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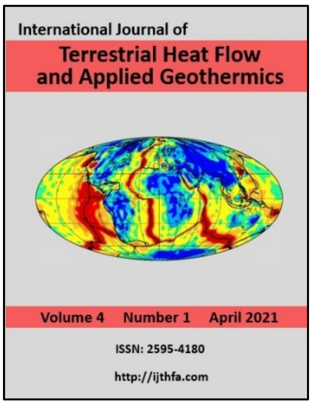

Influence of past vegetation changes on estimates of ground surface temperature histories GSTH obtained by inversion of borehole temperature logs: Example from the Western Canadian Sedimentary Basin

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Abstract

Functional space inversions (FSI) of precise temperature logs from 43 wells, located in low conductivity clastic sediments of the Western Canadian Sedimentary Basin, (WCSB), reveal evidence of extensive, recent ground surface temperature (GST) warming. Simultaneous inversion of log data acquired during the period of 1987-2005, as well as averaging of the individual site reconstructions of subsurface temperature signals, indicate evidence of high magnitude of warming of about 2°C (with standard deviations of 0.7°C). Magnitudes of such warning events exceeds 3-4 times that of globally averaged continental GST's for the 20th century and is significantly higher than that of changes in surface air temperatures (SAT) based on instrumental records in the WCSB. Within this region, GST warming in the 20th century could have been at least partially caused by changes in vegetation cover. The temporary or permanent removal of vegetation, through deforestation, forest fires, and grassland conversion for agriculture occurred in the relatively young provinces of WCSB, during centennial long settlement and development programs. This might have significantly changed the surface properties of the area, since changes in surface albedo affects the radiation budget, while changes in the thermal, moisture and aerodynamic characteristics affect the energy balance. The results of our modelling for typical range of bedrock thermal diffusivities and assumed surface warming history for studied areas in WCSB show that a possible jump in ground surface temperature can easily be interpreted in the FSI results as a gradual warming event of large amplitude and attributed to SAT.

1. Introduction

Temperature log data for boreholes in the Alaskan permafrost region has been interpreted as evidences indicative of ground surface warming (Lachenbruch and Marshall, 1986; Lachenbruch et al., 1988). Similar conclusions were reached for areas to the south of continuous permafrost in Canada (Cermak, 1971; Jessop, 1990a, b; Wang, 1992; Mareschal and Beltrami, 1992; Lewis, 1992; Lewis, 1998; Lewis and Wang, 1992; Majorowicz, 1993; Majorowicz et al., 2002a,b; Majorowicz et al., 2012; Majorowicz et al., 2014) and elsewhere in the world (Cermak et al., 1992, 2000; Deming, 1995; Pollack and Huang, 2000; Pollack et al, 2000; Harris and Chapman, 2002; Huang 2006, Bodri and Cermak, 2007; Putnam and Chapman, 1996; Šafanda et al, 2003; Hamza and Vieira, 2011). Data sets reported by Huang and Pollack, 1998 for the NOAA 2019/IHFC IASPEI continental well temperature data for borehole temperature inversion compilation of GSTs also reveal similar trends.

It has been argued that GST warming derived from FSI (Shen and Beck, 1991) inversions of temperature logs in boreholes in Western Canada, has been indicative of climate changes. But deforestation has been an ongoing activity especially in previous century. Hence the observed signal is largely affected not just by climatic warming but also by permanent step changes in ground surface temperatures, arising from land surface changes of the past (Majorowicz, 1993; Skinner and Majorowicz, 1999; Majorowicz and Skinner, 1997a, b). Similar observations were made in other places (Blackwell et al., 1980; Cermak et a.l, 1992; Lewis and Wang, 1992; Lewis 1998, and Lewis and Skinner, 2003). The effect has been an improved understanding of the subsurface warming signal as superposition of climate warming and more local-to-regional changes in subsurface temperatures due to deforestation. Here, we quantify this effect upon GST warming histories derived by FSI inversions.

The observed increase of temperature of the ground and subsurface in Alberta and Saskatchewan was demonstrated as independent from meteorological records evidence of recent climate warming. Inversions of temperature logs in remote areas of the Prairie Provinces, which underwent large land clearing for agricultures in the 20th century (Figure1) showed some 2ºC GST warming. It was by 1ºC (Majorowicz and Šafanda, 1998; 2001) higher value than SAT warming based on the meteorological stations' temperature data evidence (Environment Canada, 1992,1995).

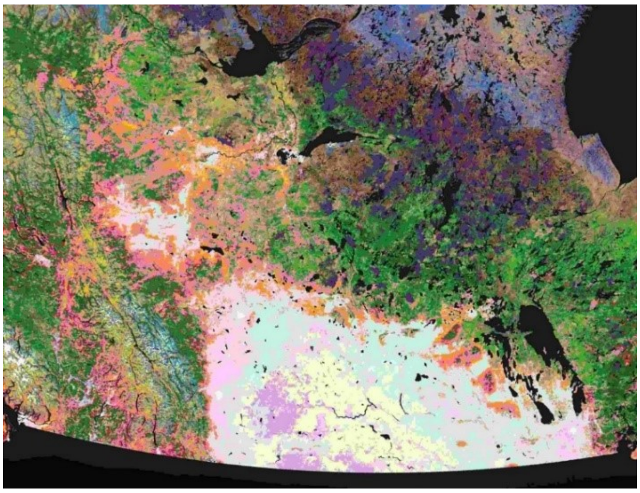

Figure 1 - The map of land cover from the Canada Centre for Remote Sensing, Government of Canada (link below). Note: lighter colors mark areas of strong agricultural activities in the Canadian Prairie Provinces. Full color scale is given here: https://www.nrcan.gc.ca/the-north/science/land-surface-vegetation/10719

2. Methodology

The basic hypothesis of borehole paleoclimatology we use in this paper is that radiative heating and heat exchange between the ground and the air directly control the ground surface temperature (GST). Time-transient changes in the GST diffuse into the subsurface by a heat conduction creating a disturbance in the T-z profile which can be inverted to determine the timing and magnitude of changes in the GST. Simplifying, we have subsurface gaining heat, diffusively changing with depth in case climate is warming and reverse when climate is cooling (Figure 2).

With inversion of temperature logs we get information about ground surface temperature history (GSTH) smoothed out by a diffusive process. Due to the low thermal diffusivity of rocks, GST changes propagate downward very slowly. Transient perturbations to the steady state temperature field calculated for a surface warming approximated by linear 'ramp' model increase, for typical values of the thermal diffusivity of rocks, i.e., about 10^{-6} m^2s^{-1} and for an onset of the surface changes 20- 250 years ago, will reach 100-300 m, respectively. (Harris and Chapman, 2002; Eppelbaum et al., 2006). Inversion methods for western Canada sedimentary basin wells (WCSB), (Majorowicz and Šafanda, 1998) used the functional space inversion technique (FSI) developed by Shen and Beck (1991, 1992), Shen et al. (1995) and Beck et al. (1992).

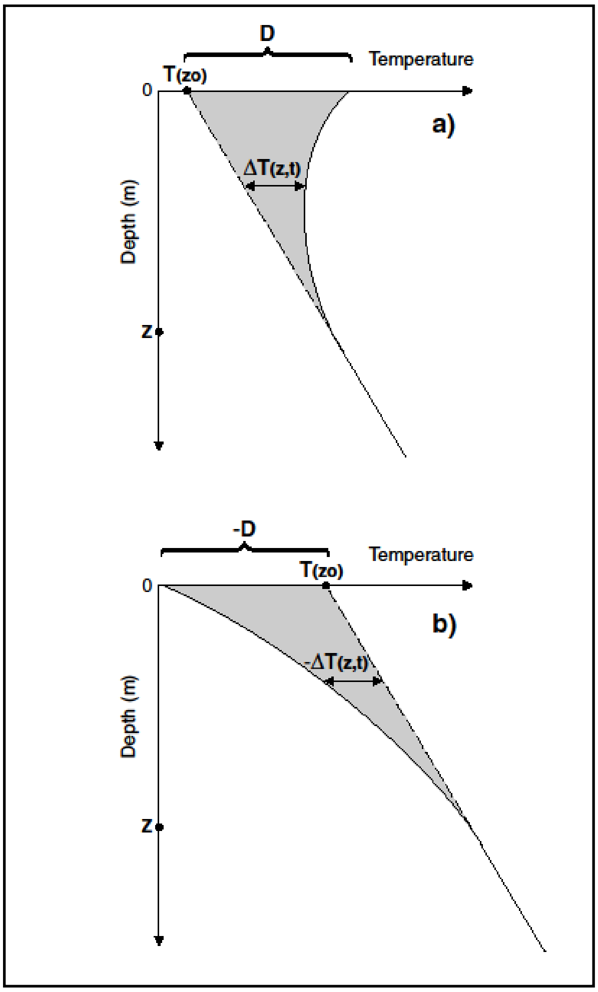

Figure 2 - Comparison of responses of a typical steady state geotherm to the ground surface temperature warming (a) and cooling (b).

The FSI method is basically the generalized least-squares inversion method. It uses the so-called Bayesian approach, when both the measured temperature profile, the parameters of the physical model and the sought history of the surface temperature are treated as random quantities in the probabilistic model defined by *a priori* estimates of these quantities and their standard deviations (SDs). The *a priori* values are modified during the inversion to reach the *a posteriori* configuration with a maximum probability. As a rule, the short-wave variations of temperature gradient are compensated for by variations in the *a posteriori* thermal conductivity profile and thus incorporated into the steady-state component of the temperature profile together with an estimate of the surface temperature T_o at time t_0 and the heat flow Q_b at the bottom at depth z_b. Therefore, during inversion, the T-z profile is decomposed into *a posteriori* steady-state and transient component. The latter component is used for the GST reconstruction.

3. Temperature depth data

The basic data used to reconstruct surface temperature history in the WCSB are unperturbed temperature profiles taken in water filled wells in equilibrium (Majorowicz, 1993; Majorowicz et al., 1999; Majorowicz et al., 2006). The logs and, in several cases, relogged temperature depth profiles were carried out in observation wells of Alberta and Saskatchewan Environment agencies of the Canadian Prairie provinces (Majorowicz et al., 1999). An example of such repeated profiles illustrating disturbed temperatures in the upper 100-m, due to surface warming of the 20th-21st century, is shown in Figure 3. The locations of such wells are indicated in the map of Figure 4.

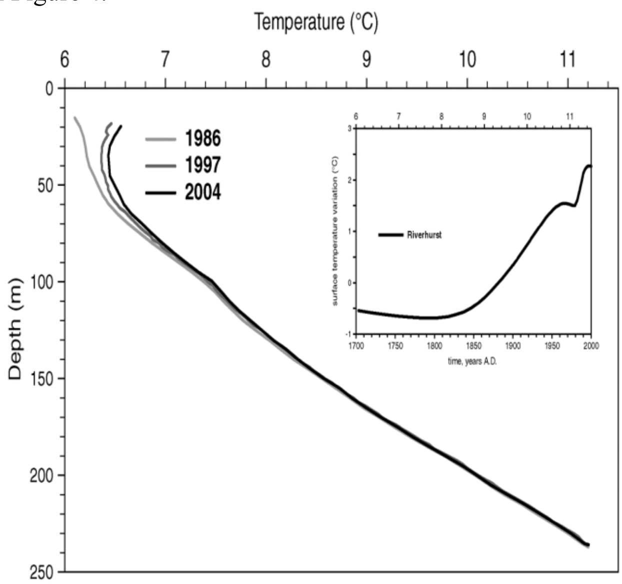

Figure 3 - Example of the temperature-depth equilibrium high precision log in well Rivenhurst in Saskatchewan, Canada. The insert refers to results of FSI inversion yielding surface temperature history at the ground level.

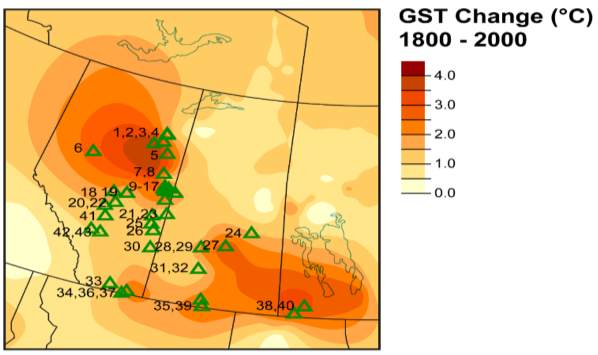

Figure 4 – Locations of well sites in Alberta, Saskatchewan and Manitoba for which past ground surface temperature (GST) histories were inferred using FSI inversion method (Majorowicz and Šafanda 1998,2001 Majorowicz at al., 1999;2002a,b;2012).

The small diameter of the wells relative to their length inhibits convective movements inside the well bore that may disturb the thermal regime. Repeated logs confirm conduction dominated downward propagation of the GST changes into the subsurface.

The observed differences between the repeated logs at relatively shallow depths also confirm the transient character of the temperature - depth profiles and give us a precise way to determine heat gain of the ground and aquifers over time of the industrial age. Inversion of this part of log data allows extraction of the warming/cooling signal of the past ground surface temperature history.

The list of log data for 43 locations in agricultural areas of the Canadian Prairies Provinces in Alberta and Saskatchewan is provided in Table1 (Majorowicz et al., 2006).

Table 1 - Canadian Prairies boreholes with temperature depth logs in equilibrium.

No.	Well	Province	Latitude	Longitude	Surface	Type
1	TFM2	AB	57.39	-111.82	flat	forested
2	TFM1	AB	57.33	-111.69	flat	forested
3	TFM14	AB	56.97	-111.85	flat	forested
4	TFM15A	AB	56.77	-112.49	flat	forested
5	Stony Mt.	AB	56.39	-111.27	flat	forested
6	Winagami	AB	55.61	-116.68	flat	grass
7	T963Kirby	AB	55.39	-111.13	flat	pasture
8	T962Wian	AB	55.35	-111.04	flat	pasture
9	BPTriad	AB	54.74	-110.71	flat	forested
10	Cold Lake944	AB	54.65	-110.51	flat	forested
11	TCL94	AB	54.62	-110.43	flat	forested
12	TCL1	AB	54.61	-110.25	flat	forested
13	TCL14	AB	54.57	-110.81	flat	forested
14	TCL10Lessard	AB	54.48	-110.62	flat	forested
15	TS941	SK	54.5	-109.87	flat	forested
16	Cold Lake4-5	AB	54.06	-110.41	flat	forested
17	Cold Lake3	AB	54.06	-110.41	flat	forested
18	T961	AB	54.01	-113.18	flat	cropland
19	T790Sion	AB	53.91	-114.11	flat	cropland
20	Devon	AB	53.41	-113.76	flat	grass
21	T765	AB	53.35	-110.01	flat	cropland
22	T791	AB	53.16	-110.98	flat	cropland
23	Warburg	AB	53.13	-114.36	flat	grass
24	T965Armley	SK	53.06	-103.95	flat	cropland
28	T966	SK	52.02	-107.12	flat	cropland
29	T967	SK	52.01	-107.11	flat	cropland
30	TSA3	AB	51.57	-110.48	flat	prairie
31	T9cRivenhurst	SK	50.95	-107	flat	prairie
32	T8cRivenhurst	SK	50.88	-106.87	flat	prairie
33	TSA6	AB	49.38	-112.21	flat	prairie
34	TSA10/10B	AB	49.18	-111.07	flat	grassland
35	TKT1	SK	49.07	-106.25	flat	grassland
36	TSA12	AB	49.02	-111.36	flat	grassland
37	TSA13	AB	49.01	-111.32	flat	grassland
38	WAWANESA	MB	49.6	-99.84	flat	grassland
39	Wood Mt	SK	49.4	-106.4	flat	prairie
40	CCDP-KT2	MB	49.2	-100.45	gentle slope	pasture
41	T784Gull lk.	AB	52.627	114.052	flat	grass
42	T767	AB	51.767	-113.968	flat	grass
43	T768	AB	51.828	-114.653	flat	grass

4. GST warming derived from remote well temperatures higher than SAT warming from meteorological stations

Temperature logs in wells of few hundred meters depth done in Alberta and Saskatchewan over period 1992-2005 provide valuable information about ground surface temperature (GST) history for several centuries to a millennium (Majorowicz et al., 2004).

These temperature transients are mainly positive pointing to the surface warming in the last circa two centuries, but their interpretation as a climatic indicator is not always straightforward and SAT warming from meteorological stations is by some 0.5-1°C lower than the GST warming derived from the inversion of well temperature profiles.

5. Experiment - GST warming model - FSI inversion of synthetic logs – GST histories

To simulate the effect in subsurface temperatures, arising from the change in original natural vegetation cover to arable land during the 20th century, we considered beside the linear increase also its superposition with a step change of 0.5 K to 1 K. Superposed models of such changes occurring at year 1920, 1940 and 1960 are illustrated in Figure 5.

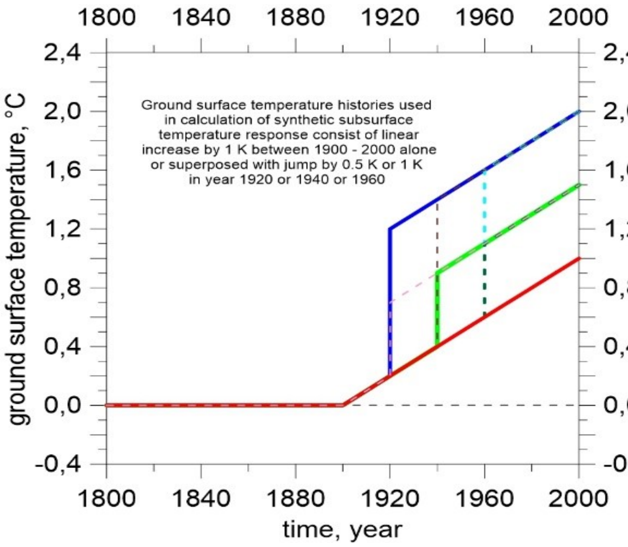

Figure 5 - Ground surface temperature histories used in calculation of synthetic subsurface temperature response are based on a recent climate warming approximated by a linear increase at rate of 1 K per 100 years with the onset at the beginning of 20th century, superposed with a jump by 0.5 K or 1 K in years 1920 or 1940 or 1960.

The synthetic transients resulting from these GST models (Skinner and Majorowicz, 1999; Majorowicz et al., 1999) are shown in Figs 6-7. Because most of our temperature-depth profiles were measured around the turn of the millennium, all transients were calculated for the year 2000. The considered alternative thermal diffusivity values of $0.6*10^{-6}$ m^2s^{-1} (Figure 6) and $0.8*10^{-6}$ m^2s^{-1} (Figure 7) represent lower and upper estimates for sedimentary rocks in the studied area.

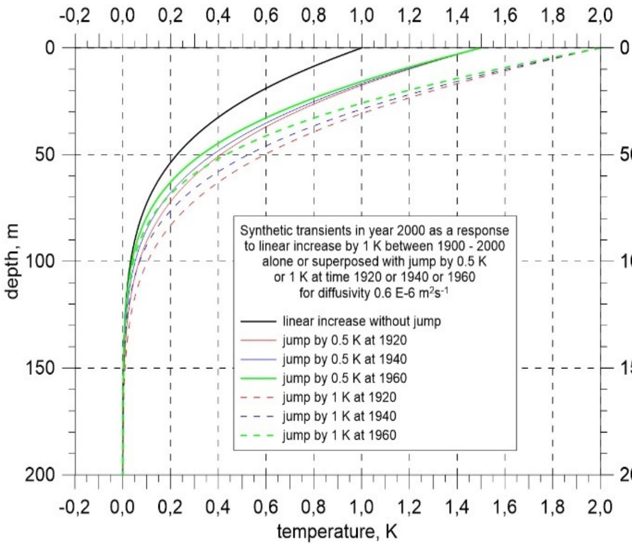

Figure 6 - Synthetic transients of the subsurface temperature response to the ground surface temperature histories shown in Figure 5 calculated for the year 2000. The considered thermal diffusivity was $0.6*10^{-6}$ m^2s^{-1}.

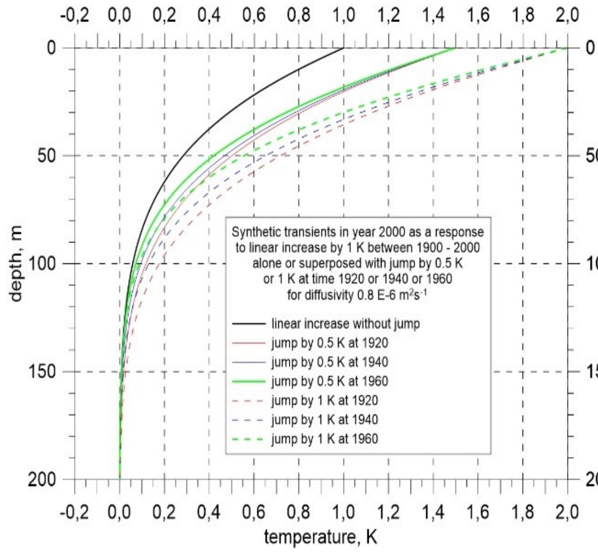

Figure 7 - Synthetic transients of the subsurface temperature response to the ground surface temperature histories shown in Figure 5 calculated for the year 2000. The considered thermal diffusivity was $0.8*10^{-6}$ m^2s^{-1}.

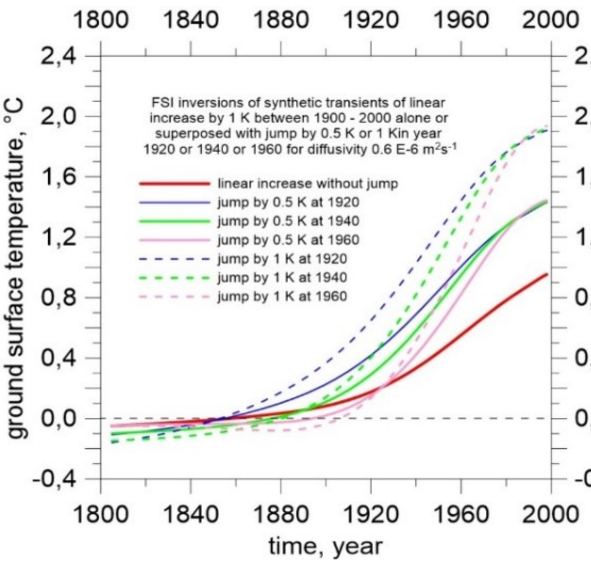

Figure 8 - The functional space inversions of synthetic transients shown in Fig 6 done for a priori value of thermal diffusivity identical with that used in calculation of the transients, i.e. 0.6 $*10^{-6}$ m^2s^{-1}.

The FSI inversions of synthetic T-z profiles calculated for the typical range of diffusivities and assumed surface warming history for areas in the WCSB, which turned from forest to farmland, are shown in Figs 8-10. They show that a jump in surface temperature caused by a change of the original vegetation cover can be easily interpreted in the FSI results because of gradual SAT warming with a large amplitude. This would be a standard 'climatic' interpretation based on the assumption that the long-term ground-air temperature offset stays constant. In the WCSB, however, this offset has increased due to the vegetation cover changes in the last century. The superposition of both warming events thus results in much larger GST warming derived by FSI inversion of well temperatures than the SAT warming observed by meteorological stations.

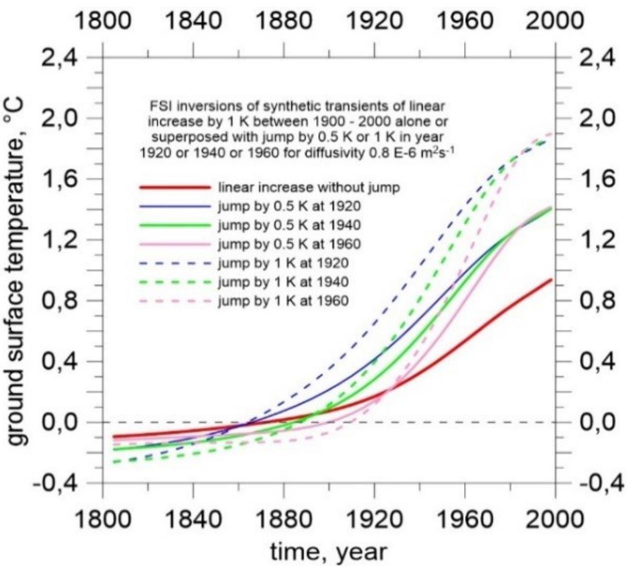

Figure 9 - The functional space inversions of synthetic transients shown in Fig 7 done for a priori value of thermal diffusivity identical with that used in calculation of the transients, i.e. $0.8*10^{-6}$ m^2s^{-1}.

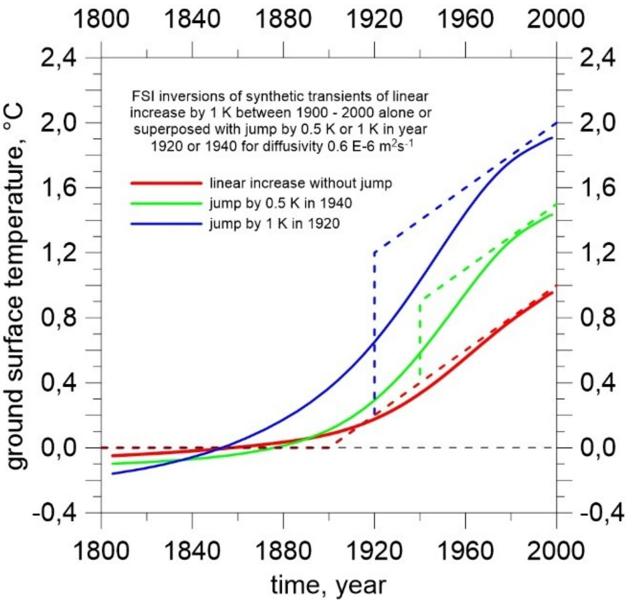

Figure 10 - Examples of reconstructed ground surface temperature histories and their comparison with the true histories.

Comparison of Figure 8 with Figure 9 documents that consideration of a proper a priori value of thermal diffusivity in the inversions, i.e. $0.6*10^{-6}$ m^2s^{-1} in Figure 8 and $0.8*10^{-6}$ m^2s^{-1} in Figure 9 yields, as expected, practically identical reconstructions of the corresponding GST histories. However, when a priori estimate differs from the correct value; the reconstructed GST history is biased. A degree of this bias is demonstrated in Figs 11-12. The considered misfit of $0.2*10^{-6}$ m^2s^{-1} between the assumed and correct values, that is fully within the uncertainty range, leads to differences of decades in the onset of the reconstructed warming. Use of higher than correct value (here $0.8*10^{-6}$ m^2s^{-1} instead of correct value of $0.6*10^{-6}$ m^2s^{-1}) delays the onset of the warming, and use of lower than correct a priori diffusivity estimate (here $0.6*10^{-6}$ m^2s^{-1} instead of correct value of $0.8*10^{-6}$ m^2s^{-1}) accelerates the onset of the warming.

Correspondence between the original and reconstructed histories is quite good in the case of the linear increase alone (Figures 10 and 11). However, in the case of the linear increase superposed with a jump, the reconstructed histories approximate the original ones rather poorly (Figure 10 and Figure 12). In this case the reconstructed curves are smoothed and without some a priori information on existence of a step warming in the past, the results would be probably interpreted as a large gradual warming.

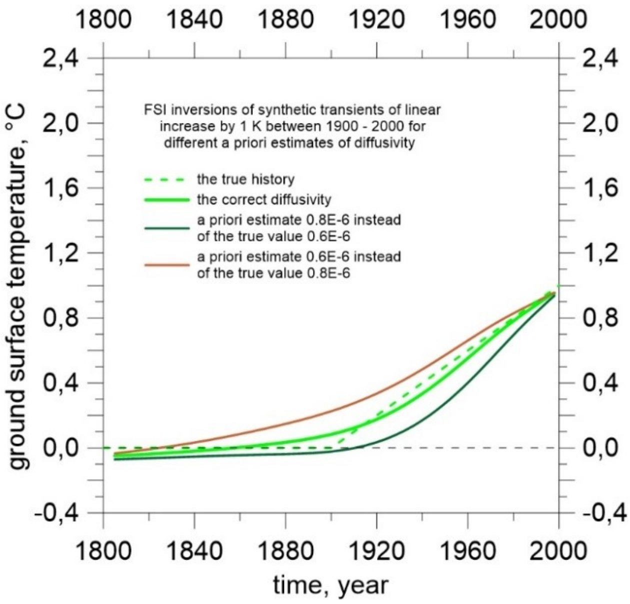

Figure 11 - Example of dependence of the functional space inversion results on a priori knowledge of thermal diffusivity for the case of the linear warming by 1 K between years 1900 - 2000.

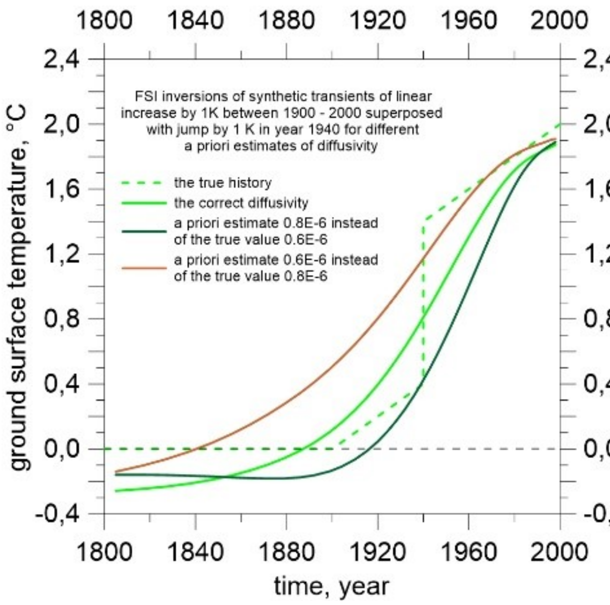

Figure 12 - Another example of dependence of the functional space inversion results on a priori knowledge of thermal diffusivity, here for the case of the linear warming by 1 K between years 1900 – 2000 superposed with a jump by 1 K in year 1940.

6. Discussion

Deforestation, land clearing or forest fires can significantly change ground surface temperature and influence underground temperature regime. Evidences for such changes has been pointed out for recently cleared areas of Cuba, and provinces of British Columbia and Alberta in Canada (Cermak et al., 1992; Lewis and Wang, 1992; Lewis and Skinner, 2003; Majorowicz, 1993; Majorowicz and Skinner, 1997a,b; Skinner and Majorowicz, 1999). Such changes observed by well temperature profiles in wells usually in remote regions may not be seen by meteorological stations far from well locations or influence tree ring growth in the far north or tree line extremes of the mountainous regions. Surface air temperature (SAT) observations are mostly located in a grass covered areas, and in many cases unlike the surrounding landscape. The record reflects mainly atmospheric-related temperature changes, and possibly the feedback effect in the regional context (Skinner and Majorowicz, 1999).

The processes such as deforestation, land clearing and land use can lead to positive skewness in normal statistical distribution of GST changes (Skinner and Majorowicz, 1999; Bodri and Cermak, 2007). GST changes as high as 3K - 5K observed in some areas (Cermak et al., 1992; Lewis and Wang, 1992; Lewis, 1998; Lewis and Skinner, 2003; Majorowicz 1993; Skinner and Majorowicz, 1999) can be result of the effects of land clearing giving a net effect of higher ground surface warming. This effect is due to land drying and loss of natural cooling mechanism provided by respiring trees (Skinner and Majorowicz, 1999; Lewis and Skinner, 2003). The transpiration component of the heat budget for the Alberta/Saskatchewan forests biomass, respectively, can be responsible for 0.5-2 K change in specific areas (Skinner and Majorowicz, 1999). These include mainly 20th century deforested areas. More complicated situations are present in naturally burned boreal forest areas in which depleting of biomass by fire results in initial ground surface warming followed by cooling due to natural or induced regrowth of the forest (Majorowicz and Skinner 1997a, b).

An offset between GST and SAT warming is possible due to reasons listed above especially that the SAT stations in standard conditions and wells with temperature logs are commonly in different environmental localities.

7. Conclusions

GST warming interpreted from FSI inversion of borehole temperature logs in WCSB (Western Canadian Sedimentary Basins of Alberta- Saskatchewan - SE Manitoba) is related to a superposition of land clearing and climate warming in the 20th century. Simultaneous FSI inversion of the borehole temperature logs, as well as averaging of the individual site FSI reconstructions, indicate that high magnitude of GST warming in the order of 2 °C, SD 0.7 °C exceeds that of surface air temperature (SAT) warming based on instrumental records of meteorological stations for the same areas. SAT data show that within the WCSB SAT warming in the 20th century was close to 1°C. The model of the step like temperature change related to land clearing and climatic warming (linear increase) shows that this observed 1°C difference in warming (GST vs. SAT) could be explained by the 20th century land clearing for farming (deforestation).

It could also partially explain the observed difference between global continental GST histories derived by inversion of the borehole temperatures and SAT histories from meteorological records. Climate change record in subsurface temperature logs shows in a global perspective that the GST warming in the continents is much higher than SAT based warming (Pollack and Huang, 2000; Pollack et al, 2000; Huang et al, 2000; Huang 2006).

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