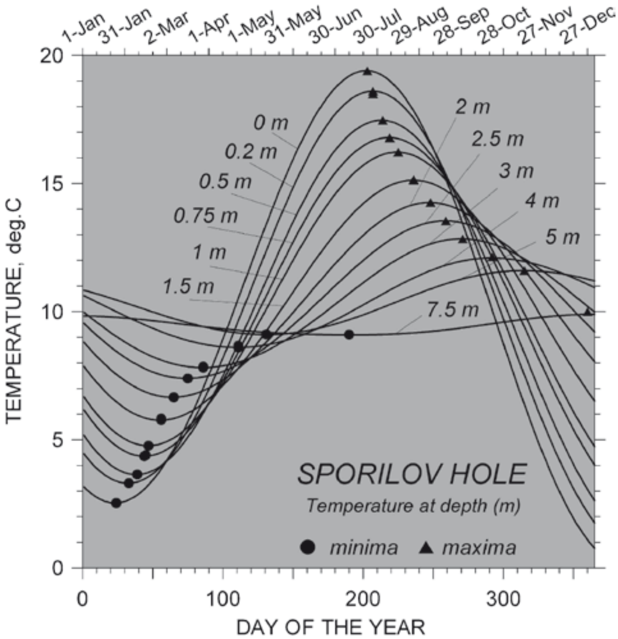

Fig. 11.2 Characteristic temperature distribution in shallow subsurface corresponding to the annual temperature variations on the surface (daily variations ignored). The individual curves illustrate the amplitude decrement and phase delay of the temperature response penetrating downwards. Based on 6-year-long temperature monitoring in the Sporilov hole

Figure 11.2 demonstrates the amplitude attenuation of the temperature signal when propagating downwards and the delay of its phase by presenting the results of the 12-year temperature monitoring in the Sporilov hole. The daily temperature wave is practically not observable below 1 m depth. On the other hand, the temperature at 1 m depth represents integrated average of the daily signal of the previous day(s). Similarly, annual GST oscillations practically vanish at about 15–20 m depth, the temperature field below 20–30 m depth is free of any response to the annual or shorter temperature variations and contains exclusively the fingerprints of longer scale evens with characteristic time of several last years.

The 12-year (1994–2005) record of temperature recorded at 38.3 m depth in the Sporilov hole (Fig. 11.3) clearly demonstrates the yearly increases of temperature (records 2000–2005). Bottom panel summarizes the general temperature increase from 10.63ºC in 1994 to 10.99ºC in 2005 together with early warming rates ranging from 0.02 K/year in 1994 to 0.04 K/year in 2006 (with the mean of 0.0296 K/year). Even when the observed warming rate at depth is not identical with the SAT warming, it can well serve as a certain measure to describe the recent climate evolution.

Figure 11.4 presents monitoring series of temperature at 40 m depth in borehole Kocelovice, where due to technical problems only two shorter monitoring series

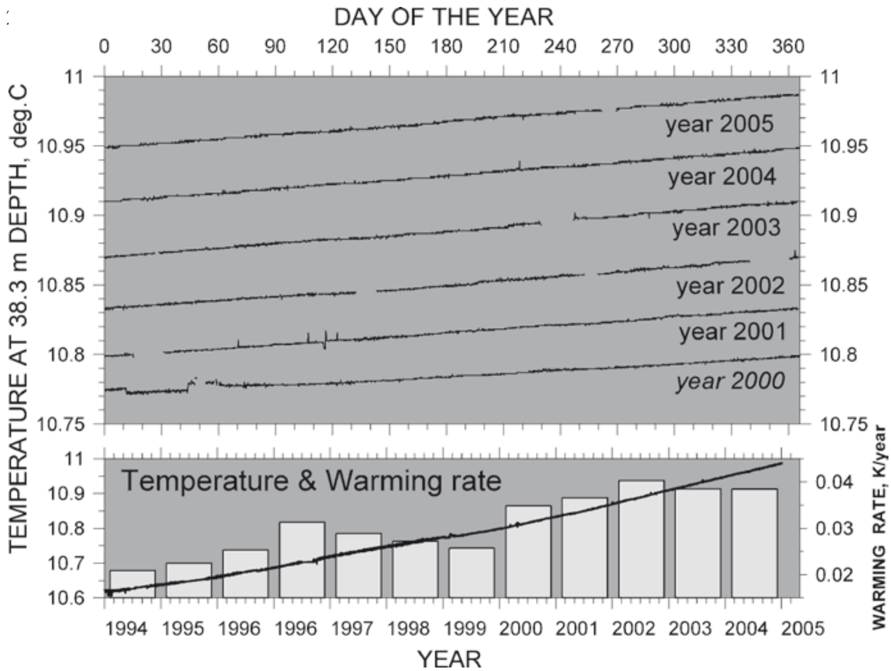

Fig. 11.3 Results of temperature monitoring at 38.3 m depth (Sporilov hole), years 2000–2005. Bottom: the 12-year record together with the warming rates calculated for the individual years

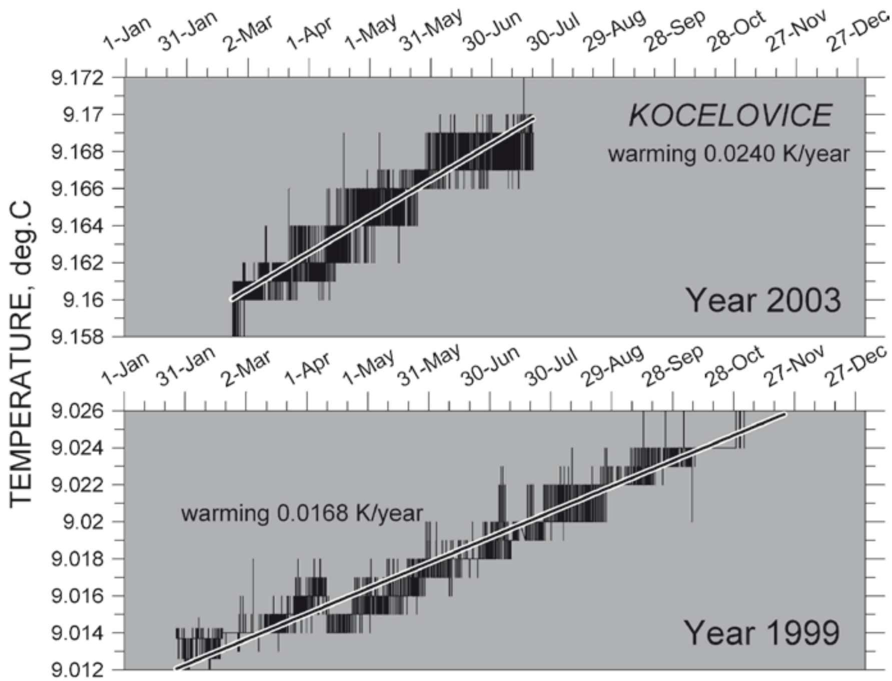

Fig. 11.4 Results of temperature monitoring at 40 m depth (Kocelovice hole). Two records correspond to 1999 and 2003 monitoring series

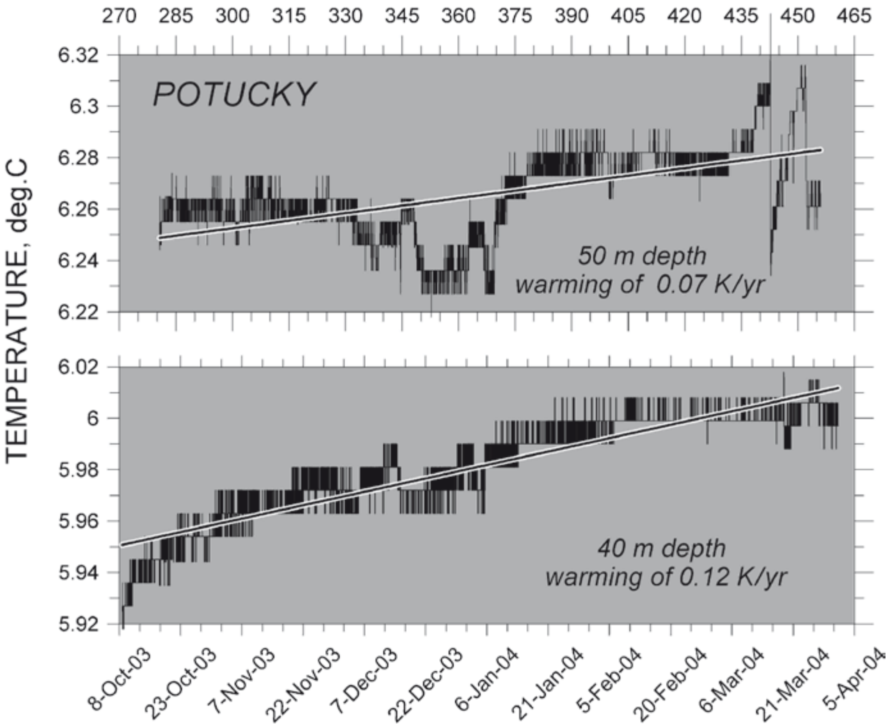

Fig. 11.5 Results of temperature monitoring at 40 and 50 m depths (Potucky hole). Contrary to Sporilov and Kocelovice data, temperature field at Potucky is less stable and obviously disturbed by local hydrogeology

could be obtained, both confirmed warming rate, namely 0.0168 K/year (in 1999) and slightly higher rate of 0.0240 K/year in 2003. In years 2003–2004 a similar experiment was performed in an abandoned hole at Potucky site located in the Ore (Krušné Hory) Mountains, north-western Bohemia (50.43ºN, 12.78ºE, 864 m a.s.l.). The site is in close vicinity of a forested area of coniferous woods (mostly Norwegian spruce, *Picea abies*), and served for several experiments (see further). The temperature data in this hole, however, may be disturbed by complex hydrological conditions in the subsurface and are thus less reliable. The monitoring confirmed surprisingly high warming rates (Fig. 11.5), namely 0.12 K/year at 40 m depth and 0.07 K/year at 50 m depth, which so far are difficult to interpret. It is, however, interesting to mention, that the north-western part of the country belongs to the areas most industrially polluted and that the meteorological SAT record from the near-by station Fichtelberg also revealed a steep increase of air temperature in the last 25 years of 0.0537 K/year (Fig. 11.6).

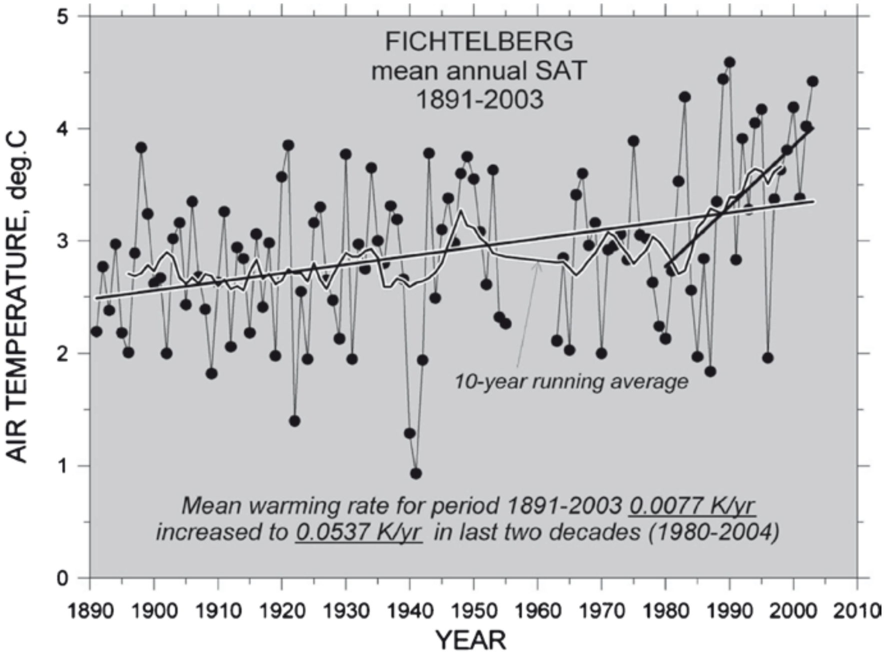

Fig. 11.6 Surface air temperature measured at Fichtelberg meteorological station (1891–2003)

11.5 Surface and Near Surface Effects

11.5.1 Snow Cover and Ground Freezing

Modeling the GST-SAT coupling have confirmed that on longer timescales the GST represents a good SAT indicator and their variations repeat each other (see e.g. González-Rouco et al. 2003, 2006). The problem can be, to what extend the observed GST variations can track SAT changes on a shorter timescale, such as the monthly or yearly series. No doubt, that large spatial-scale GST differences are determined by ground heating by incoming solar radiation, its transformation, distribution and the amount of heat penetrating into the subsurface. Thermal balance on the ground surface is thus determined not only by the actual air temperature, but also by the surface absorption and reflection. Of special concern is the GST-SAT coupling in locations, where e.g. the ground loses a substantial part of information about air cooling in winter because snow insulates the ground and reflects the incoming solar radiations. Even when snow is sporadic, the complicated latent heat effects and winter freezing/thawing processes can complicate the heat transfer. Of similar importance can be the GST-SAT coupling due to rain precipitation producing changes in moisture content, infiltration, evaporation and runoff, as well as the seasonal (micro)vegetation changes and chemical weathering.

To understand the GST-SAT coupling, the experimental site (microclimate station) was built on the campus of the Geophysical Institute in 2002 to monitor the shallow subsurface temperature field below several characteristic surfaces, namely bare soil, sand, grass and asphalt. Air temperatures at 5 and 200 cm above surface as well as soil temperatures at depth levels of 2, 5, 10, 20 and 50 cm are recorded at 5 min interval. All yearly (2003–2005) air temperature averages at 5 cm above the ground are surface dependent, but appeared lower than the soil averages for all types of surface. The differences between air temperature at 5 cm above the ground and the soil temperature at 2 cm depth amounted to 1.4–1.6 K, 1.8–2.0 K, 0.2 -0.4 K, and 4.1–4.8 K for bare soil, sand, grass and asphalt, respectively. These results hint that on the annual scale the soil is warmer than the air and corroborates the similar observations reported by e.g. Backer and Ruschy (1993)) and Putnam and Chapman (1996). The interannual variability is also surface type dependent and ranges within the first tenths of degree Kelvin.

In general, the magnitude of the GST-SAT difference may exhibit significant variations. Subsurface heat conduction as well as the factors related to the movements and/or diffusion of air and/or moisture masses (wind, evaporation/transpiration, vertical soaking of soil moisture and precipitation) tends to equalize air and soil temperatures. Soil temperature generally follows the air temperature course when average SAT is above 0°C, but the GST-SAT coupling is violated at the presence of snow in winter when the air temperature drops below zero. Snow insulates the ground surface and reduces heat loss. As an example Figure 11.7 shows the temperature variations of the air (SAT) temperature together with the 2 cm depth soil data under different surfaces and illustrates the effect of the snow cover on the GST-SAT coupling. During the week February 20–27 the SAT-GST data decoupled, then the coupling started to restore after snow cover thawed away (on January 28) and continued till February 8 when new snow appeared again. For the most of February till the early March the GST-SAT data decoupled again. Similar results were obtained at Potucky (Fig. 11.8), where temperature was recorded at 2 cm depth and 5 cm height above ground. The coupling of the temperatures is almost perfect in fall and spring and breaks down during most of the winter.

Smerdon et al. (2004, 2006) have generalized the results of the above experiments in the relation to several temperature time series measured at other localities, namely at Fargo (North Dakota), Cape Henlopen State Park (Delaware) and Cape Hatteras (North Carolina). These sites represent different kinds of subsurface strata and/or climatic settings located within the mid-latitude zone, and can be used for the spatial consideration. On the annual scale the GST signal (even attenuated and phase shifted) generally follows the SAT variations. The slight differences between annual GST and SAT signals may occur in both winter and summer seasons. The GST-SAT difference depends on the site location and its climate and terrain characteristics. The GST-SAT decoupling at Fargo occurs mainly during the winter, whereas at Capes Henlopen and Hatteras the observed attenuation of the GST signal has taken place during the summer season. The seasonal partitioning of the GST-SAT decoupling is caused mainly by the corresponding partition of the summer precipitation and snow. While the Fargo location is characterised by the modest

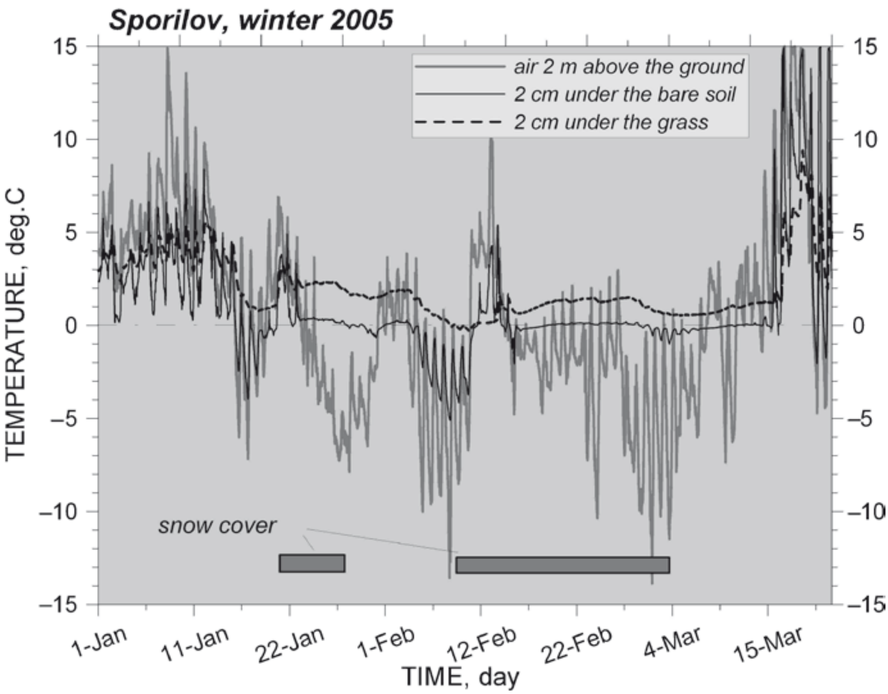

Fig. 11.7 Time series of air (at the height 2 m) and soil temperatures (at 2 cm depth) recorded under different surface at Prague-Sporilov. Soil temperatures follow SAT at temperatures above 0ºC, but are decoupled when the surface is covered by snow

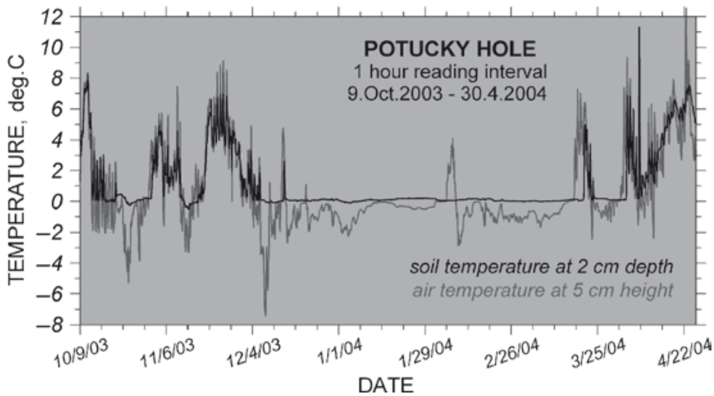

Fig. 11.8 Time series of air (at 5 cm above surface) and soil (at 2 cm depth) temperatures recorded at Potucky hole in 2003–2004 winter. Between mid December 2003 and March 20, 2004, when the ground was covered by snow, soil temperature was practically constant and showed practically no response to the SAT variations

rainfall and significant amount of snow, the Cape Henlopen and Hatteras stations have negligible or no snowfall. Similarly to the Czech monitoring results, the North American stations confirmed influence of the snow cover on the GST-SAT coupling. In all investigated locations snow cover has affected heat transfer in the surface in such a manner that mean daily soil temperature under snow cover was warmer relative to the SAT.

The above experiments have detected also finer features of the GST-SAT decoupling during cold season, such as the dependence of the soil temperature on the thickness of snow layer and snow quality, the date when the first snowfall started, and the effect of the vegetation cover. Numerical modeling by Gosnold et al. (1997) of the GST-SAT tracking in the presence of the snow cover have detected that the winter soil temperatures are more sensitive to the presence or absence of snow rather than to variations in its thickness. Thus, the exact amount of the winter snowfall is unlikely a decisive factor of the GST-SAT coupling in winter. Our monitoring experiments have also revealed certain effect of the surface type on the ground-air temperature tracking. The grassland preserves the snow cover longer than the bare surface, where snow is not isolated from the ground. Combination of snow and grass provides better insulation and the temperature under such surface remains above zero, the rate of snow melting is thus surface dependent. The thicker snow cover is characteristic for the grass. Similar studies were also done by the research group of the Utah University, see for more discussion in Bartlett et al. (2004, 2005, 2006)

It is to be stressed that our results are representative of the typically mid-latitude seasonal GST-SAT relationships, i.e. for mild winters, with relatively less snow and generally late snowfall. Winter temperatures are rarely cold enough to cause a massive soil freezing. At high-latitude regions where SAT temperature remains below 0°C for a considerably longer time, the effect of freezing may even surpass the influence of the snow cover, depending on the date what comes first, snow or frost. Here we can only partly contribute by demonstrating the effect of the soil freeze/thaw events on the GST as reflected by the relatively rare situation on the time series at Potucky site (Fig. 11.9). The period October–December 2003 was characterized by the absence of snow and by two episodes of the sharp air temperature fall below 0°C. The ground temperature at shallow depths of 2 and 10 cm remained almost constant, close to 0°C and to 1–1.5°C, respectively, demonstrating a so-called "zero-curtain effect" that occurs due to latent heat released from the freezing of soil. Recorded temperatures indicated that the soil freezing at Potucky station during this period did not penetrated deeper than 10 cm. The uppermost "active" layer experienced a complex combination of heat transfer from the frozen upper and undisturbed lower layer as well as the heat release from the advancing freezing front, the corresponding temperature-time series reflected pure influence of the freeze/thaw processes on the GST. The anomalous SAT variations were significantly attenuated at the depth of 50 cm with a time delay of days. Temperatures at that depth are lower than the highest positive air temperatures by approx. 3–4 K and may be higher than the lowest negative air temperatures by 8–10 K.

Figure 11.10 shows the ground temperatures under sand and grass surfaces during February 2006 at the Prague-Sporilov station. Due to several frosty days and

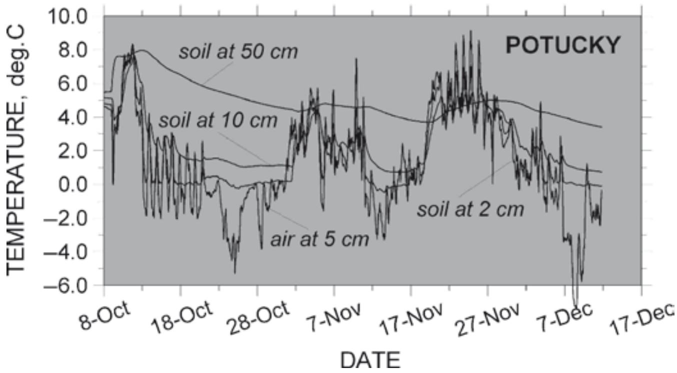

Fig. 11.9 Time series of air (at 5 cm height) and soil temperatures at 2, 10 and 50 cm depth at Potucky hole (October–December 2003)

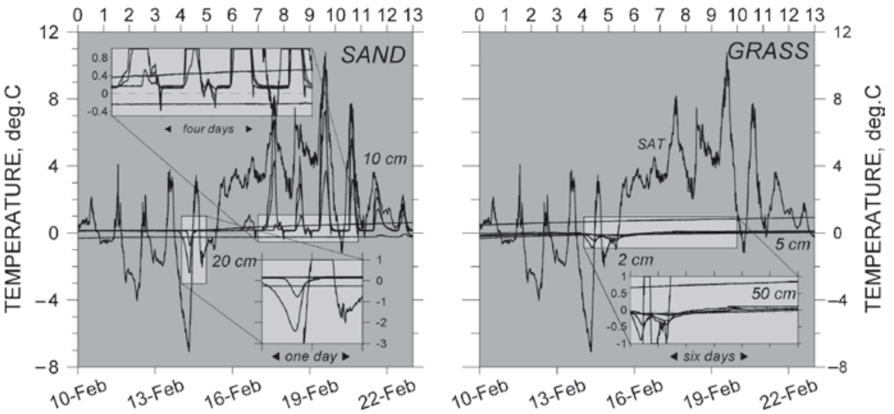

Fig. 11.10 Shallow soil temperatures at different depths below sand and grass surface during short freezing cycles in February 2006. Data from Sporilov hole

absence of snow in January, the subsurface temperature below both surfaces dropped below the freezing point. Temperature at 20 cm depth was stable at approx. 0°C and/or −0.3°C under the grass and the sand, respectively. The higher temperature under the grass occurred due to insulation effect of the vegetation cover. In the first half of February, when SAT was oscillating around zero, the GST under both surfaces remained practically constant. Its sharp decrease between 2 and 5 cm depths was observed only on February 14–15 and was the result of a similar SAT drop. During the second half of February, when the air temperature increased above zero, the subsurface temperature under the sand surface followed the SAT course. However, the phase changes of soil moisture substantially reduced the GST variations. The surface temperature variations vanished at the interface of the frozen and thawed soil layers and remained at zero temperature. Temperature at 20 cm depth was practically constant, that hints that all heat coming from the surface was spent to melt the soil moisture (Fig. 11.10, left). Under the grass, where insulation of the surface and low thermal diffusivity of the soil slowed down the penetration of the surface warming, at all measured depth soil temperature remained close to 0°C (Fig. 11.10, right).

11.5.2 Rain Precipitation

Summer soil temperature is controlled by combined effect of air temperature variations and soil moisture content. An increase in rainfall during summer season can increase both surface wetness and soil moisture. This requires more energy consumption for evaporation and produces cooling of the ground surface (Yasunari et al. 1991; Matsuyama and Masuda 1998). In principle, such soil moisture feedback mechanism may explain soil cooling during summer, when air temperatures increase. Rain precipitation is thus another factor determining the subsurface thermal regime because it affects the amount of soil moisture and therefore the amount of energy removed from soil by latent heat flux. Because the thermophysical properties of the subsurface rock, like thermal conductivity and heat capacity, depend on the water content, the rainfall can influence not only energy balance of the ground surface-air system, but also thermophysical and/or hydrological characteristics of the ground. Regions with low porosity and permeability will likely be less affected, while less consolidated medium will experience more pronounced changes.

Primarily influence of the precipitation on the GST-SAT coupling occurs on the very short time scales (during and just after rain events) through advective transport of heat by falling water that may significantly contribute to the development of shallow subsurface temperatures. Figure 11.11 displays temperature difference between the ground surface ($T_{z=0}$) and temperature at 2 cm depth measured in a dry and in a rainy period at Prague-Sporilov. During a 10-day interval with no rain the differences have shown quasi-periodic oscillations with maximum positive values in the daytime and negative values at night. The range of variations achieved ~9 K. The temperature differences were negative after rain events over both day and night (air temperature at wet surface is lower than at 2 cm depth, like e.g., June 30-July 2 and/or July 5–6 intervals). Its variations were significantly reduced and ranged within only ~3–4 K. On the other hand, evaporation goes relatively quickly, thus, depending on the rain strength the “dry” regime was restored after 1–2 days after rainfall.

The role of rain precipitation appears to be far more important on seasonal and/or annual scales because of its possible seasonal persistence. In the mid-latitudes snowfall and soil freezing represent generally sporadic events and their effect on the GST-SAT coupling is not perceptible already under decadal averaging. On the contrary, rainfall occurs more regularly during much of the summer and its annual distribution remains preserved for the long periods. The Prague site represents typical example of the seasonal timing of precipitation. Daily precipitation at Prague has no significant linear long-term trend, but is characterized by

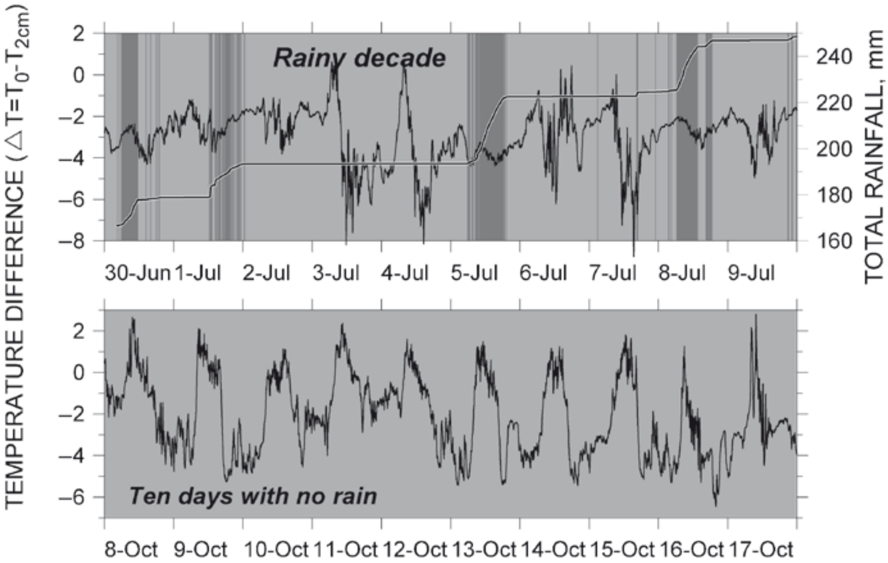

Fig. 11.11 Temperature differences between ground surface and soil temperature at 2 cm depth at Prague-Sporilov station; comparison of the rainy decade with dry period. *Top panel* also shows total rainfall amount

a certain seasonal character (Bodri et al. 2005); the wetter season falls on May–August period and the precipitation minimum occurs in winter. Figure 11.12 shows time series of daily averages of SAT temperature (at 5 cm height) and soil temperatures at the depths of 0.05, 1, 2 and 5 m measured at station Prague-Sporilov during the "rainy" year 2000. The amount of precipitation is shown by the histogram below. Detectable high-frequency oscillations of the soil temperature record in summer are caused mainly by the rains that change the moisture content of the soil and correspondingly affect both latent and sensible heat flow at the ground surface. As seen, rainfall events are accompanied by the corresponding changes of both air and ground temperatures. The main observation fact about summer GST-SAT interrelation is that the rainfall does not cause total decoupling of both temperatures similar to that what occurs in winter due to snow cover and freezing/thawing cycles. The air temperature record at 5 cm height and the GST records at the air-soil interface practically repeat each other. Correlation of both temperatures amounts to 0.96.

Surface temperature oscillations are practically imperceptible at 2 m and at deeper levels. Ground temperatures below 1 m depth are steadily lower than air temperatures from May to September and are higher than the air temperatures from November to February. At shallow depths variations of the GST around SAT are more erratic. At the shallow subsurface soil temperatures remain steadily higher than air temperatures only during November–February). During most of the year shallow GST irregularly oscillates above and below air temperature depending on

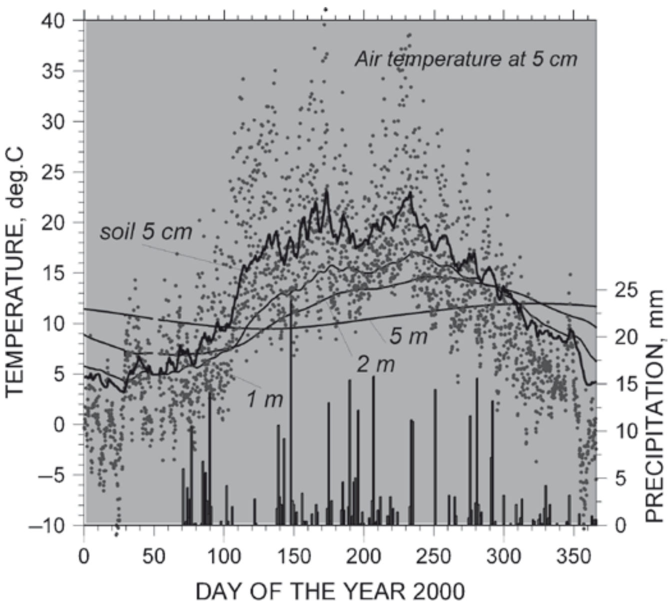

Fig. 11.12 Time series of daily averages of air temperature (5 cm height) and soil temperatures at 5, 100, 200 and 500 cm depth (Prague-Sporilov station). The histogram below shows precipitation amount

the temporal pattern of the rainfall. These oscillations likely will disappear under long scale averaging.

11.6 Meteorological Data and Regional Warming Pattern

Long-term meteorological SAT series from a number of Czech stations were compared with the ground surface temperature evidence obtained by inverting almost one hundred borehole temperature-depth profiles (Bodri and Čermak 1999). Both sets of data showed a certain similarity, which suggested that, the urban and industrial areas with higher population might have recently experienced greater warming than areas predominantly farming. It was presupposed that shallow temperature monitoring may usefully help to assess the potential anthropogenic component of the present (global) warming (Čermak et al. 2000). Now, we have repeated this procedure with the updated SAT data from 32 local meteorological stations for period 1960–2006. Regardless of the nature of the year-to-year fluctuation, all records documented local warming, with a characteristic regional mean of 0.0284 K/year (Fig. 11.13).To void the differences in the recorded local temperatures due to the altitude of the individual station reduced temperatures (relative to the mean of the particular station) are shown. The calculated cross-correlation coefficients between the SAT records from the

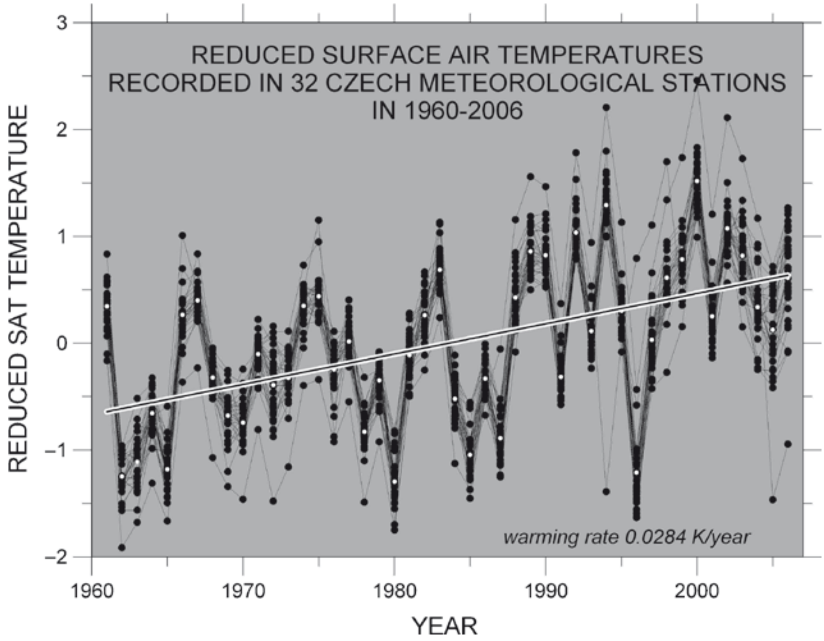

Fig. 11.13 Reduced surface air temperatures recorded in 32 local meteorological stations in the Czech Republic (1960–2006)

individual stations ranges from 0.92 to 0.99, which means that the whole territory of the Czech Republic can be considered as a single homogenous unit and the few existing gaps in data series could have been repaired by using data from the near-by stations with an appropriate datum-offset. All individual warming rates well fitted to the general interval of 0.01–0.04 K/year (Fig. 11.14) (with minimum of 0.0146 K/year at Olomouc station and maximum of 0.0384 K/year at Doksany) with an average value of 0.0284 K/year, which supports the reality of the continuing warming. The previous works (Čermak et al. 2000) focused the attention to decide whether the present warming is just a natural phenomena or there is a certain anthropogenic contribution reflecting the negative consequences of human activities. Figure 11.15 presents a histogram of the warming rates, when the respective sites were subdivided into three categories: (a) sites located in typically farming regions and (c) sites located in the typically industrial regions or near large urban centers. All remaining sites were rated as (b) mixed, when it was difficult to unambiguously affiliate the respective site to one of the above category. Whatever, such subdivision may be a speculative, the predominantly agriculture (rural) regions seem to be characterize by lower warming than industrial regions. Modification of land surface, production of waste heat, pollution and lack of vegetation, that all contribute to the irreversible change in the energy balance. The "urban heat island effect" known in meteorology describing the fact that average temperatures are higher in metropolitan than in rural areas may be thus applicable on the larger regional scale.

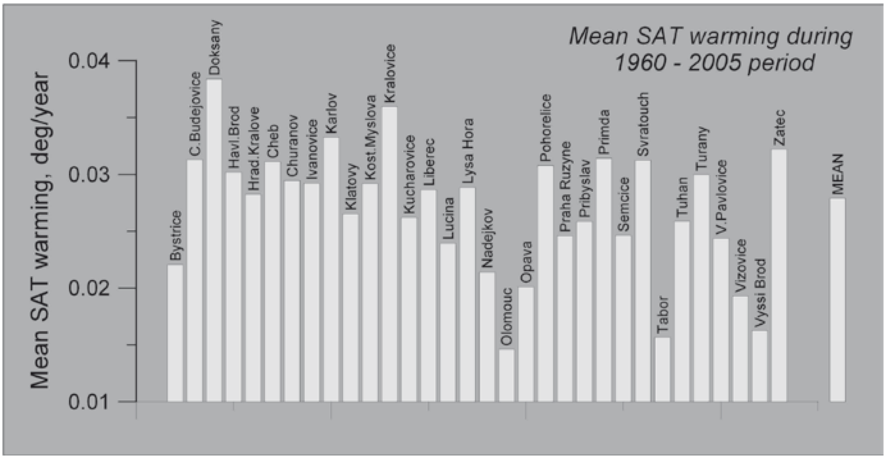

Fig. 11.14 Mean SAT warming recorded in the individual meteorological stations

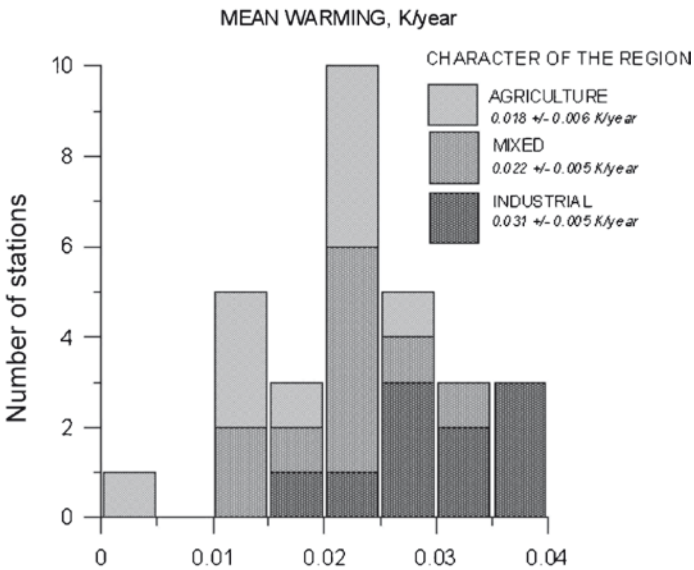

Fig. 11.15 Histogram of observed warming rates (1960–2006) vs dominant character of the region (farming, mixed, industrial)

11.7 Conclusions

Monitoring results have shown that the SAT forcing represents the main cause for the GST changes and this fact supports the use of the GST as an indicator for the climate reconstruction. Differences between the GST and SAT signals are closely linked to the processes occurring at the ground surface and in the shallow subsurface of upper first few meters.

GST-SAT coupling over short-term timescales (such as single year) is complex. The winter snow cover and freeze/thaw effects may present serious influences causing GST-SAT decoupling. Because snow cover insulates the ground in the cold season, its systematic and persistent variations may distort their relation and hinder the direct comparison of both variables. In regions with short-duration snow cover its random fluctuation tends to vanish in longer averages. The summer rain precipitation and the corresponding moisture transpiration and evaporation have likely weaker effect on the GST-SAT decoupling.

On the daily scale, the GST may be either warmer or cooler than SAT and their difference progressively increases as the seasons become more extreme. However, the mean annual GST is generally always higher than the SAT. For the mid-latitude regions their difference amounts to 1–2 K. This value is higher in the regions of deep, long-duration snow cover or of extreme soil freeze/thaw cycles. The GST-SAT difference may be also much higher under artificial cover-types, such as concrete and asphalt exposed to direct solar radiation. The GST-SAT comparison may also be problematic in regions subjected to significant land use changes. Although snow does decouple SAT and GST on a daily and perhaps monthly basis, ground temperatures still track climate change as long as the characteristics of the snow season (onset and duration) has not changed systematically through time (Bartlett et al. 2004, 2005).

All detected processes that could break the GST-SAT coupling have only short-term effects on the heat transfer in the shallow subsurface, particularly of daily to seasonal timescales. In general, the short-term GST-SAT differences cannot considerably violate the assumption on the tracking of both temperatures on the long timescales.

The shallow-depth temperature monitoring proved to be a useful tool to assess a certain measure proportional to the present-day warming rate. The 12-year (1994–2005) experiment at Sporilov clearly demonstrated a gradual increase of warming rate within the range 0.025–0.040 K/year with a mean value of 0.0296 K/year. Shorter record from Kocelovice revealed lower warming rate of 0.0168–0.0240 K/year. Both values are in good agreement with the observational results of local meteorological SAT series and with the GST histories extracted from the deeper holes. The observed higher warming rate at Sporilov relative to Kocelovice together with the results of the SAT data from a number of local meteorological stations may confirm the assumption of regional character of the present-day (climate) warming and reflects an anthropogenic contribution to warming.

The monitoring technique itself, if applied in an extensive area network of enough measuring sites, may suitably contribute to knowledge of regional aspects of the recent climate evolution.

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