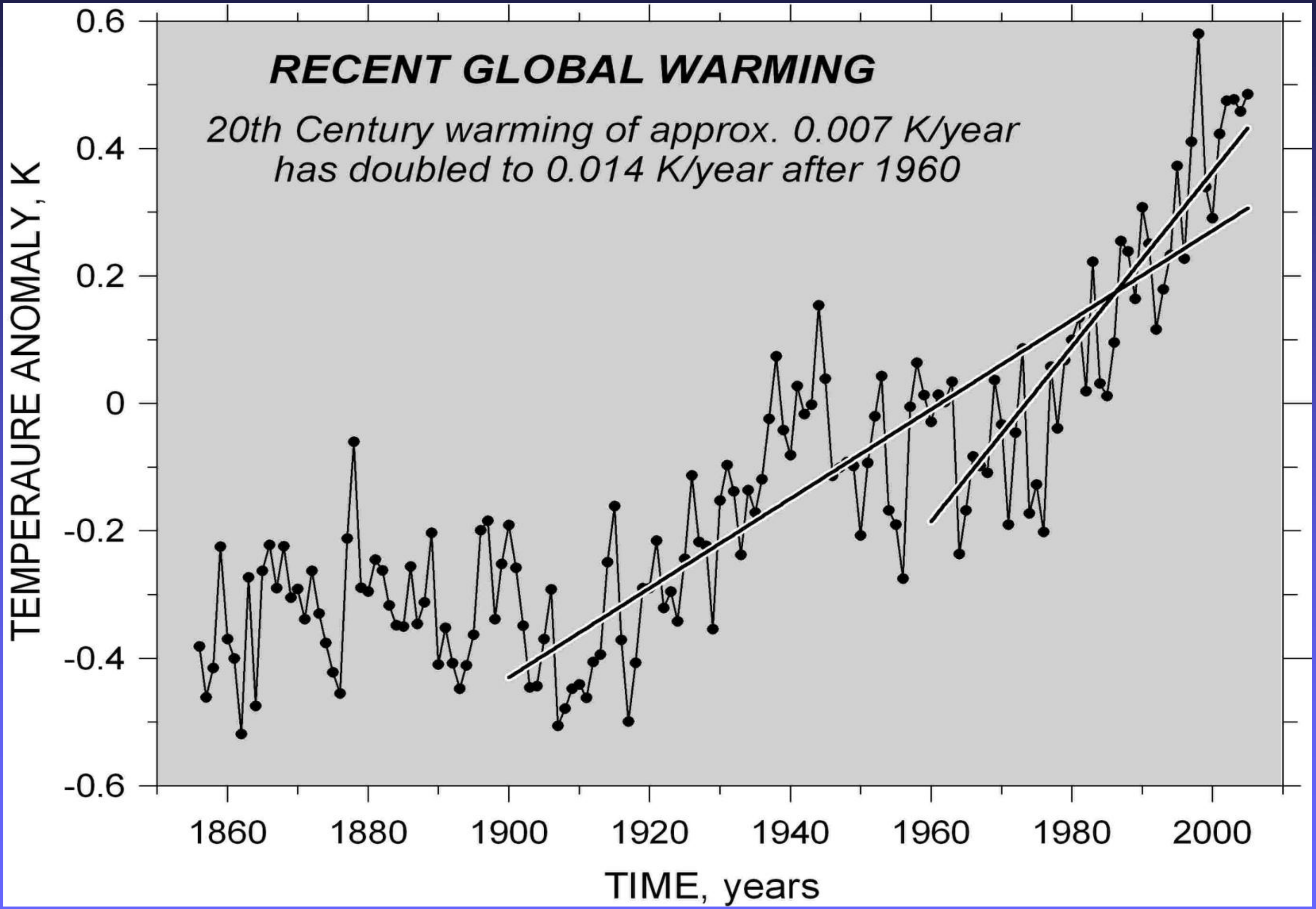
# Air-Ground–Bedrock Temperature Coupling,
# Its Monitoring at Borehole Climate Observatories

# Basic Facts :

- Global SAT means in 1998 & 2002-2007 were warmest since 1861 (NASA, 2010, WMO, 2005).
- Warming 0.7±0.2 K typical of past 100-150 years > evidence that the world climate has been changing (Jones and Moberg, 2003)
- Alarming > warming rate has been accelerating in last 3-4 decades (Houghton et al., 2001).



RECENT GLOBAL WARMING
20th Century warming of approx. 0.007 K/year
has doubled to 0.014 K/year after 1960
TEMPERAURE ANOMALY, K
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1860
1880
1900
1920
1940
1960
1980
2000
TIME, years

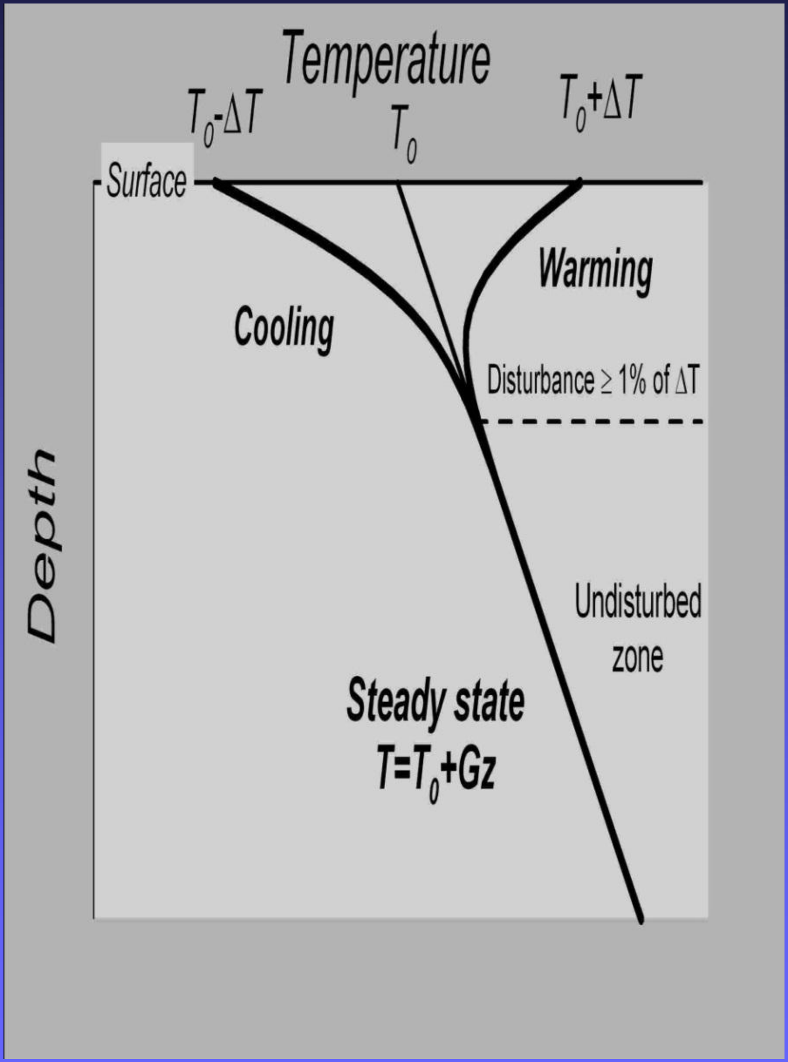
*Important question*

*this (climate) change is due to*

*(i) natural long-term climate variability or*

*(ii) indication of certain anthropogenic activities*

- *Meteorological records are relatively short*
- *Warming climate - increasing mean SAT - affects GST*
- *GST variations penetrate downwards & perturbe background temperature field*
- *Thermal diffusivity of rocks is low - that what happened some 10, 100 and 1000 years ago produced temperature anomalies centered at 25, 80, and 250 m, resp.*



***Reconstructing GSTHs from T(z)-logs > independent and physically justified method to obtain information about past climate on time scale of hundreds to thousands years.***

***Subsurface T(z) logs can be suitably completed with long-run temperature-time monitoring at selected depth levels Tz(t), namely at the surface (z=0) and within & just below the near-surface „active“ layer affected by seasonal temperature variations***

# *Air-Ground–Bedrock Temperature Coupling, Its Monitoring at Borehole Climate Observatories*

- *to test the validity of the assumption that GST variations track the SAT changes*
- *to study various local/environmental effects: such as vegetation cover, its type/change, surface (rock) type, rain/snow precipitation, thawing/melting/freezing, solar radiation, etc.*
- *to understand different environments: e.g. urban vs. countryside*
- *to distinguish the potential anthropogenic contribution vs. natural climate variability.*

# BOREHOLE CLIMATE OBSERVATORY

- Site (hole), specially equipped or adopted for this purpose
- In operation minimum for 1 year  (or more)
- Penetrating below the near-surface “active” layer (30-50 m)
- Standard „surface“, kept unchanged all year-round
- Alternatively several different types (grass, soil, rock, concrete, asphalt, etc)
- Geothermal equipment (multiple temperature sensors at several depths) completed with meteorological instrumentation (air temperature, wind meter, snow depth, rain precipitation, incident solar radiation, etc.
- Monitoring air temperatures & soil temperatures
- Repeated temperature logs

# Existing Borehole Climate Observatories

- Emigrant Pass Geothermal Climate Observation (ETO), Utah, USA
- Choutuppal Geothermal Climate Change Observatory, India
- Caravenlinha Geothermal Observatory, Portugal
- Malence Geothermal Observatory, Slovenia
- Sporilov Observarory, Prague, Czech Republic

# Emigrant Pass Geothermal Climate Observation, Utah

*M.G.Bartlett, D.S.Chapman & R.H.Harris, Journal of Climate, 19 (2006) 3722-3731*

- ***41°30´N, 113°42´W, 1750 m a.s.l.***
- ***In operation since 1993***
- ***SAT (2m, 0.1 m above), SGT (0.025, 0.1, 0.2, 0.5 and 1.0 m below surface)***
- ***incident solar radiation, snow cover, rainfall, wind speed and direction, soil moisture and humidity***
- ***Hole GC-1 drilled in 1978 (150 m deep), granite, constant thermal conductivity, negligible hydrology, repeated thermal logs***

- SAT variations explain 94% of the variance in SGT
- Incident solar radiation is a primary variable governing the remaining misfit (important during summer)
- Solar radiation accounts for 1.3% of the variance in SGT
- Solar radiance accounts for 2.47 K offset in ground-air temperature difference, offset is the largest in summer (up to 5+ K) and falls to nearly 0 K in winter. When averaged over diurnal cycle it varies from -10 to + 14 K.
- During winter : snow plays role in governing SGT variability, but only minor influence on the annual tracking of GST or SAT

# Choutuppal Geothermal Climate Change Observatory

*A.V.Vyasulu & Sukanta Roy, Physics and Chemistry of the Earth, JPCE-D-10-00145*

- ***NGRI campus, 60 km east of Hyderabad, Southern India***
- ***17.29°N, 78.92° E***
- ***Typical forest land, dry in summer, fresh grass in winter***
- ***Two boreholes, CH-11 (21 m) and CH-10 (210 m deep)***
- ***drilled in April 2009, originally dry, plastic tube filled with water***
- ***13 m-thick weathered rock overburden above solid granite, narrow range conductivity (2.8±0.1 $Wm^{-1} K^{-1}$)***
- ***repeated precise temperature logs***
- ***SAT, GST, relative humidity, rainfall, solar radiation***
- ***Three other boreholes (up to 300 m deep) located in an area around***

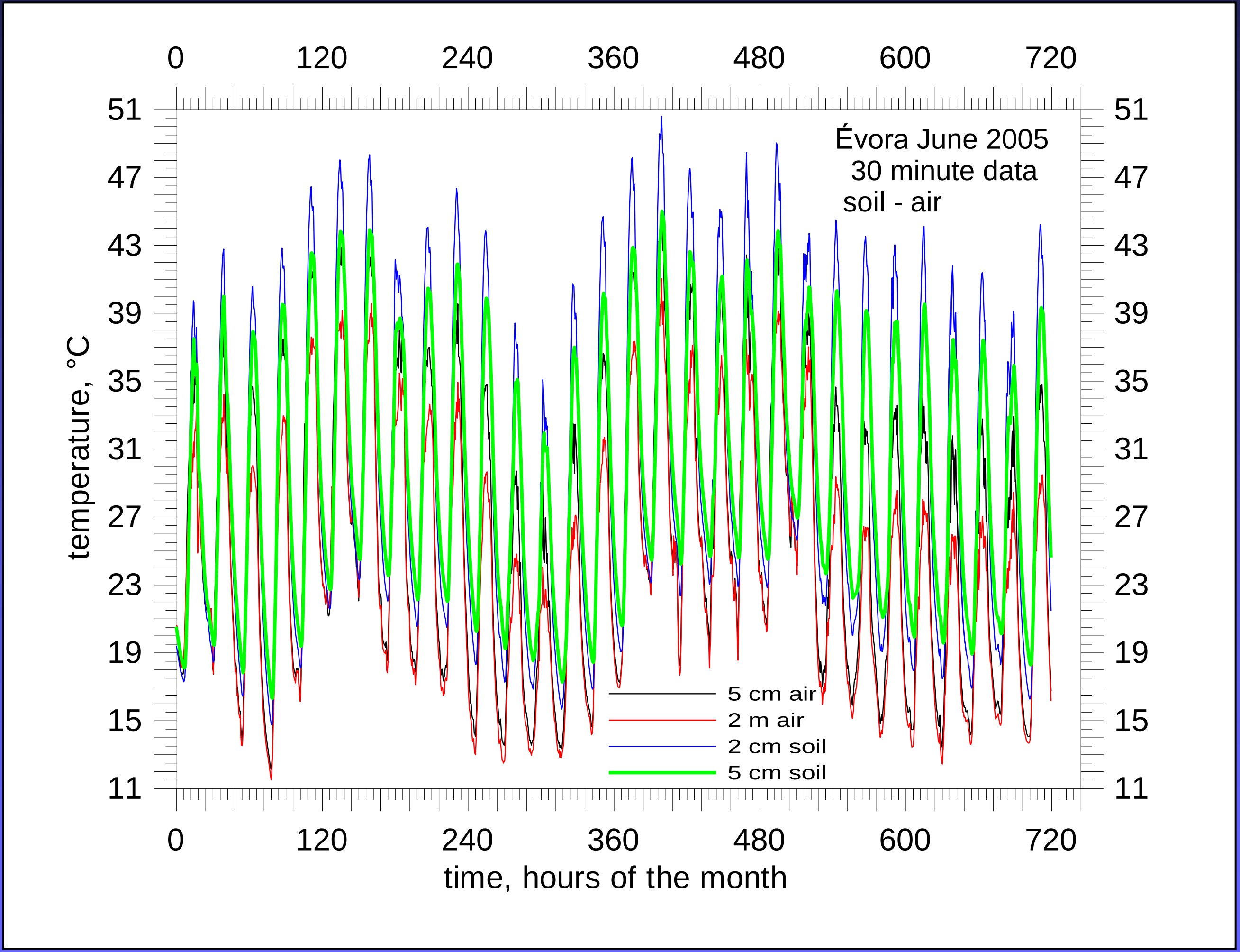
- *The first and only one in low latitude regions*
- *Inversion of the T(z) profile supported warming trend of 0.5 deg since about 1917 over the past century, characteristic from Indian meteorological data*
- *In addition a recent and more localized cooling of 0.7 deg with onset around 1970 superimposed over the general warming*
- *Explained by probable change in local land use*

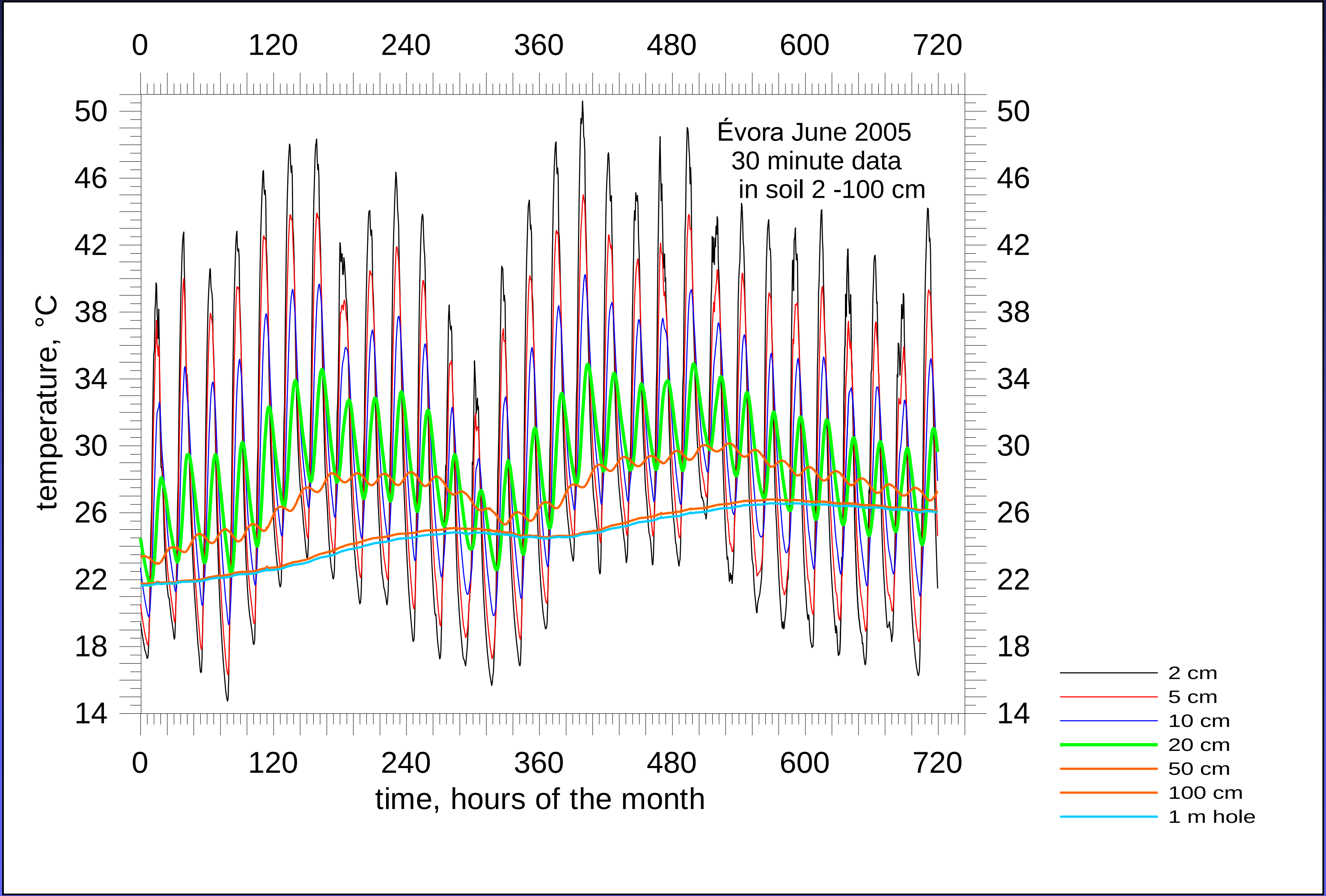
# Caravenlinha Geothermal Observatory, Univ. Evora

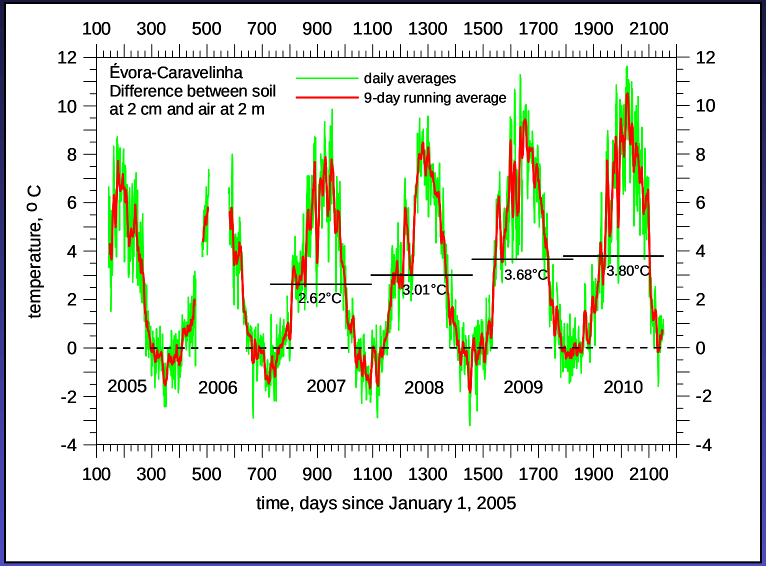
Antonio Correia (University of Evora) & Jan Safanda

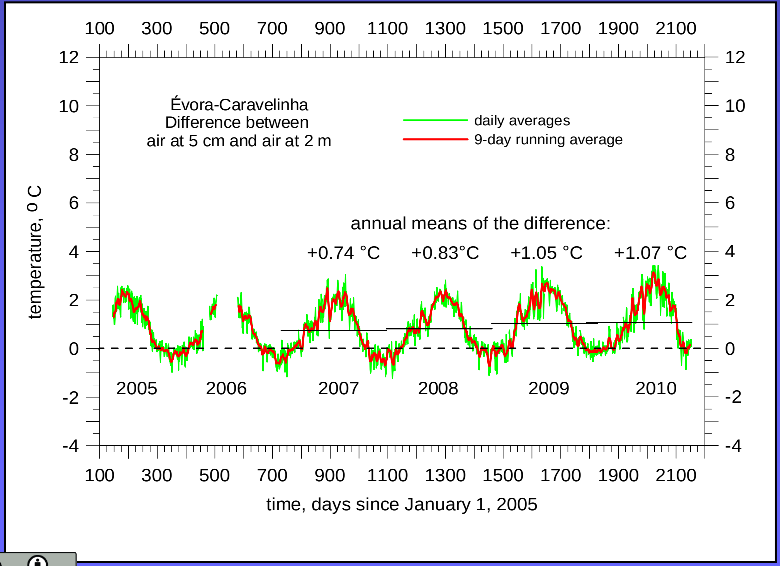
- *5 km NW of Evora, Portugal, (38°36’ N, 7°54.6’ W, 330 m asl).*
- *Since May 2005 a string of platinum sensors in the uppermost 40 m of the 200 m deep hole.*
- *Hole is cased with a plastic tube filled with water.*
- *Site presents an old cork tree forest, vegetation has not changed at least in the last hundred years, topography is subdued*
- *Immediate surroundings – bare compact gravel, deeper rock porphyric granite*
- *Soil temperatures at depths 2 cm, 5 cm, 10 cm, 20 cm, 50 cm and 100 cm and air temperatures at 2 m and 5 cm above the ground*

# One-month record (SAT & near-surface GST)



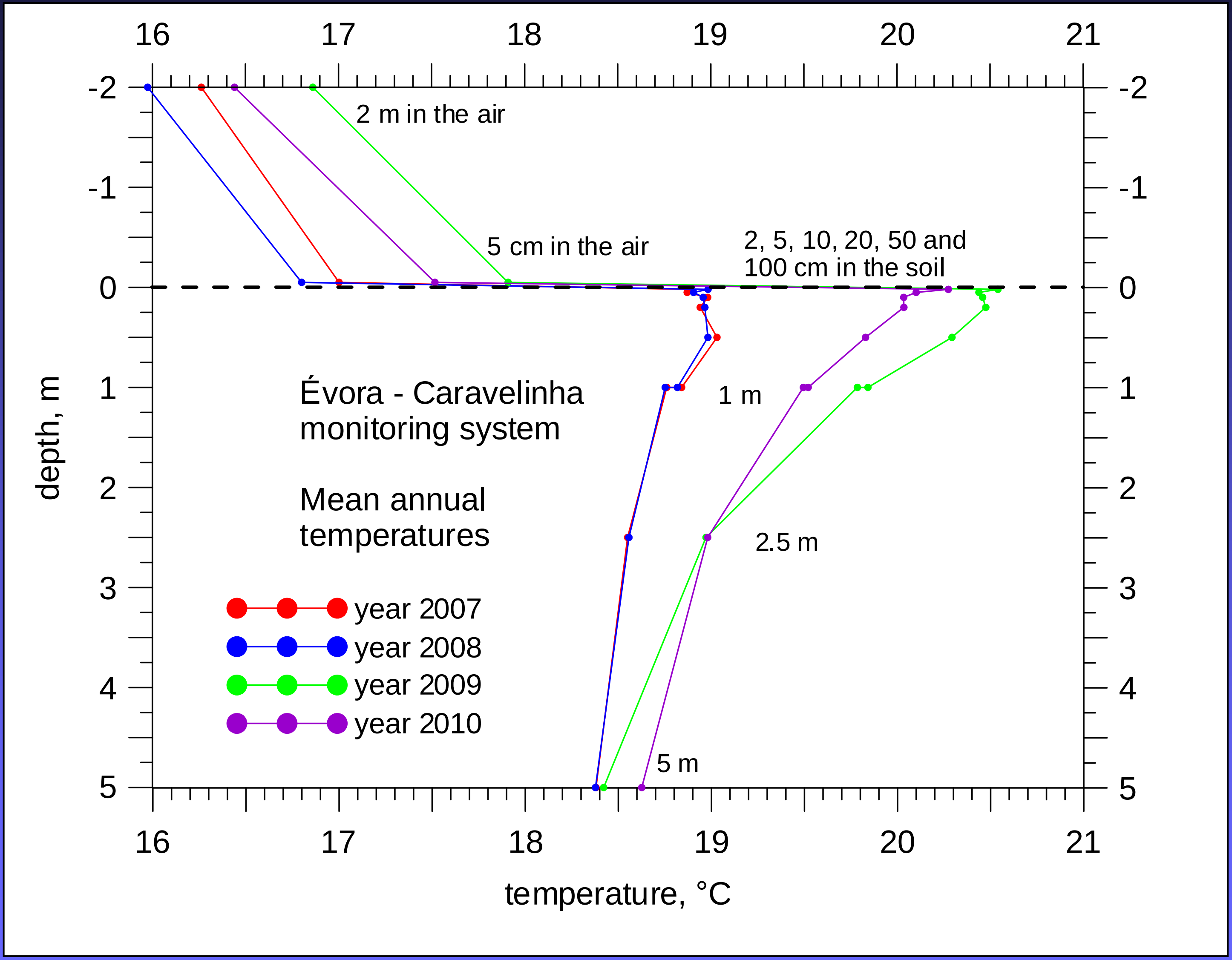

Évora June 2005
30 minute data
in soil 2 -100 cm
temperature, °C
time, hours of the month
0
120
240
360
480
600
720
14
18
22
26
30
34
38
42
46
50
2 cm
5 cm
10 cm
20 cm
50 cm
100 cm
1 m hole




# *soil - air difference, years 2007, 2008, 2009, 2010*

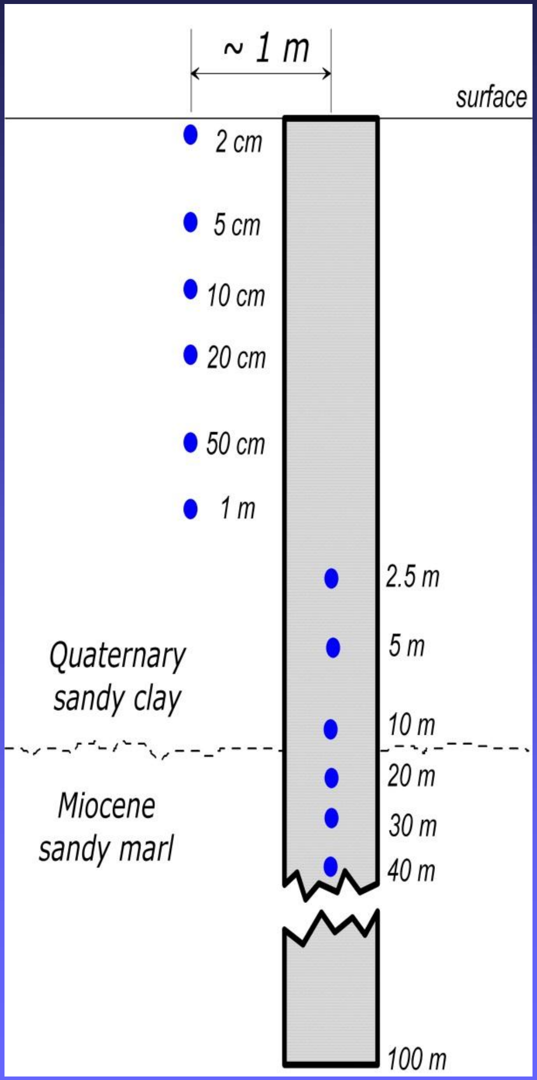
- ***The ground is covered by whitish gravel with very sparse vegetation.***
- ***It is evident that soil is warmer than air for most days of the year (by up to +11 °C) and slightly colder (up to -3 °C) only in short periods during winter.***
- ***A similar pattern is revealed by the air at 5 cm and air at 2 m difference, albeit with much smaller amplitude.***

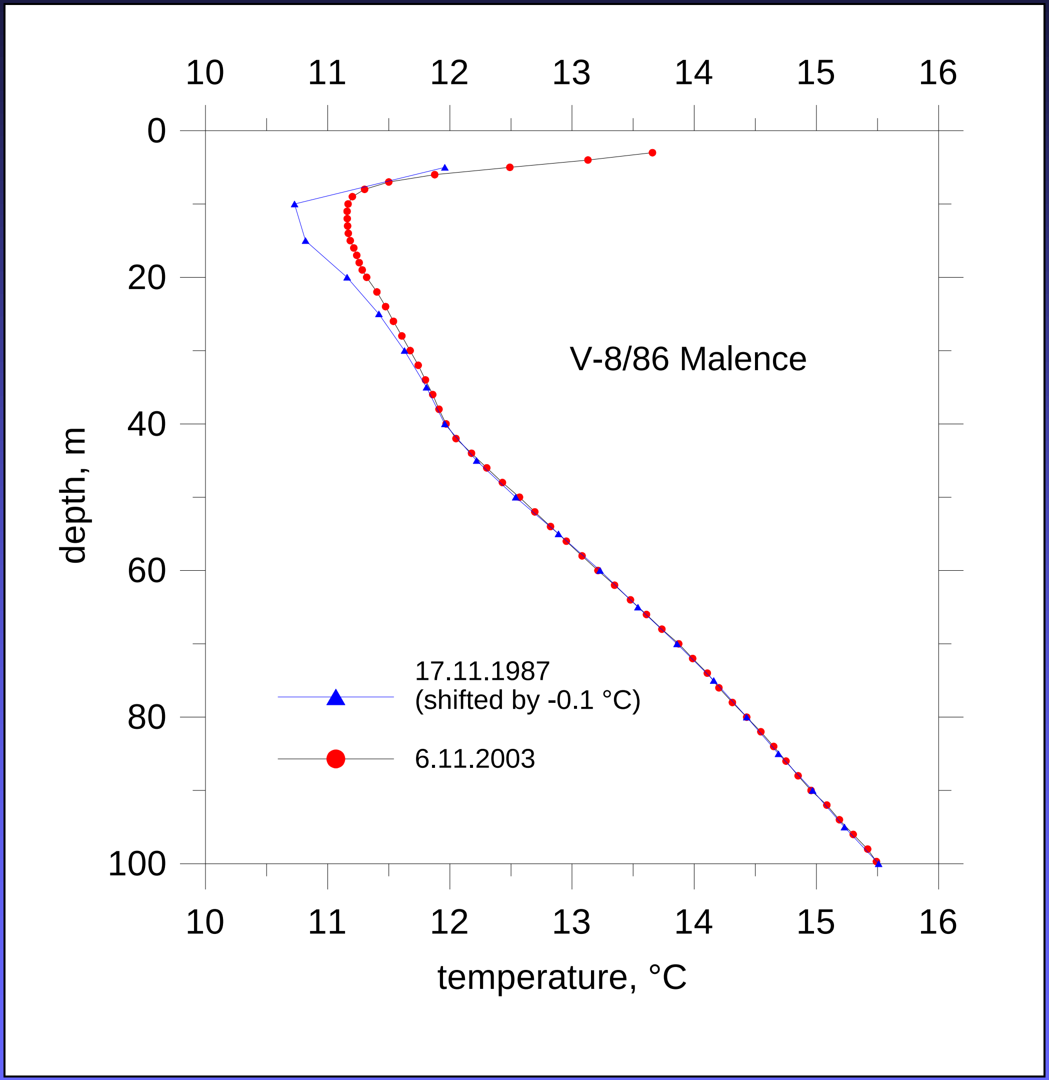

16
17
18
19
20
21
-2
-1
0
1
2
3
4
5
2 m in the air
5 cm in the air
2, 5, 10, 20, 50 and
100 cm in the soil
1 m
2.5 m
5 m
Évora - Caravelinha
monitoring system
Mean annual
temperatures
year 2007
year 2008
year 2009
year 2010
depth, m
temperature, °C

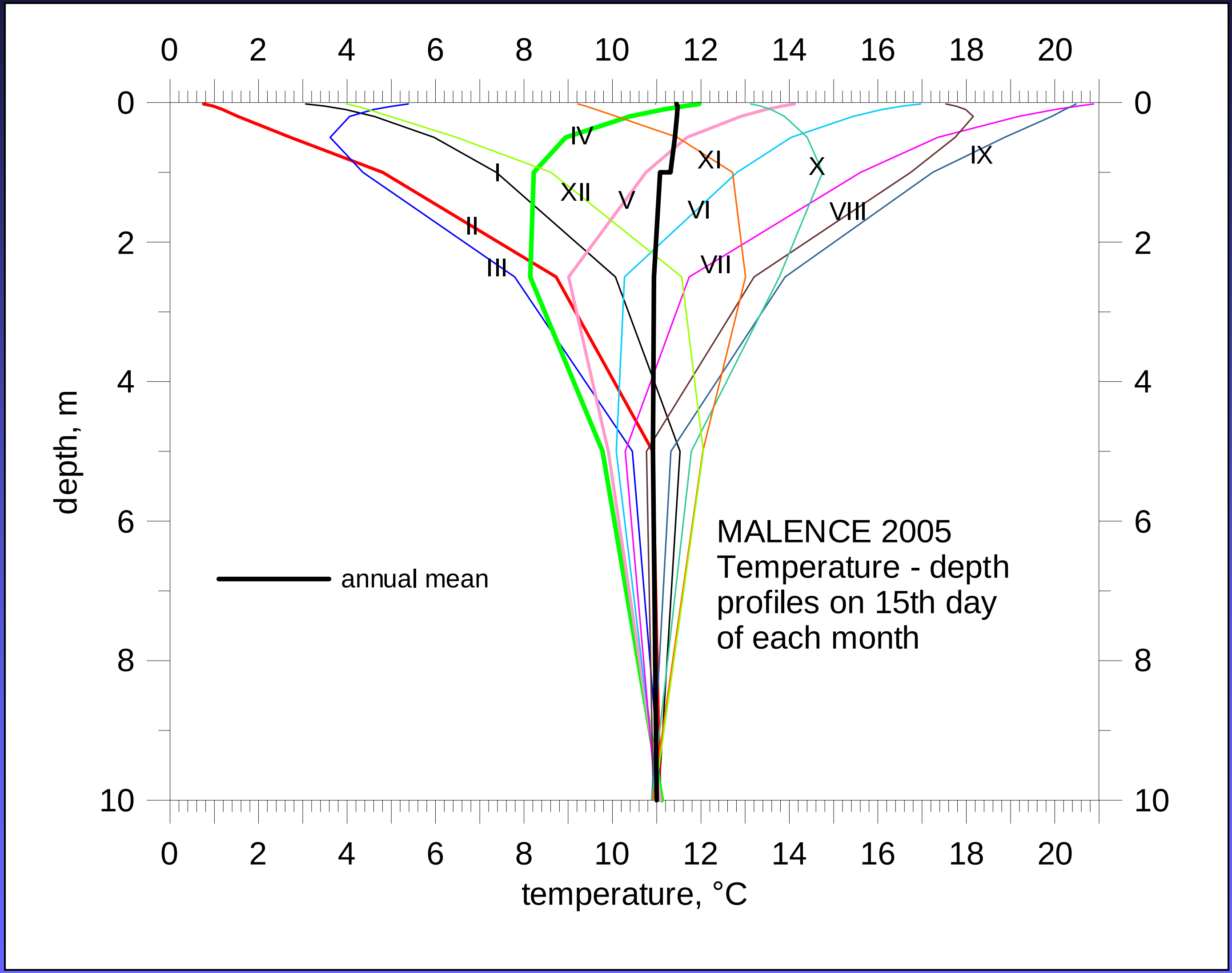
# Malence Geothermal Observatory, GSS Ljubljana

Dusan Rajver (Geological Survey of Slovenia) & Jan Safanda

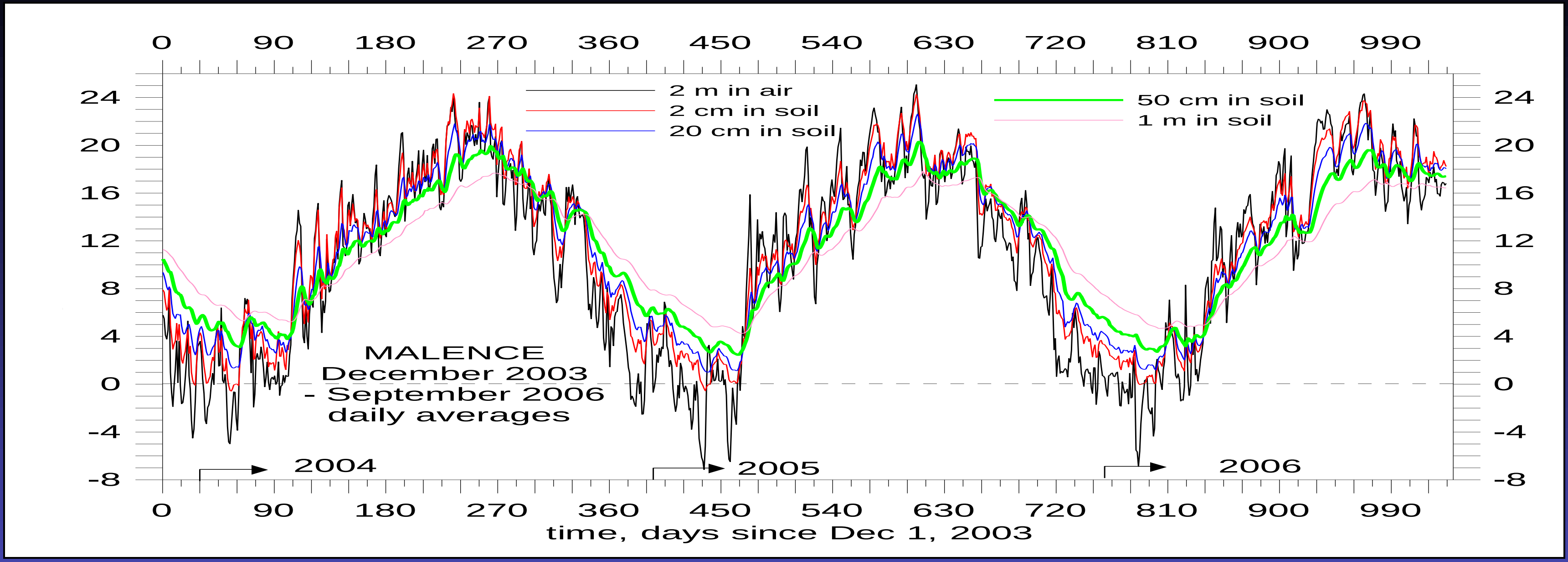
- Rural area of the Krško basin, SE Slovenia, 45° 52.10’ N, 15° 24.50’ E, 152 m a.s.l.
- Established in November 2003 in the borehole V-8/86 (drilled in 1986).
- Penetrated 16 m of Quaternary clay, sand and gravel, down to bottom at 100 m. Thermal conductivity (1.45 - 1.7 $Wm^{-1}K^{-1}$), thermal diffusivity estimated as 0.6 – 0.8 x $10^{-6}$ $m^2s^{-1}$.
- Logged in 1987 and several times later.
- In 2003 a chain of sensors for temperature monitoring installed within the depth interval 1 to 40 m.
- The data logger system records air temperatures at 2 m and 0.05 m above ground level and soil temperatures at 0.02, 0.05, 0.1, 0.2, 0.5 and 1 m below the surface and bedrock temperatures in borehole at the depths of 2.5, 5, 10, 20, 30 and 40 m.

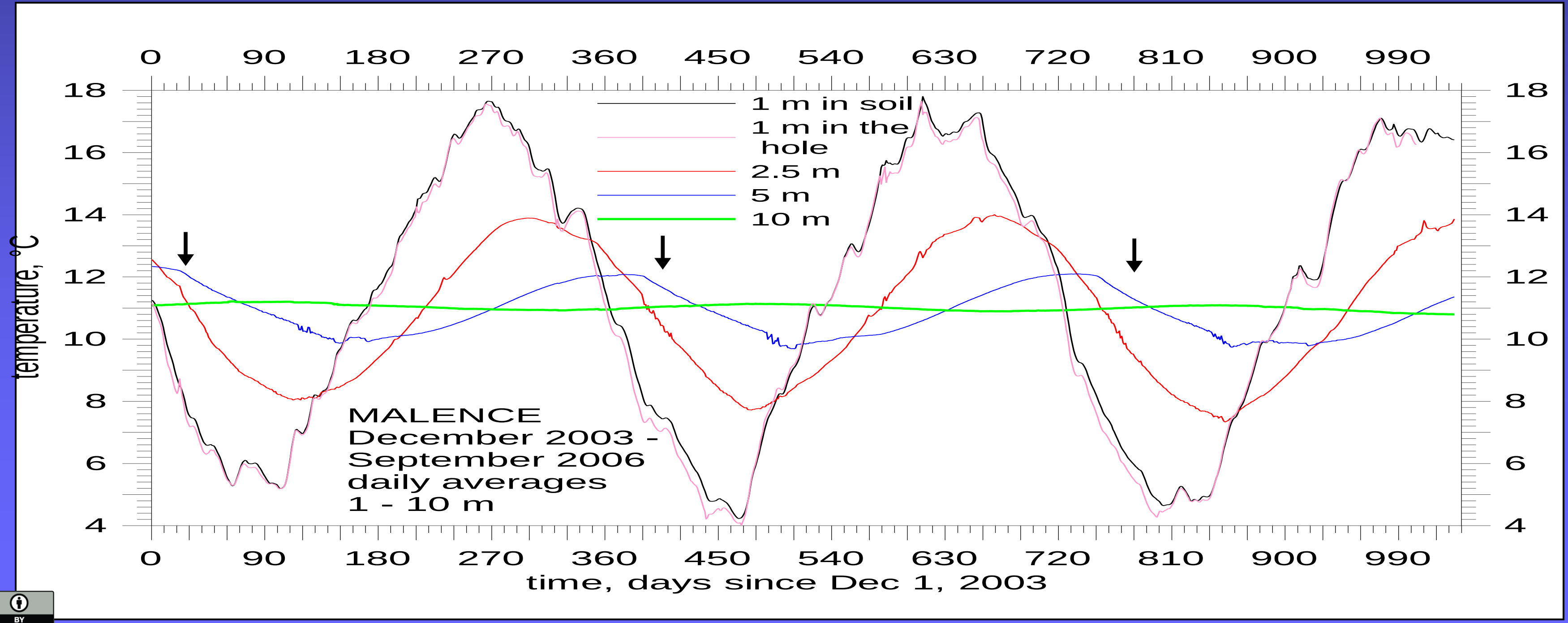

~ 1 m
surface
2 cm
5 cm
10 cm
20 cm
50 cm
1 m
2.5 m
5 m
Quaternary sandy clay
10 m
20 m
Miocene sandy marl
30 m
40 m
100 m

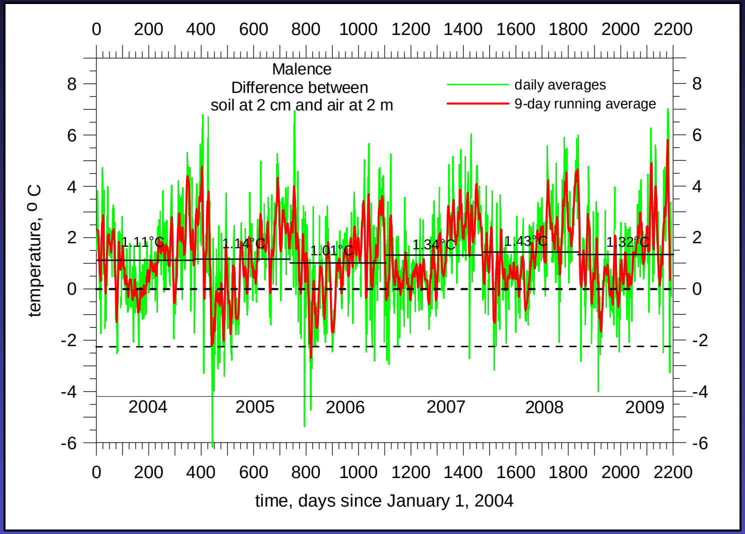

10 11 12 13 14 15 16
0
20
40
60
80
100
depth, m
V-8/86 Malence
17.11.1987
(shifted by -0.1 °C)
6.11.2003
temperature, °C

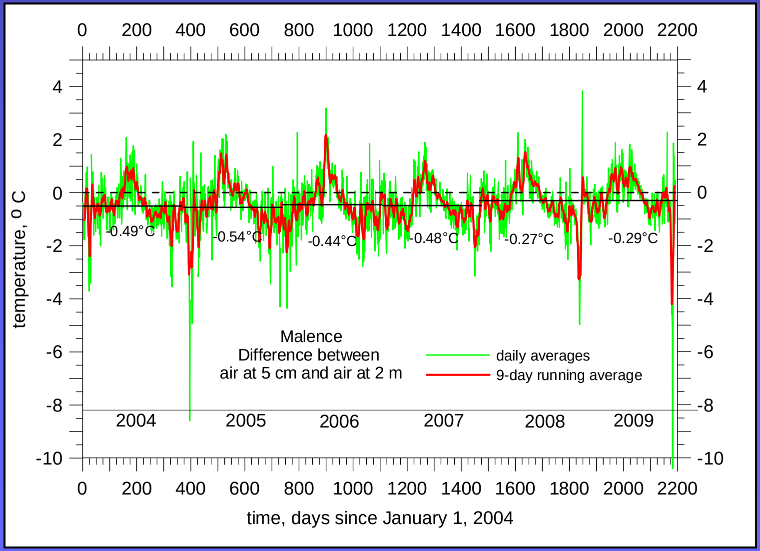


0 2 4 6 8 10 12 14 16 18 20
depth, m
temperature, °C
I
II
III
IV
V
VI
VII
VIII
IX
X
XI
XII
annual mean
MALENCE 2005
Temperature - depth
profiles on 15th day
of each month


2 m in air
2 cm in soil
20 cm in soil
50 cm in soil
1 m in soil
MALENCE
December 2003
- September 2006
daily averages
2004
2005
2006
time, days since Dec 1, 2003

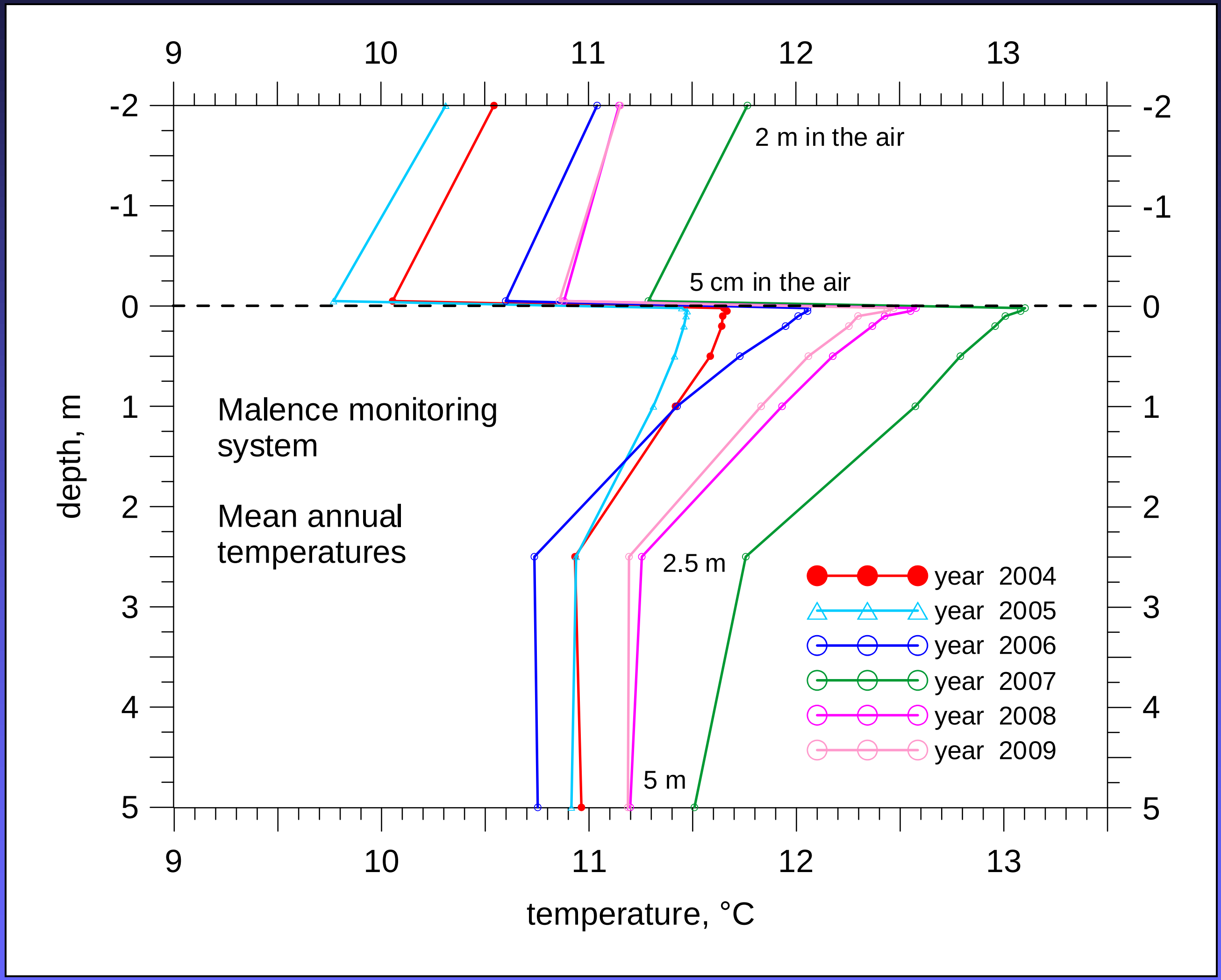

1 m in soil
1 m in the hole
2.5 m
5 m
10 m
temperature, °C
MALENCE
December 2003 -
September 2006
daily averages
1 - 10 m
time, days since Dec 1, 2003




## *The annual mean of the soil - air difference in the period 2004 - 2009.*

- *The ground is covered by grass (similar to grassy surface at Spořilov station)*
- *The mean annual difference of air temperatures at 5 cm and 2 m above the ground was negative and varied between -0.27 °C and -0.54 °C in the same period.*
- *Contrary to Portuguese station, the difference is negative – air near the ground is colder than air at 2 m.*

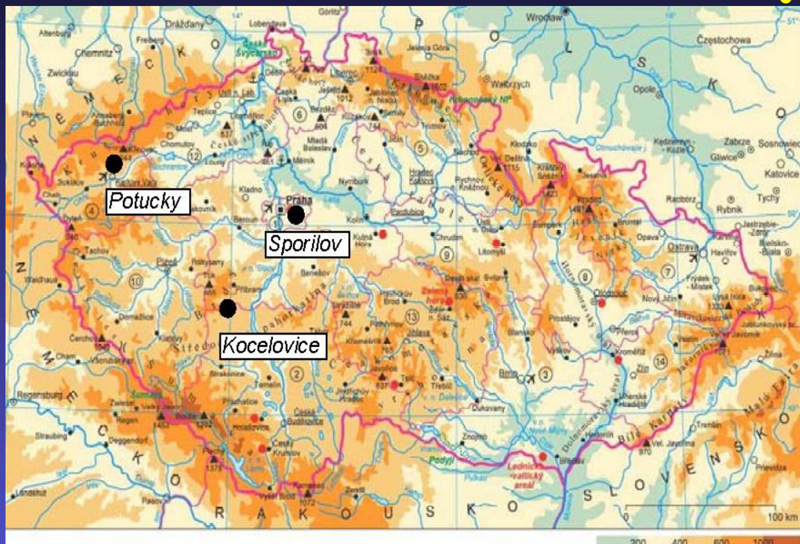


Malence monitoring system
Mean annual temperatures
2 m in the air
5 cm in the air
2.5 m
5 m
year 2004
year 2005
year 2006
year 2007
year 2008
year 2009
depth, m
temperature, °C
9
10
11
12
13
-2
-1
0
1
2
3
4
5

# Sporilov Geothermal Observatory, Prague

Vladimir Cermak, Jan Safanda, Petr Dedecek & Milan Kresl

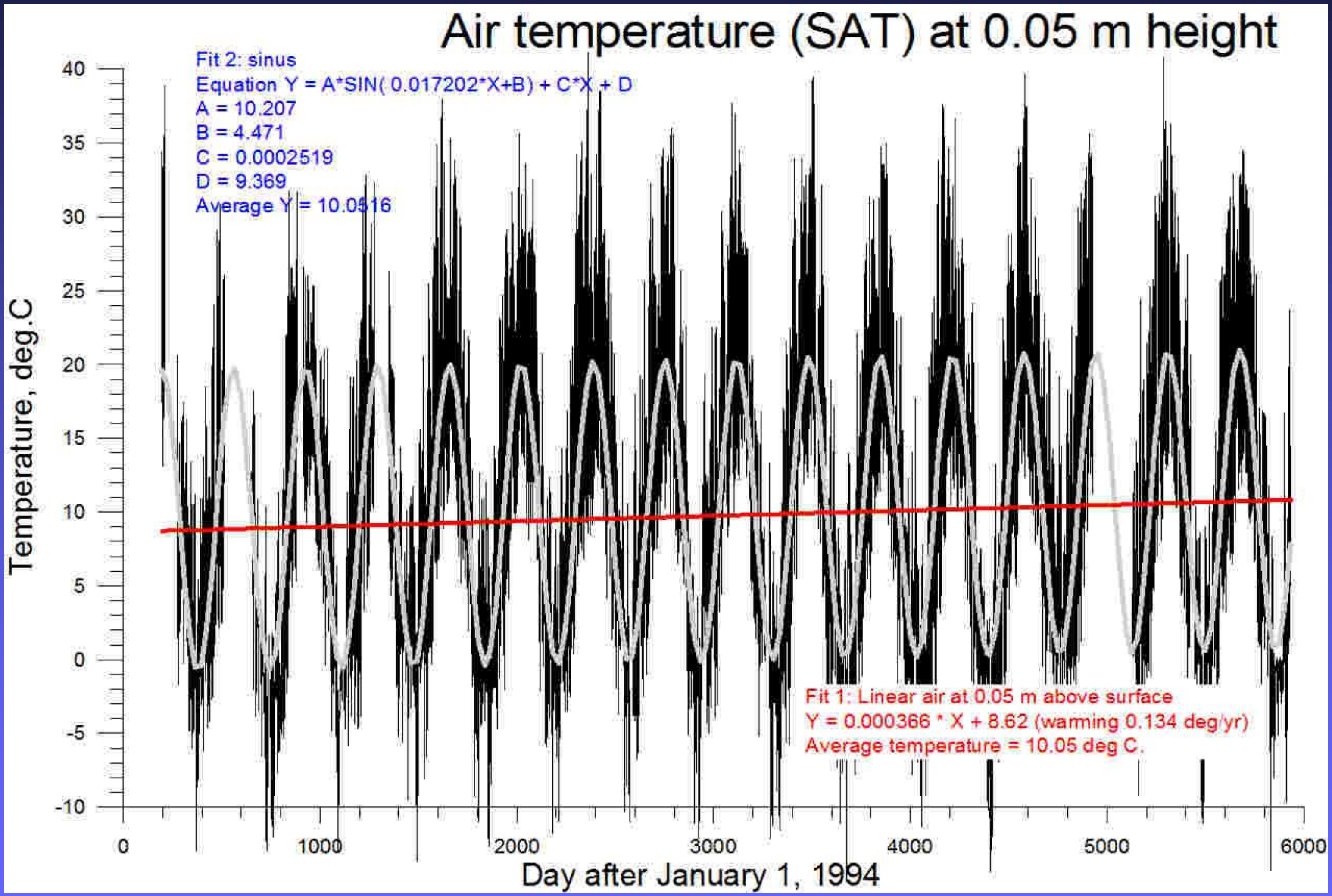
- *Southern rim of Prague, Central Bohemia, Czech Republic 50º02´28.5"E, 14º28´40.2" N, 274 m a.s.l., typically urban area*
- *Two holes drilled in 1992, 38.3 m and/or 150 m deep*
- *Penetrated sediments: loam (1- 4 m),weathered shale (4-14 m), silty shale (14-126 m) followed by clay shale, thermal conductivity of ~3 $Wm^{-1}K^{-1}$, thermal diffusivity 0.6 – 0.8 x $10^{-6}$ $m^2s^{-1}$.*
- *Deeper hole - calibrating logging instrument, repeated temperature logs, paleoclimate studies & long-term monitoring of oscillatory convection occurring in a fluid column.*
- *Shallow hole reserved for continuous subsurface temperature monitoring; thermistor chain, automatic data logger system : air temperatures at 2 m and 0.05 m above ground level, soil temperatures at 0, 0.05, 0.1, 0.2, 0.5, 0.75 and 1 m below the surface plus bedrock temperatures in the hole at 1, 1.5, 2, 3, 4, 5, 7.5,10, 15, 20, 25 and 38.3 m.*
- *Experiment started on January 1, 1994.*

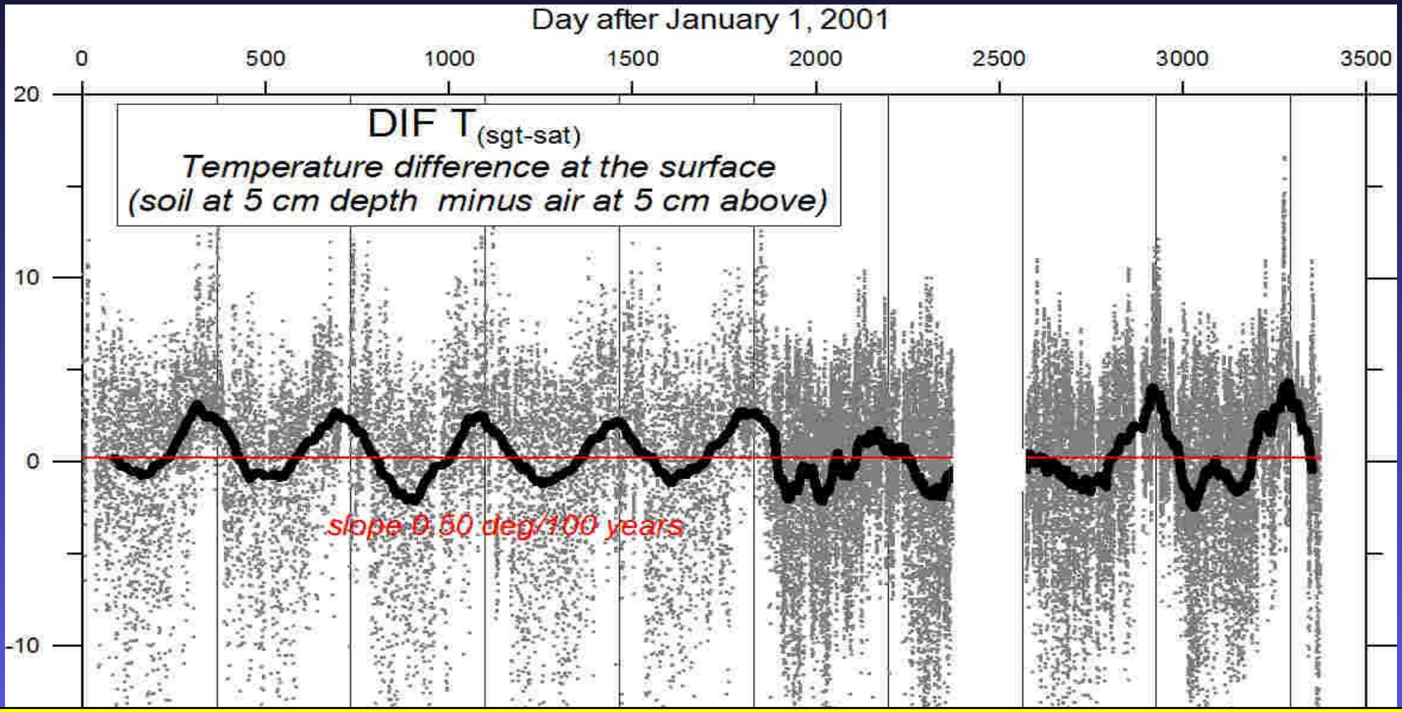



- *Similar 40 m deep hole drilled in 1998 at meteorological station in Kocelovice, southern Bohemia (49.47°N, 13.84°E, 518 m a.s.l.).*
- *Rural (farming) area.*
- *Hole penetrated homogenous granite covered by thin Quaternary sediments, flat terrain is covered with short-cut grass.*
- *Soil temperatures monitored with thermistors at 15 levels (1 to 40 m)*

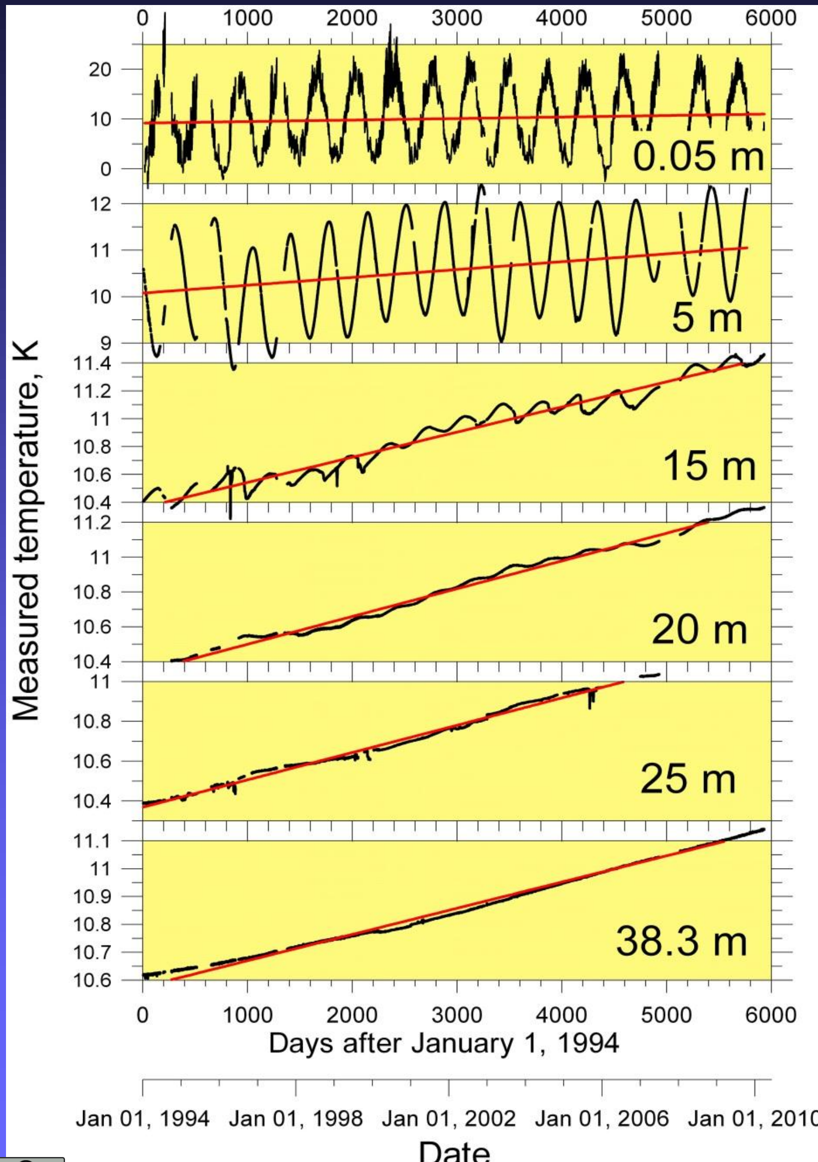
- *Additional site Potucky (50.43°N, 12.78°E, 864 m a.s.l.), western part of the Ore (Krusne Hory) Mts., NW Bohemia*
- *Rural, but industrially heavily polluted area.*
- *Used only irregularly and for limited time periods within 2002-2005.*

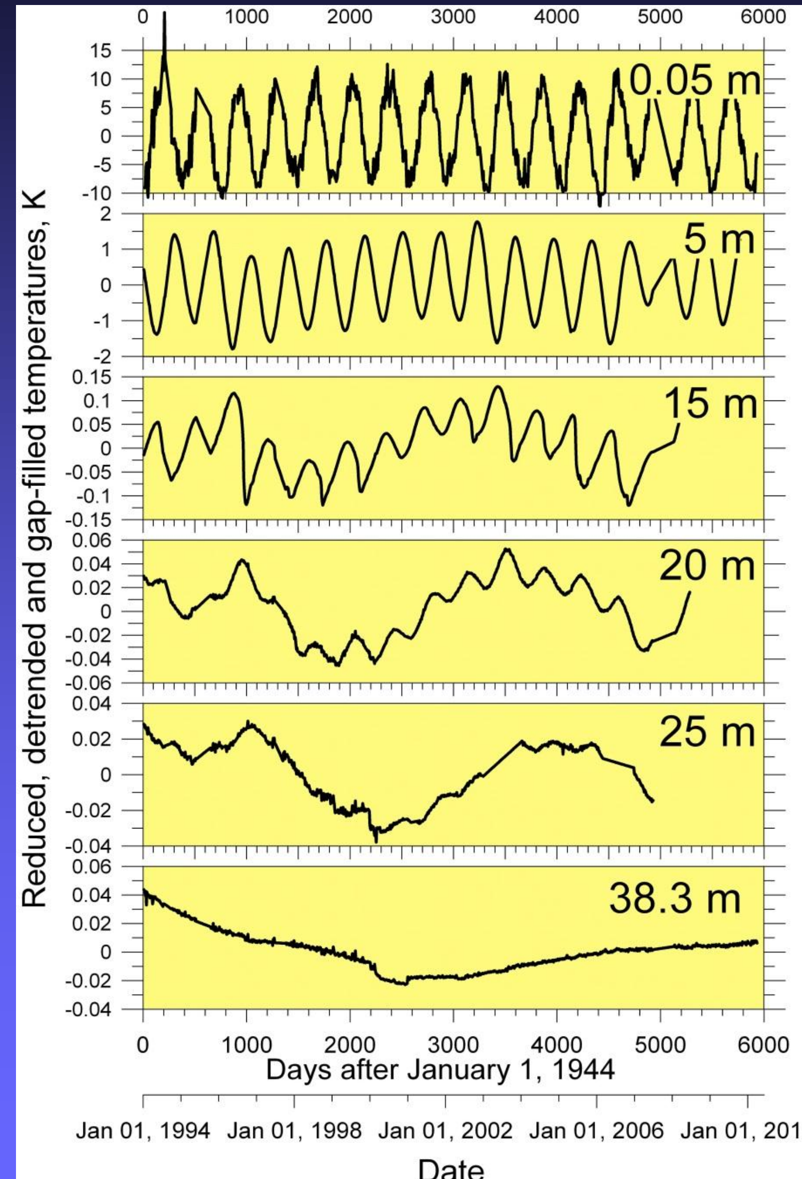
**In 2002 complex polygon studies at Sporilov were completed by monitoring shallow subsurface temperatures under different surfaces (sand, grass, bare soil, asphalt) in the uppermost 1 m thick layer.**


Air temperature (SAT) at 0.05 m height
Fit 2: sinus
Equation Y = A*SIN( 0.017202*X+B) + C*X + D
A = 10.207
B = 4.471
C = 0.0002519
D = 9.369
Average Y = 10.0516
Fit 1: Linear air at 0.05 m above surface
Y = 0.000366 * X + 8.62 (warming 0.134 deg/yr)
Average temperature = 10.05 deg C.
Temperature, deg.C
Day after January 1, 1994
40
35
30
25
20
15
10
5
0
-5
-10
0
1000
2000
3000
4000
5000
6000

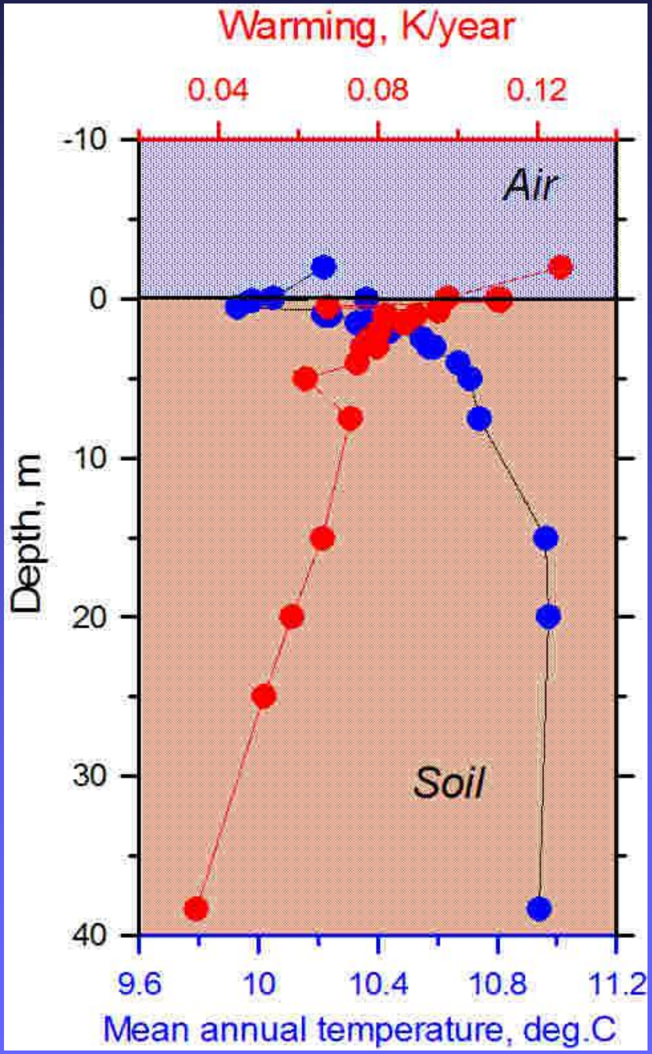



***mean offset SGT-SAT only 0.27 K***
***no clear tendency, offset changes even during day/month/year***
***winter : ground mostly warmer, protected by snow as well as by grass from cold wind***
***hot summer : ground can be slightly colder due to grass protection from sun radiation***
***In general > solar radiation does not play a substantiall role and GST well tracks SAT***


0.05 m
5 m
15 m
20 m
25 m
38.3 m
Measured temperature, K
Days after January 1, 1994
Jan 01, 1994
Jan 01, 1998
Jan 01, 2002
Jan 01, 2006
Jan 01, 2010
Date


0.05 m
5 m
15 m
20 m
25 m
38.3 m
Reduced, detrended and gap-filled temperatures, K
Days after January 1, 1944
Jan 01, 1994
Jan 01, 1998
Jan 01, 2002
Jan 01, 2006
Jan 01, 2010
Date

# Formal 1994-2010 statistics

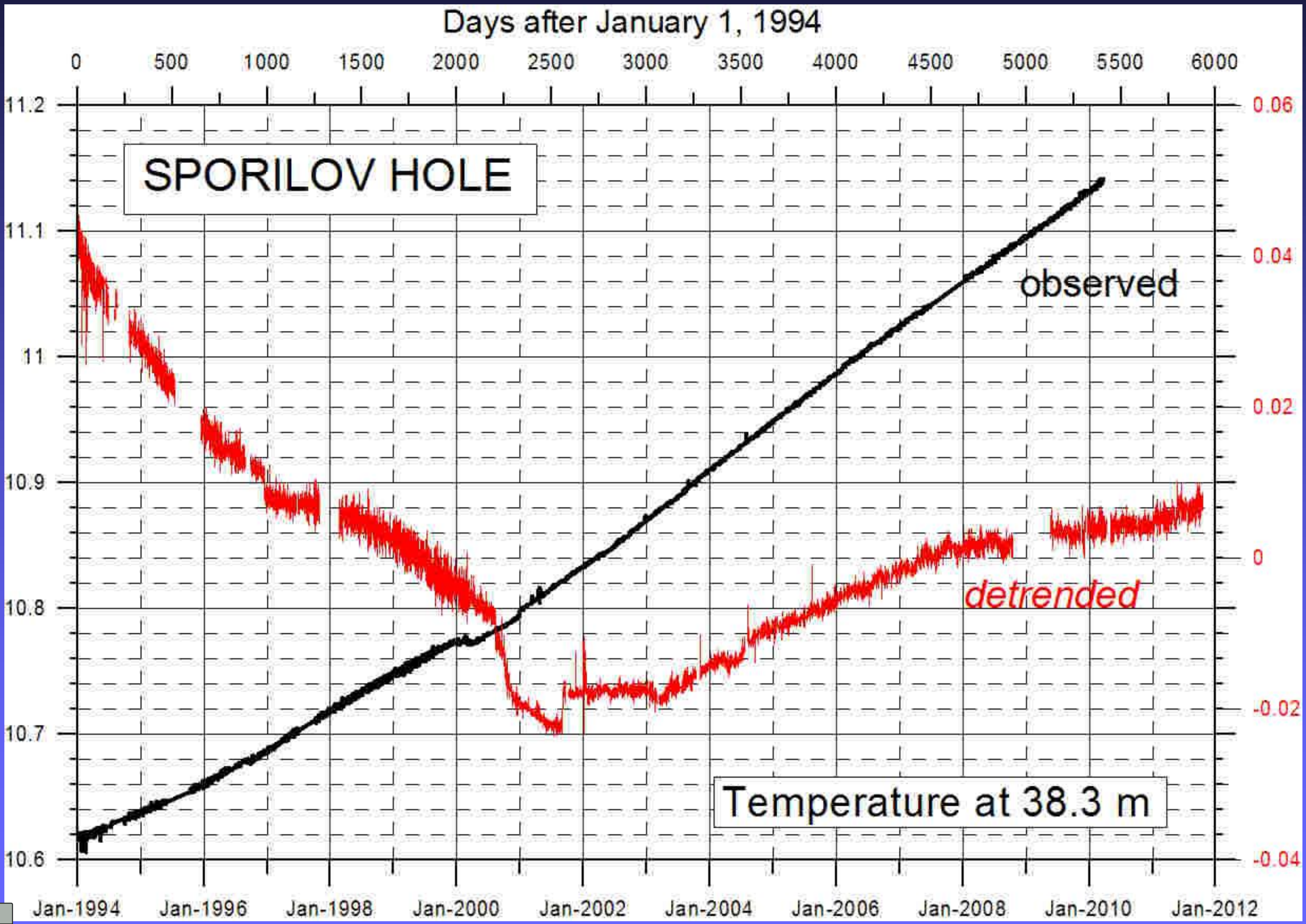


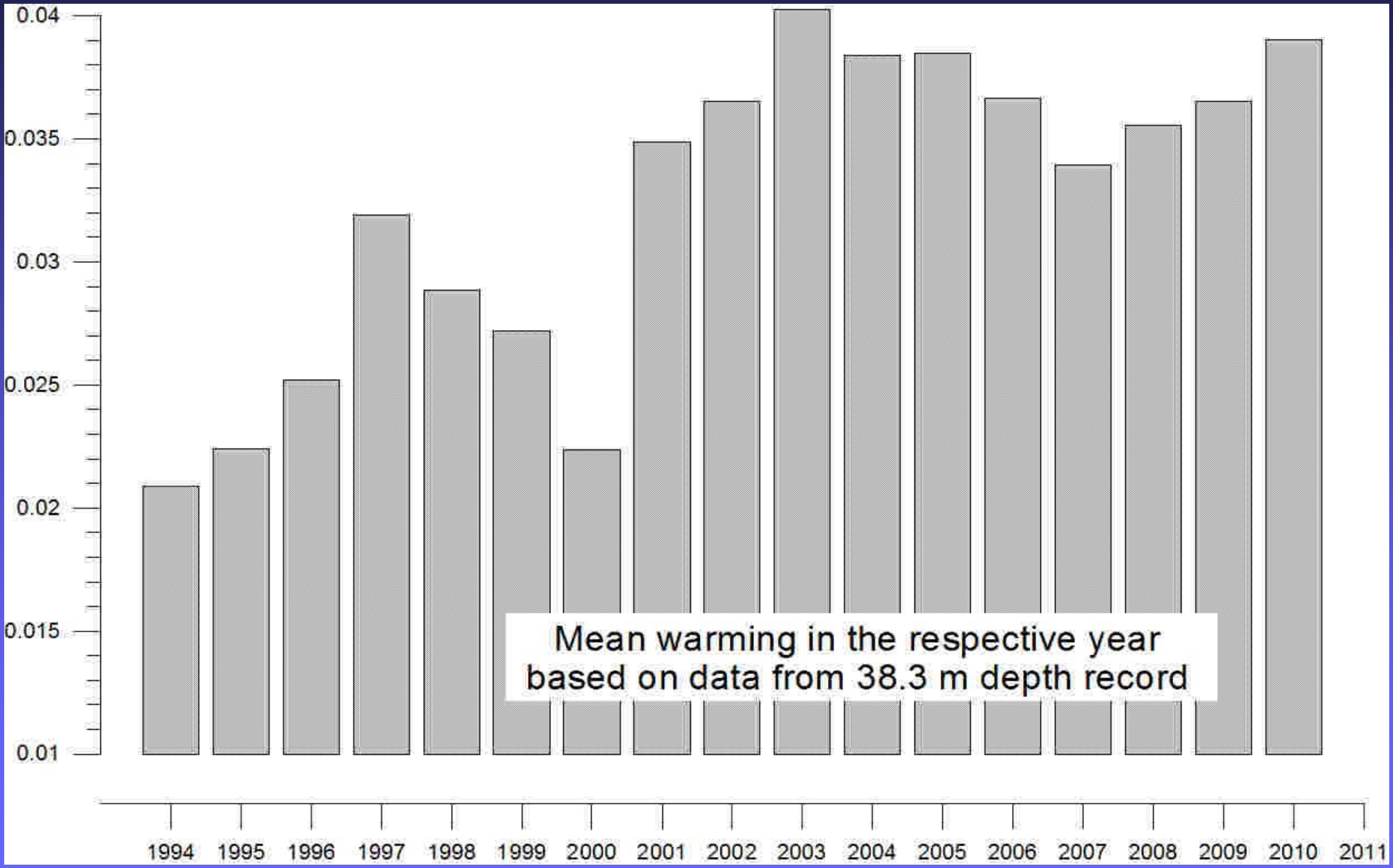

*Characteristic warming rates for individual depth levels decreases downward*

*Warming at surface > 0.1 K/year, at 40 m depth 0.03-0.04 K/year*

*Mean annual temperatures increase downward*

*At surface T(0)=10.36 increases to T(40)=10.94 due to heat flow*

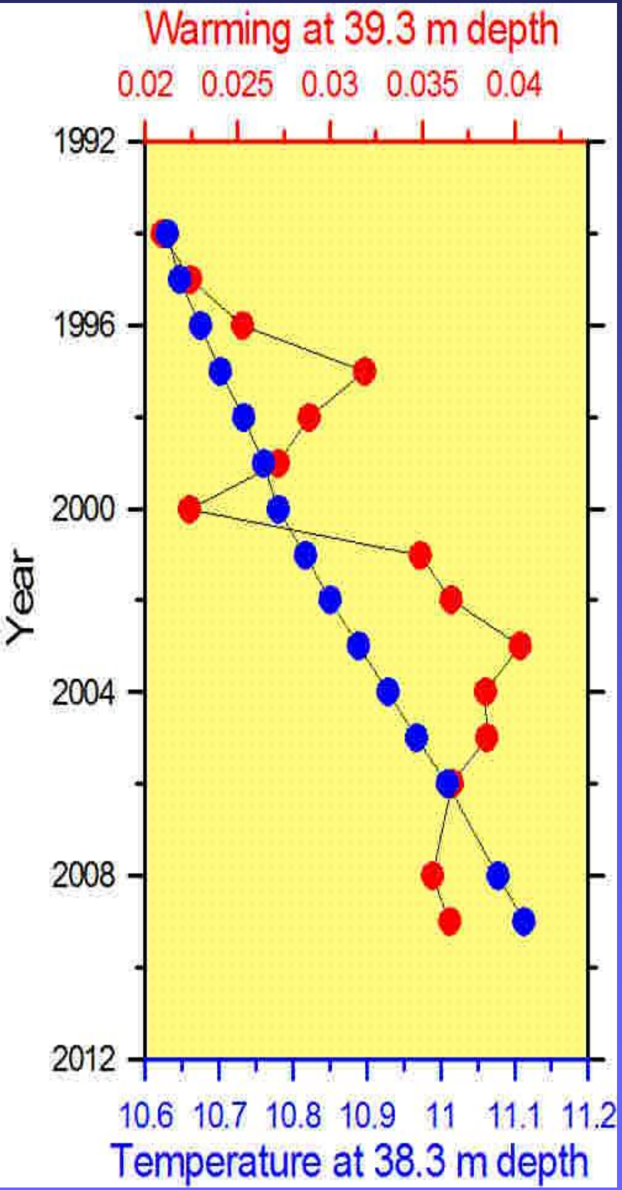

Days after January 1, 1994
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
SPORILOV HOLE
observed
detrended
Temperature at 38.3 m
11.2
11.1
11
10.9
10.8
10.7
10.6
0.06
0.04
0.02
0
-0.02
-0.04
Jan-1994
Jan-1996
Jan-1998
Jan-2000
Jan-2002
Jan-2004
Jan-2006
Jan-2008
Jan-2010
Jan-2012

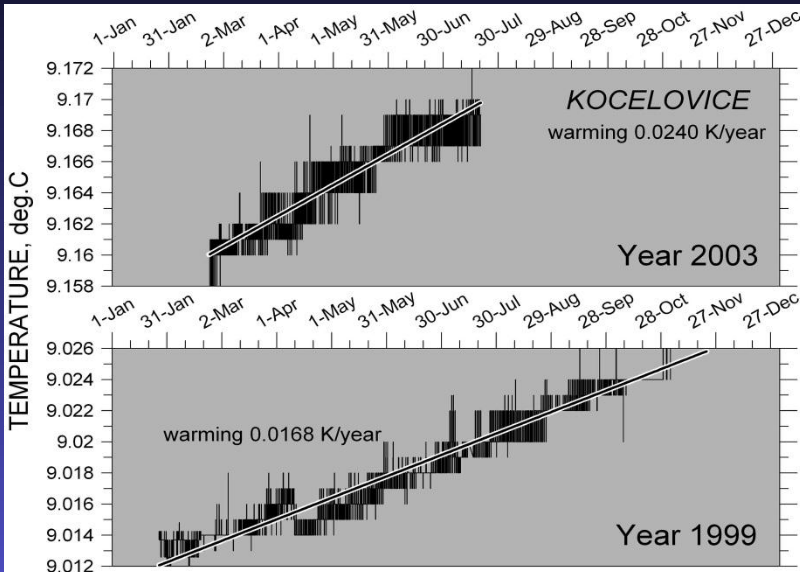

Mean warming in the respective year
based on data from 38.3 m depth record
0.04
0.035
0.03
0.025
0.02
0.015
0.01
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011

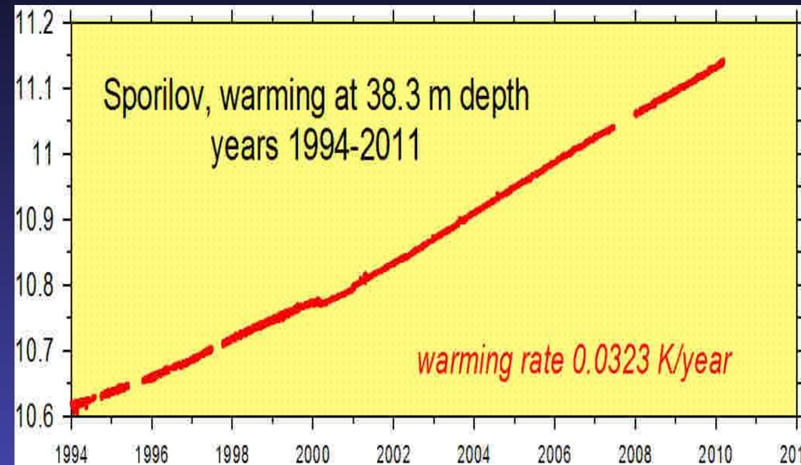
| Year | warming (deg/yr) | mean temp. (deg) | number of data | res.sum squares |
|---|---|---|---|---|
| 1994 | 0,0209 | 10,630 | 948 | 0,00225 |
| 1995 | 0,0224 | 10,647 | 1365 | 0,00099 |
| 1996 | 0,0252 | 10,674 | 2102 | 0,00229 |
| 1997 | 0,0319 | 10,701 | 1704 | 0,00122 |
| 1998 | 0,0288 | 10,733 | 2482 | 0,00233 |
| 1999 | 0,0272 | 10,761 | 2359 | 0,00249 |
| 2000 | 0,0224 | 10,781 | 2496 | 0,00822 |
| 2001 | 0,0349 | 10,816 | 2438 | 0,00079 |
| 2002 | 0,0365 | 10,850 | 2267 | 0,00151 |
| 2003 | 0,0403 | 10,889 | 2412 | 0,00146 |
| 2004 | 0,0384 | 10,929 | 2562 | 0,00072 |
| 2005 | 0,0385 | 10,968 | 2502 | 0,00080 |
| 2006 | 0,0366 | 11,008 | 7718 | 0,00337 |
| 2007 (a) | 0,0340 | 11,033 | 4031 | 0,00169 |
| 2008 | 0,0355 | 11,078 | 6703 | 0,00294 |
| 2009 | 0,0365 | 11,113 | 8538 | 0,00351 |
| 2010 (b) | 0,0390 | 11,136 | 2003 | 0,00079 |
| **mean** | **0,0323** | **10,8674** | **54630** | |

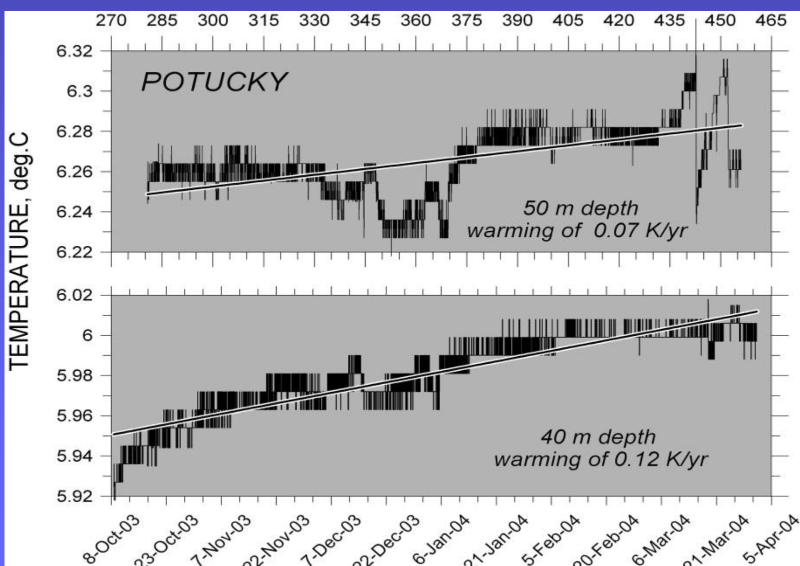
(a) half a year only

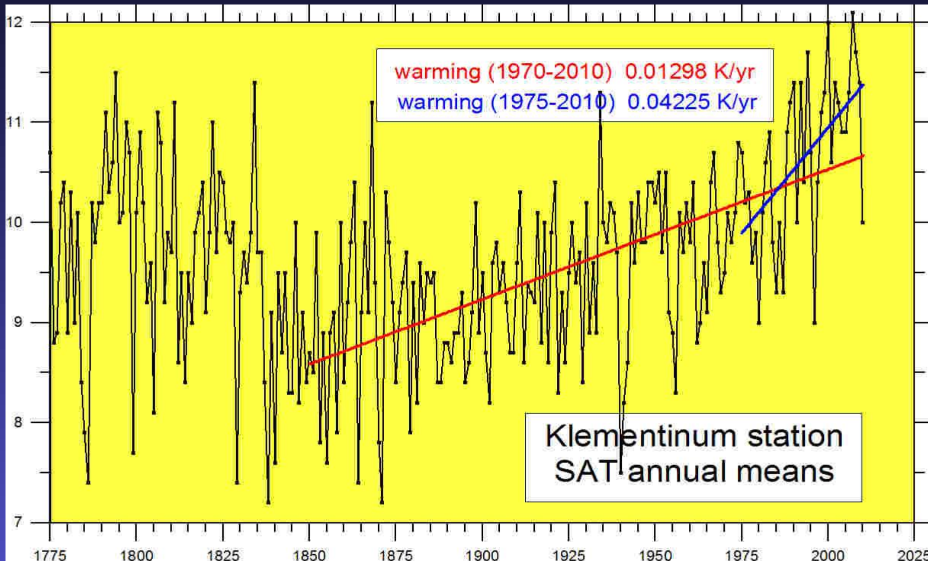
(b) three months only

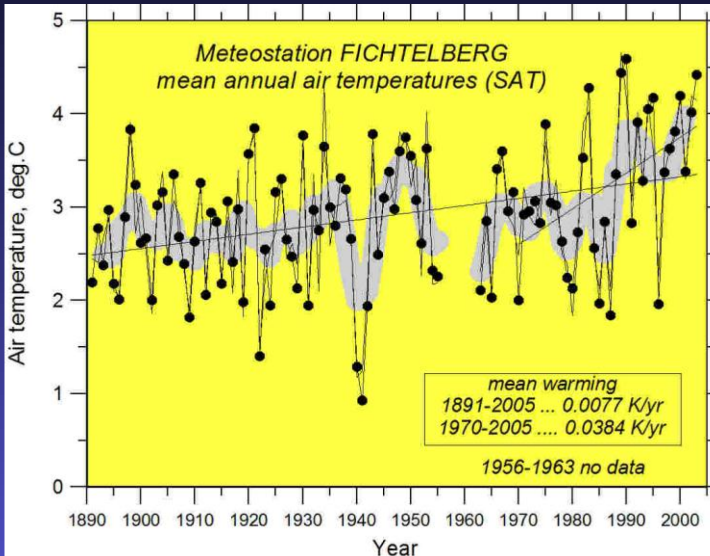


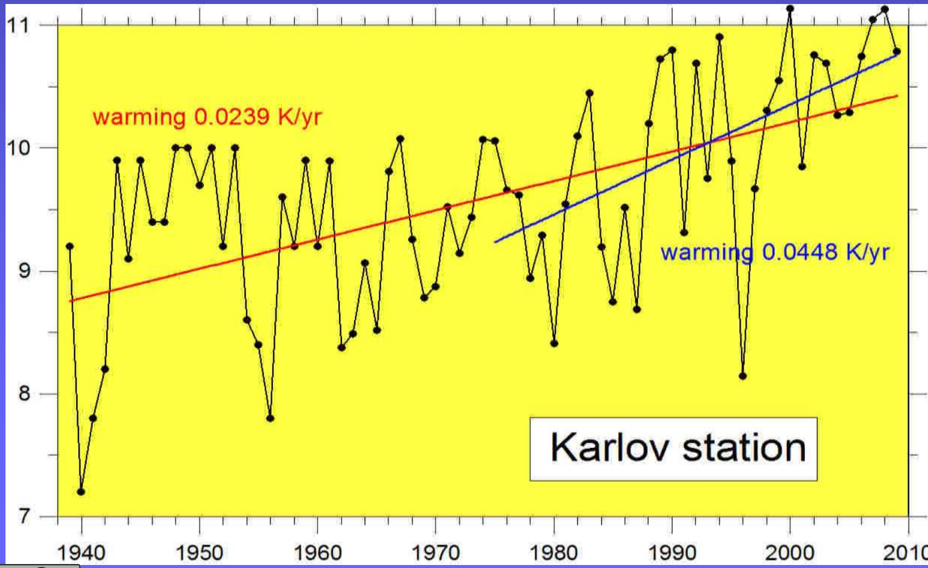

TEMPERATURE, deg.C
1-Jan
31-Jan
2-Mar
1-Apr
1-May
31-May
30-Jun
30-Jul
29-Aug
28-Sep
28-Oct
27-Nov
27-Dec
9.172
9.17
9.168
9.166
9.164
9.162
9.16
9.158
KOCELOVICE
warming 0.0240 K/year
Year 2003
9.026
9.024
9.022
9.02
9.018
9.016
9.014
9.012
warming 0.0168 K/year
Year 1999

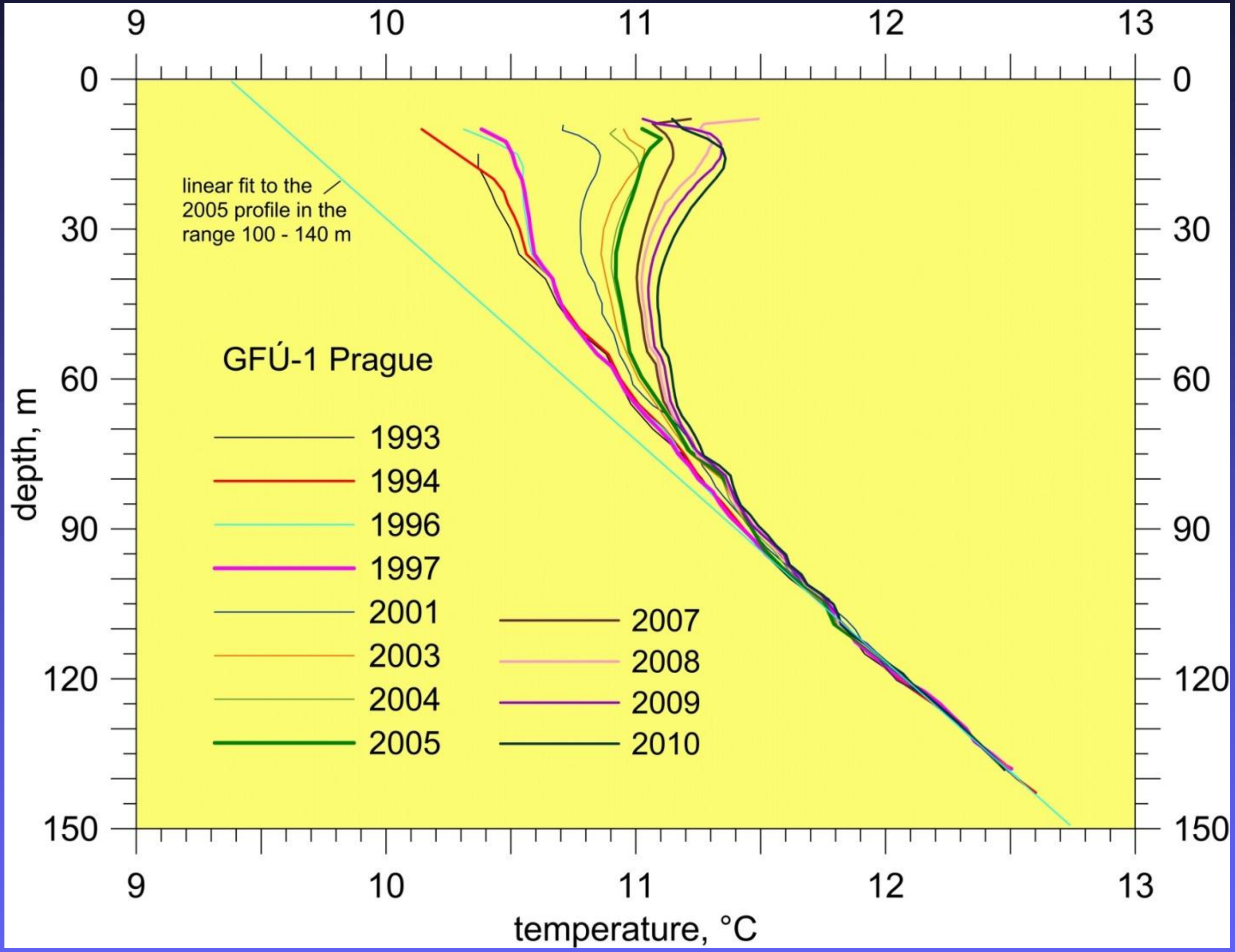

11.2
11.1
11
10.9
10.8
10.7
10.6
Sporilov, warming at 38.3 m depth
years 1994-2011
warming rate 0.0323 K/year
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012


TEMPERATURE, deg.C
270
285
300
315
330
345
360
375
390
405
420
435
450
465
6.32
6.3
6.28
6.26
6.24
6.22
POTUCKY
50 m depth
warming of 0.07 K/yr
6.02
6
5.98
5.96
5.94
5.92
40 m depth
warming of 0.12 K/yr
8-Oct-03
23-Oct-03
7-Nov-03
22-Nov-03
7-Dec-03
22-Dec-03
6-Jan-04
21-Jan-04
5-Feb-04
20-Feb-04
6-Mar-04
21-Mar-04
5-Apr-04

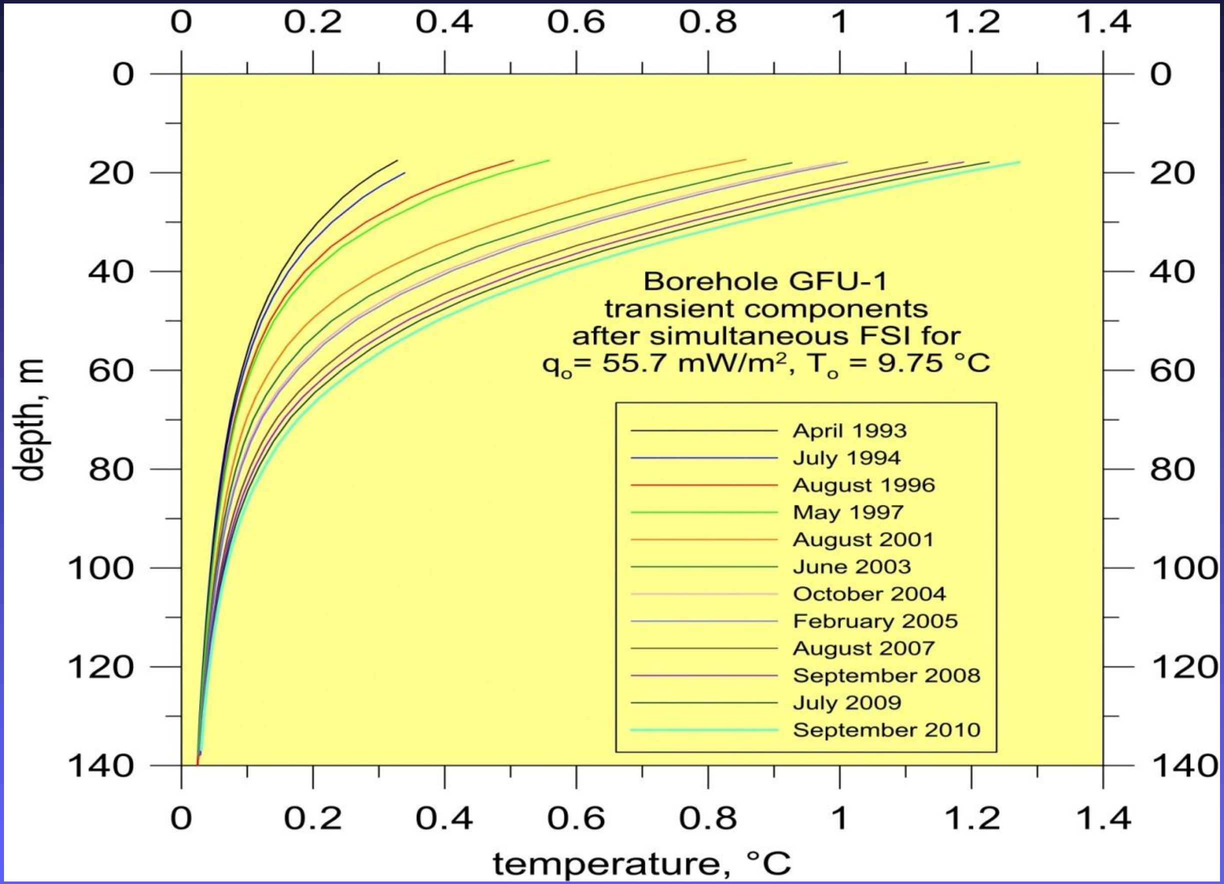

warming (1970-2010) 0.01298 K/yr
warming (1975-2010) 0.04225 K/yr
Klementinum station
SAT annual means
12
11
10
9
8
7
1775
1800
1825
1850
1875
1900
1925
1950
1975
2000
2025


Meteostation FICHTELBERG
mean annual air temperatures (SAT)
Air temperature, deg.C
mean warming
1891-2005 ... 0.0077 K/yr
1970-2005 .... 0.0384 K/yr
1956-1963 no data
5
4
3
2
1
0
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

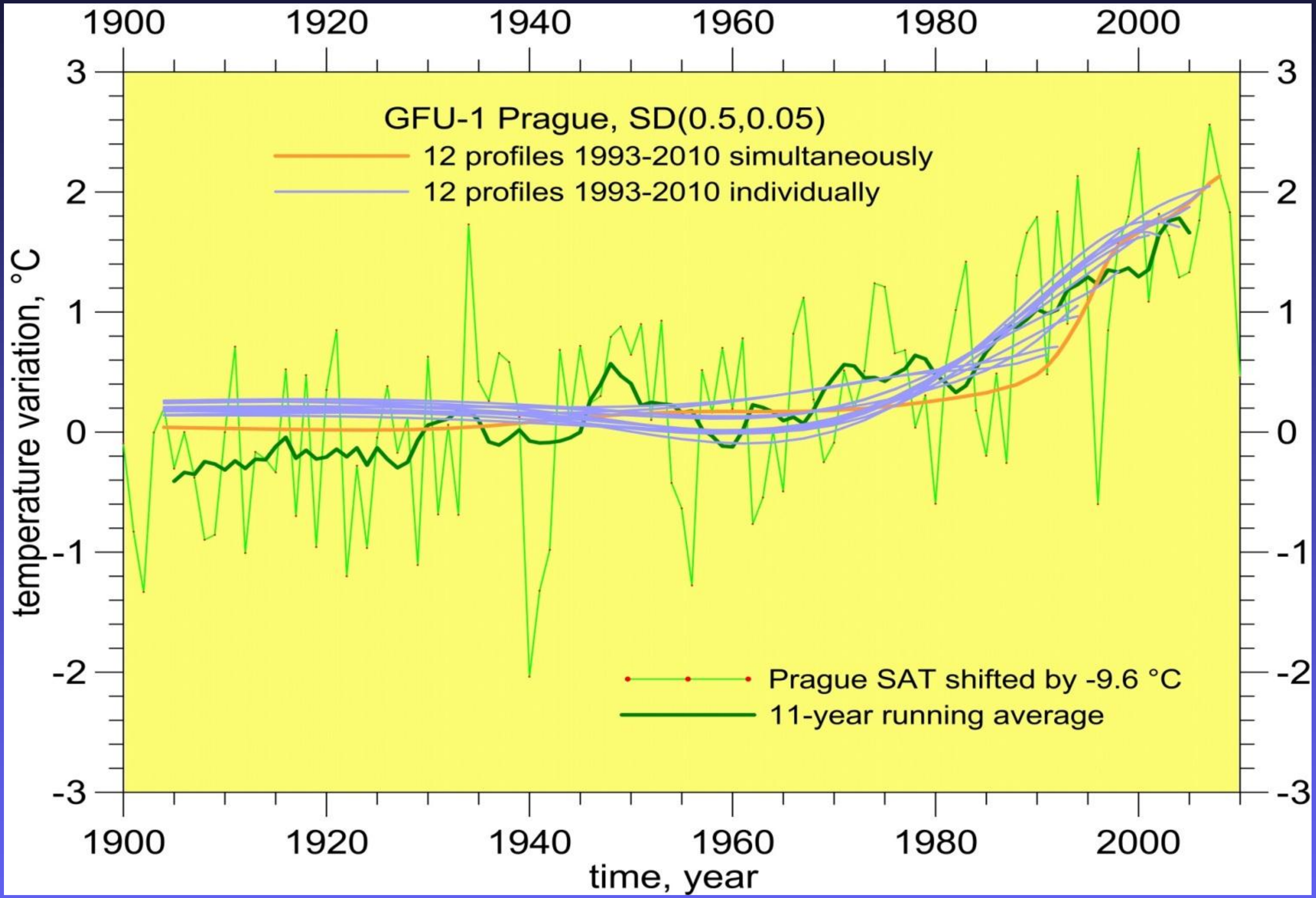

warming 0.0239 K/yr
warming 0.0448 K/yr
Karlov station
11
10
9
8
7
1940
1950
1960
1970
1980
1990
2000
2010




***Repeated temperature logs (1993 – 2010) – a direct evidence of (climate) warming, gradual increase of temperature in the upper part of the borehole***



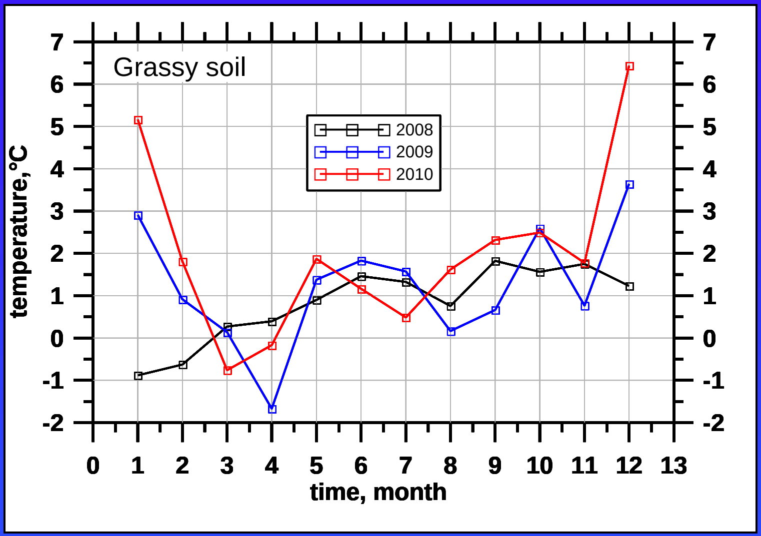

***Transient components of the individual logs > subsurface warming has been progressing continuously since 1993. Whereas the amplitude of warming at 20 m depth was 0.3 K in 1993, it amounts to 1.2 K in 2010.***

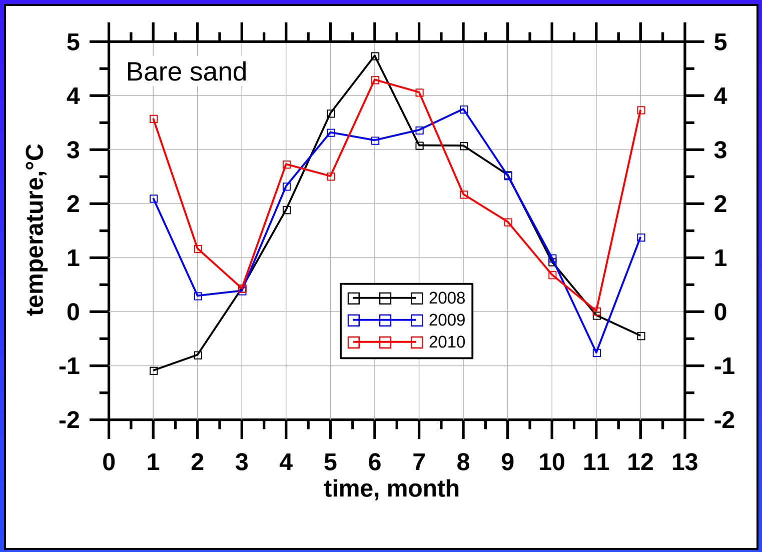


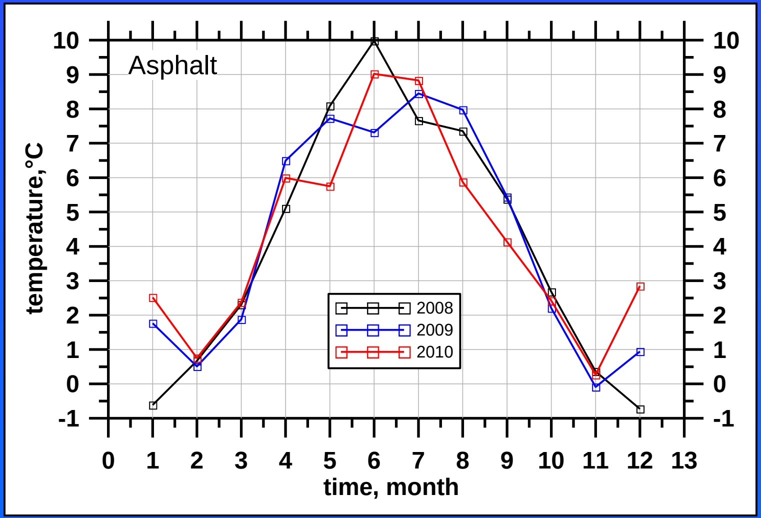

*The 12 profiles measured in the period 1993 – 2010, were inverted for the ground surface temperature history of the last 100 years obtained ... temperature series from the Prague's meteorological station Klementinum.*

*The simultaneous inversion is more representative, because it eliminates ... effects and noise contained in the individual logs.*

# *Mean monthly GST-SAT difference - Spořilov station in 2008-2010*



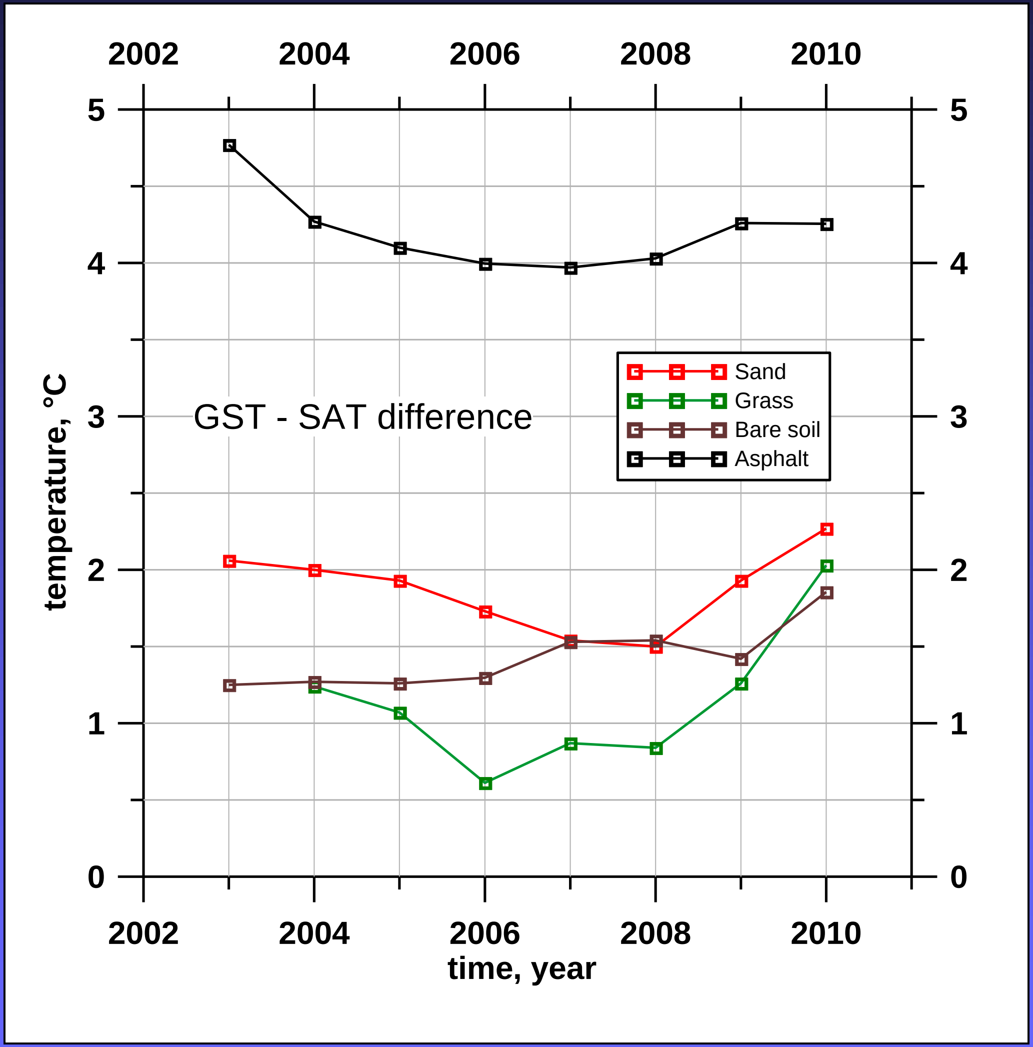




***Year 2009 was relatively rich in snow during January and February.***

***For grass, the snow cover plays a fundamental role.***

***On the contrary, asphalt with low albedo is affected mainly by intensity of solar radiation and maximum difference occurs during summer months.***

***In case of bare sand with higher albedo and lower thermal diffusivity than asphalt, the GST – SAT difference is determined by both factors.***


2002
2004
2006
2008
2010
5
4
3
2
1
0
temperature, °C
GST - SAT difference
Sand
Grass
Bare soil
Asphalt
time, year

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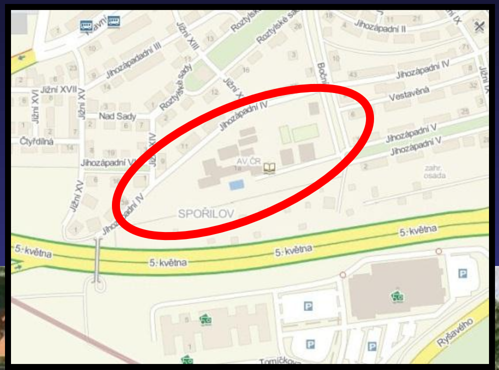


*Thank for your attention*