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 exceed 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 et al., 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, 2006; 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 al., 1992; Lewis and Wang, 1992; 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 agriculture in the 20th century (Figure 1) showed some 2°C GST warming. It was by 1°C (Majorowicz and Šafanda, 1998; 2001) higher than SAT warming based on the meteorological stations’ temperature data evidence (Environment Canada, 1992, 1995).

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 $10^{-6}$ m²/s² 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).

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 $T_s$ 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.

The list of log data for 43 locations in agricultural areas of the Canadian Prairies Provinces in Alberta and Saskatchewan is provided in Table 1 (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   | TFM4   | AB       | 56.97    | -111.85   | flat    | forested      |
| 3   | TFM1A  | SK       | 57.14    | -112.24   | flat    | forested      |
| 4   | TFM15A | SK       | 56.77    | -112.34   | flat    | forested      |
| 5   | Stony Mt. | AB   | 56.39    | -111.27   | flat    | forested      |
| 6   | Winagami | AB     | 55.61    | -116.68   | flat    | pasture       |
| 7   | Abishley | AB     | 55.39    | -113.13   | flat    | pasture       |
| 8   | T962Wian | AB     | 55.35    | -111.04   | flat    | pasture       |
| 9   | BPTriad | AB       | 54.74    | -110.75   | flat    | forested      |
| 10  | Cold Lake944 | AB | 54.65 | -110.51 | flat | forested |
| 11  | TCI94  | AB       | 54.62    | -110.43   | flat    | forested      |
| 12  | TCL1   | AB       | 54.61    | -110.25   | flat    | forested      |
| 13  | TCL4   | AB       | 54.57    | -110.85   | flat    | forested      |
| 14  | TCL16Lessard | AB | 54.48 | -110.62 | flat | forested |
| 15  | T941   | SK       | 54.5     | -109.87   | flat    | forested      |
| 16  | Cold Lake4-S | AB | 54.06 | -110.30 | flat | forested |
| 17  | Cold Lake3 | AB | 54.06 | -110.43 | flat | forested |
| 18  | T961   | AB       | 54.01    | -113.18   | flat    | cropland      |
| 19  | T96otion | AB     | 53.91    | -114.11   | flat    | cropland      |
| 20  | Devon  | AB       | 53.41    | -113.76   | flat    | grass         |
| 21  | T765   | AB       | 53.35    | -110.02   | flat    | cropland      |
| 22  | T791   | AB       | 53.16    | -110.08   | flat    | cropland      |
| 23  | Warburg | AB       | 53.13    | -114.36   | flat    | grass         |
| 24  | T96GArmley | AB   | 53.06    | -109.95   | flat    | cropland      |
| 25  | T966   | SK       | 52.02    | -107.12   | flat    | cropland      |
| 26  | T967   | SK       | 52.01    | -107.11   | flat    | cropland      |
| 27  | T9A5A  | SK       | 51.57    | -101.43   | flat    | cropland      |
| 28  | T9A13  | SK       | 51.01    | -113.32   | flat    | pasture       |
| 29  | T9A19Rournhust | SK | 50.95 | -107 | flat | pasture |
| 30  | T9B1Rournhust | SK | 50.88 | -106.67 | flat | pasture |
| 31  | T9A16  | AB       | 49.38    | -112.21   | flat    | pasture       |
| 32  | T9A110B | AB       | 49.18    | -111.07   | flat    | grassland     |
| 33  | T7K7   | SK       | 49.07    | -106.25   | flat    | grassland     |
| 34  | T5A12  | AB       | 49.02    | -110.36   | flat    | grassland     |
| 35  | T7A13  | AB       | 49.01    | -113.32   | flat    | pasture       |
| 36  | WAWANESA | MB     | 49.6     | -99.84    | flat    | grassland     |
| 37  | Wood M't | SK     | 49.4     | -106.4    | flat    | pasture       |
| 38  | CCDF-K72 | MB     | 49.2     | -100.45   | gentle slope | pasture |
| 39  | T7M6cSft. | AB     | 52.627   | -114.052  | flat    | grass         |
| 40  | T767    | AB       | 51.767   | -113.968  | flat    | grass         |
| 41  | 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.

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^2 s^-1 (Figure 6) and 0.8*10^-6 m^2 s^-1 (Figure 7) represent lower and upper estimates for sedimentary rocks in the studied area.

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.
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.

Comparison of Figure 8 with Figure 9 documents that consideration of a proper a priori value of thermal diffusivity in the inversions, i.e. $0.6 \times 10^{-6}$ m$^2$/s in Figure 8 and $0.8 \times 10^{-6}$ m$^2$/s 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 $0.2 \times 10^{-6}$ m$^2$/s 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 $0.8 \times 10^{-6}$ m$^2$/s instead of correct value of $0.6 \times 10^{-6}$ m$^2$/s) delays the onset of the warming, and use of lower than correct a priori diffusivity estimate (here $0.6 \times 10^{-6}$ m$^2$/s instead of correct value of $0.8 \times 10^{-6}$ m$^2$/s) accelerates the onset of the warming.

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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