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Analysis of ground temperature variations on the basis of years-long measurements

Анализ изменения температуры грунта на основе многолетних измерений

G.P. Vasilyev,
V.F. Gornov,
JSC "INSOLAR-INVEST", Moscow, Russia
P.I. Konstantinov,
Lomonosov Moscow State University, Moscow, Russia
M.V. Kolesova,
JSC "INSOLAR-INVEST", Moscow, Russia
I.A. Korneva,
Federal State Budgetary Institution «Institute of Global Climate and Ecology of Federal Service for Hydrometeorology and Environmental Monitoring and Russian Academy of Sciences», Moscow, Russia

Д-р техн. наук, науч. руководитель
Г.П. Васильев,
директор проектного отделения
В.Ф. Горнов,
ОАО "ИНСОЛАР-ИНВЕСТ", г. Москва, Россия
канд. геогр. наук, старший преподаватель
П.И. Константинов,
Московский государственный университет им. М.В. Ломоносова, г. Москва, Россия
ведущий инженер-эколог М.В. Колесова,
ОАО "ИНСОЛАР-ИНВЕСТ", г. Москва, Россия
канд. геогр. наук, ст. науч. сотрудник
И.А. Корнева,
ФГБУ «Институт глобального климата и экологии Федеральной службы по гидрометеорологии и мониторингу окружающей среды и Российской академии наук», Москва, Россия

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Ключевые слова: температура грунта; грунтовый теплообменник; потепление грунта; термический режим; геотермальная теплонасосная система

Abstract. The article deals with results of the analysis of years-long measurements of the ground temperatures, for example: Russia, Moscow. Data are given on variations of the ground temperatures in the course of a year, at a 10-days interval, in two plots of land – one under exposed surface, the other under natural cover. Trends of ground temperature variations have been shown, for a period of over 50 years. As a part of research, an important application task is being handled, that is acquisition of information on a typical curve of ground temperatures to enable carrying-out more correct calculations of ground heat exchangers for any region of any country, and making forecasts of operating efficiency of geothermal heat pump systems, including long-term forecasts.

Аннотация. В статье представлены результаты анализа данных многолетних измерений температуры грунта на примере России г. Москвы. Приводятся данные по изменению температуры грунта в течение года с 10-дневным интервалом независимо для двух участков - с обнажённой (exposed) поверхностью и под естественным покровом. Выявлены и продемонстрированы тенденции изменения температуры грунта за период более 50 лет. В ходе исследования решается важная в прикладном плане задача – получение климатической информации о типовом ходе температур грунта, которая позволит более корректно выполнять расчёты грунтовых теплообменников для любого региона любой страны, а также прогнозировать эффективность работы геотермальных теплонасосных систем, в том числе и на длительную перспективу.

Introduction

Geothermal heat pump systems (GHPS) are gaining ground everywhere, including Russia [1–5]. As a heat source GHPS uses ground heat exchangers of various designs, both vertical and horizontal [6]. At present, greater emphasis is put on issues of improved operation efficiency of ground heat

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exchangers. Thus, in studies [7–10] various modifications of existing designs of ground heat exchangers are offered, and in [11–13] new versions of heat exchangers are under review. In addition to the design of the ground heat exchanger itself, a crucial factor that must be obligatorily taken into account for design process of a GHPS is a set of ground parameters in which the ground heat exchanger will operate including, among other things, data on its temperature [14, 15]. Importance of climatic conditions consideration during ground heat exchangers design process is analyzed in [16], where conclusion was made that air temperature fluctuations can lead to a reduction in ground heat exchangers depth. The purpose of the present study is analysis of years-long data on thermal conditions of the ground at a depth up to 5 meters in the Moscow region over a period, appropriate to show climatic trends. This way, an important application task is being handled, that is acquisition of climatic information on a ground temperature curve to enable carrying-out more correct calculations of ground heat exchangers and making forecasts of operating efficiency of geothermal heat pump systems, including long-term forecasts.

Measuring methods

As recommended by the World Meteorological Organization, under today climatic conditions, affected by various regional trends, for research one shall use a series of continuous measurements, taken over a period of at least 30 years [17]. With these considerations, the period from 1982 till 2011 has been chosen for a 10-day analysis.

As source data on ground temperatures, results of years-long measurements have been used, taken by the meteorological observatory of the Lomonosov Moscow State University, where thermal regime of the ground has been observed since 1955 at eleven depth points. Considered were mean 10-day ground temperatures at specified depths as follows: 20 cm, 40 cm, 60 cm, 80 cm, 120 cm, 160 cm, 240 cm and 320 cm.

The measurement method of the parameter discussed in the article (soil temperature) is established on the state network of meteorological stations during the last fifty years. According to it, in standard meteorological time the current and maximum surface temperatures are measured by mercury thermometers, and the minimum temperature – by an alcohol thermometer, as well as the ambient air temperature in the psychrometric box [22]. This operation is performed every 3 hours throughout the year. Measurements in the soil stratum are carried out as follows: to more accurately measure the parameters of the thermal balance of the earth's surface in the period from spring to autumn, temperatures at a depth of 5, 10, 15 and 20 cm are measured with the help of Savinov cranked mercury thermometers. Deeper horizons (starting from 20 cm) use bottom-hole thermometers TPV-50. Unlike the Savinov thermometers, these devices are arranged as follows: to reduce vertical heat transfer they are shielded by a protective tube and copper or brass sawdust is put around the reservoir to increase their inertia. At present, both ebonite and low-density polyethylene serve as the material of the tubes [22]. This method of measurement should be recognized as fairly accurate: the error in measuring temperature is in the range from 0 to 40 °C is ± 0.2 °C, and in the range of negative temperatures from 0 to -20 °C is ± 0.3 °C.

Every day, every three hours, measurements of current, maximum and minimum temperatures on an underlying surface are taken (warm season: soil surface, cold season: snow surface). To measure a surface temperature a standard mercury-filled thermometer was used; to measure a maximum surface temperature a mercury-filled meteorological thermometer was used; and minimum temperature was measured by an alcohol meteorological thermometer.

As far as ground heat exchangers may be placed both under maintained areas with no vegetation cover, where snow is removed in winter time (parking areas, roads, pedestrian ways), and under lawns, during research it was enabled to compare thermal regime of a surface with vegetation cover and surface free of it, in all seasons. For that, measurements were taken simultaneously in two plots of land: in grounds under exposed surface and under natural cover (Figure 1).

Bottom-hole thermometers are read once a day, with the exception of depths of 20 and 40 cm, where measurements are taken 8 times a day under natural cover and 4 times a day under exposed surface. With a significantly high snow cover (more than 15 cm, when it increases, and more than 5 cm, when it melts), all the 8 bottom-hole thermometers are read once a day.

Area of a plot of land with exposed surface is 12×20 m (Figure 1.a).

Figure 1. Subsurface temperature measurements a) exposed surface; b) natural cover

Calculation methods

Considering that depths at which ground heat exchangers can be placed may vary depending upon tasks being handled, designs of the ground heat exchangers and plot features, data on ground temperature conditions up to deeper depths than those that turn out to be possible for standard measurements could appear to become necessary. To obtain this data, values of ground temperatures at deeper levels have been calculated on a basis of measurements in higher layers.

In the present study mean 10-day data on ground temperatures at a depth of 40–320 cm were used, collected for a period from 1982 till 2011. Values of ground temperatures at a depth of 400 cm and 480 cm have been calculated by means of Fourier method. The method is based on the Fourier law, where the temperature conductivity coefficient in depth is supposed to be constant. That is described by an equation as follows:

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2}, \tag{1}$$

where “T” is ground temperature (°C), “z” is depth (m), “t” is time (s), “k” is temperature conductivity coefficient (m^2/s). In this manner, the temperature conductivity coefficient of the ground and temperatures at higher levels are sufficient to calculate values at deeper levels.

From Equation (1) the temperature conductivity coefficient has been calculated for a deepest of measured levels – 160–320 cm – using an equation as follows:

$$k = \frac{\partial T}{\partial t} \Big/ \frac{\partial^2 T}{\partial z^2}, \tag{2}$$

where derivatives have been approximated using central differences:

$$\frac{\partial T}{\partial t} = \frac{T_{i+2} - T_i}{t_{i+2} - t_i}, \tag{3}$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{T_{j-1} - 2T_j + T_{j+1}}{(z_j - z_{j-1})^2}, \tag{4}$$

where “i” is a number of a 10-day period, “j” is depth. On the basis of the mean (throughout the period) temperature conductivity coefficient, ground temperatures at deeper levels have been calculated:

$$\mathrm{T_{j+1}} = \frac{\mathrm{(T_i - T_{i+2})(z_j - z_{j-1})^2}}{\mathrm{(t_i - t_{i+2})k}} - \mathrm{T_{j-1}} + 2\mathrm{T_j}, \tag{5}$$

where T_{j+1} is a desired value of temperature at a deeper level. Equation (5) has been used to obtain temperatures at a depth of 400 cm and 480 cm.

Results and Discussion

After measurements for 80–320 cm have been averaged, as well as calculations for depths of 400–480 cm, for each 10-day period tables were drawn up, to contain mean temperatures for the period from 1982 till 2011 (exposed surface / natural cover). Tables 1 and 2 present these results, correspondingly.

Table 1. Mean 10-day ground temperatures at various depth points, 1982–2011 (exposed surface, with no turf in warm season and with no snow in cold season)

Month	**Decade No.**	**80 cm**	**120 cm**	**160 cm**	**240 cm**	**320 cm**	**400 cm**
January	1	-0.1	2.2	3.9	6.8	8.4	9.2
January	2	-0.6	1.6	3.3	6.3	8.0	8.7
January	3	-1.0	1.1	2.8	5.8	7.5	8.4
February	1	-1.7	0.7	2.4	5.3	7.1	8.2
February	2	-2.2	0.1	1.9	4.9	6.8	8.0
February	3	-2.0	-0.1	1.6	4.6	6.4	7.7
March	1	-1.7	-0.2	1.4	4.3	6.1	7.4
March	2	-1.0	0.0	1.3	4.0	5.9	7.2
March	3	-0.5	0.2	1.3	3.8	5.6	7.0
April	1	0.0	0.4	1.3	3.7	5.4	6.9
April	2	0.9	0.9	1.6	3.6	5.3	6.8
April	3	2.8	1.9	2.2	3.8	5.2	6.9
May	1	5.8	3.8	3.4	4.2	5.3	7.1
May	2	8.7	6.5	5.4	5.0	5.6	7.6
May	3	11.1	8.8	7.4	6.1	6.3	8.1
June	1	13.5	11.1	9.4	7.4	7.1	8.6
June	2	14.8	12.6	10.9	8.6	8.0	9.1
June	3	15.7	13.7	12.1	9.7	8.9	9.6
July	1	16.9	14.8	13.1	10.7	9.7	10.1
July	2	18.0	15.9	14.1	11.6	10.4	10.8
July	3	18.6	16.7	15.1	12.5	11.2	11.3
August	1	18.6	17.1	15.7	13.2	11.9	11.7
August	2	18.0	17.0	15.9	13.7	12.5	12.1
August	3	17.1	16.5	15.7	14.0	12.9	12.4
September	1	15.8	15.7	15.3	14.1	13.2	12.5
September	2	14.1	14.6	14.6	14.0	13.3	12.5
September	3	12.6	13.3	13.7	13.6	13.2	12.4
October	1	10.9	12.0	12.7	13.2	13.0	12.3
October	2	9.4	10.7	11.6	12.6	12.7	12.0
October	3	7.5	9.2	10.4	11.9	12.3	11.7
November	1	5.8	7.7	9.2	11.1	11.8	11.4
November	2	4.5	6.4	8.0	10.3	11.2	11.1
November	3	3.4	5.4	7.0	9.5	10.7	10.7
December	1	2.4	4.5	6.1	8.8	10.1	10.3
December	2	1.7	3.7	5.4	8.1	9.5	9.9
December	3	0.7	2.9	4.6	7.4	9.0	9.5

Table 2. Mean 10-day ground temperatures at various depth points, 1982–2011 (plot of land with natural cover, turf height not exceeding 5 cm)

Month	Decade No.	80 cm	120 cm	160 cm	240 cm	320 cm	400 cm	480 cm
January	1	2.3	3.3	4.6	6.0	7.0	7.7	8.0
January	2	2.1	3.1	4.2	5.6	6.7	7.4	7.7
January	3	1.9	2.8	3.9	5.2	6.3	7.0	7.5
February	1	1.8	2.6	3.7	4.9	6.0	6.8	7.4
February	2	1.7	2.5	3.5	4.7	5.7	6.6	7.2
February	3	1.6	2.3	3.3	4.5	5.5	6.4	7.0
March	1	1.6	2.3	3.2	4.3	5.3	6.2	6.8
March	2	1.5	2.2	3.1	4.1	5.1	5.9	6.5
March	3	1.7	2.2	3.0	4.0	4.9	5.7	6.4
April	1	2.2	2.5	3.0	3.9	4.8	5.6	6.3
April	2	3.5	3.3	3.5	3.9	4.7	5.5	6.3
April	3	5.3	4.6	4.3	4.3	4.8	5.5	6.2
May	1	7.2	6.1	5.4	4.9	5.0	5.5	6.2
May	2	8.6	7.5	6.6	5.7	5.4	5.7	6.3
May	3	9.9	8.7	7.6	6.5	5.9	6.0	6.4
June	1	11.4	10.0	8.7	7.3	6.5	6.3	6.6
June	2	12.6	11.1	9.7	8.1	7.1	6.7	6.8
June	3	13.5	12.0	10.6	8.8	7.7	7.2	7.1
July	1	14.3	12.9	11.4	9.6	8.3	7.7	7.5
July	2	15.2	13.7	12.1	10.2	8.9	8.1	7.8
July	3	15.8	14.4	12.9	10.9	9.5	8.6	8.1
August	1	15.9	14.7	13.4	11.5	10.0	9.0	8.4
August	2	15.7	14.7	13.6	11.9	10.5	9.4	8.7
August	3	15.2	14.5	13.6	12.2	10.8	9.8	9.0
September	1	14.4	14.0	13.4	12.3	11.1	10.0	9.2
September	2	13.3	13.3	13.0	12.2	11.2	10.2	9.3
September	3	12.1	12.3	12.4	11.9	11.2	10.3	9.5
October	1	10.9	11.3	11.7	11.5	11.0	10.3	9.5
October	2	9.7	10.3	10.9	11.0	10.8	10.3	9.5
October	3	8.2	9.1	10.0	10.4	10.5	10.1	9.5
November	1	6.8	7.8	9.0	9.7	10.1	9.9	9.4
November	2	5.5	6.6	7.9	9.0	9.6	9.6	9.3
November	3	4.5	5.7	7.1	8.3	9.0	9.2	9.1
December	1	3.7	4.9	6.3	7.6	8.5	8.9	8.8
December	2	3.1	4.3	5.7	7.0	8.0	8.5	8.5
December	3	2.7	3.8	5.1	6.5	7.5	8.1	8.3

Table 3 presents mean annual ground temperature at various depth points, 1955–2011, under natural cover and exposed surface

Trends of ground temperature distribution with depth under natural cover and exposed surface differ essentially from each other. On average, within 1955 – 2011, ground temperature under natural cover does not vary with depth, and its value is 7.7°C, accurate to a tenth. Ground temperature distribution with depth under exposed surface is characterized by temperature rise with depth increase, with a maximum value at a depth of 320 cm.

Table 3. Mean annual values of ground temperatures at various depth points, 1955–2011

Depth, cm	**Under natural cover, °C**	**Under exposed surface, °C**
20	7.7	6.9
40	7.7	6.9
60	7.7	6.9
80	7.7	7.0
120	7.7	7.2
160	7.7	7.8
240	7.7	8.3
320	7.7	9.1

Table 4 shows minimum and maximum measured ground temperatures at various depth points, 1955–2011.

Table 4. Minimum and maximum ground temperatures at various depth points, 1955–2011

Depth, cm	**Under natural cover, °C**		**Under exposed surface, °C**	
	Min.	Max.	Min.	Max.
20	-5.7	25.0	-17.3	43.0
40	-3.3	23.7	-15.8	31.9
60	-2.2	21.3	-11.5	26.6
80	-0.7	20.1	-10.7	25.0
120	0.3	18.3	-5.1	21.9
160	1.2	16.7	-1.9	19.9
240	2.6	14.6	1.4	17.7
320	3.6	12.8	-6.1	15.4

As the tables show, at a depth of 20 cm ground temperatures vary most as compared to deeper levels due to stronger impact of underlying surface conditions. That is why a temperature curves under natural cover and exposed surface differ essentially from each other at that depth. Under natural cover an annual temperature range makes 30.7 °C, while it is 60.3 °C under exposed surface due to absence of a thermal insulating layer at higher levels (snow cover in winter / turf and grass cover in summer). Under natural cover another ground temperature distribution trend is observed at this depth: it remains almost constant from January till April. This trend is related to seasonal snow cover within these months that prevents ground cooling in winter and ground warming in spring.

Figure 2 shows annual variations of ground temperatures at various depths. Figure 2a shows that after snow cover melting (March–April) at a depth of 20 cm ground temperature intensively rises, while under exposed surface ground temperature begins to rise at that depth a month earlier.

Ground at a depth of 160 cm (Figure 2b) under exposed surface cools down in winter and warms in summer more intensively than that under exposed surface. This effect is to be taken into account for design of horizontal ground heat exchangers for GHPS, because lower ground temperatures in winter, when GHPS operates in heating mode and heat is extracted from the ground, will cause lower operation efficiency of the system. In summer, when GHPS operates in cooling mode, higher ground temperatures will hinder heat discharge into the ground and use of passive cooling. Considering this, GHPS ground heat exchangers shall be rather placed under natural cover.

At a depth of 320 cm in winter inverse distribution of ground temperatures can be observed, as compared to levels mentioned above: under exposed surface the ground temperature turns out to be higher than that under natural cover. In summer a trend of temperature variations remains the same.

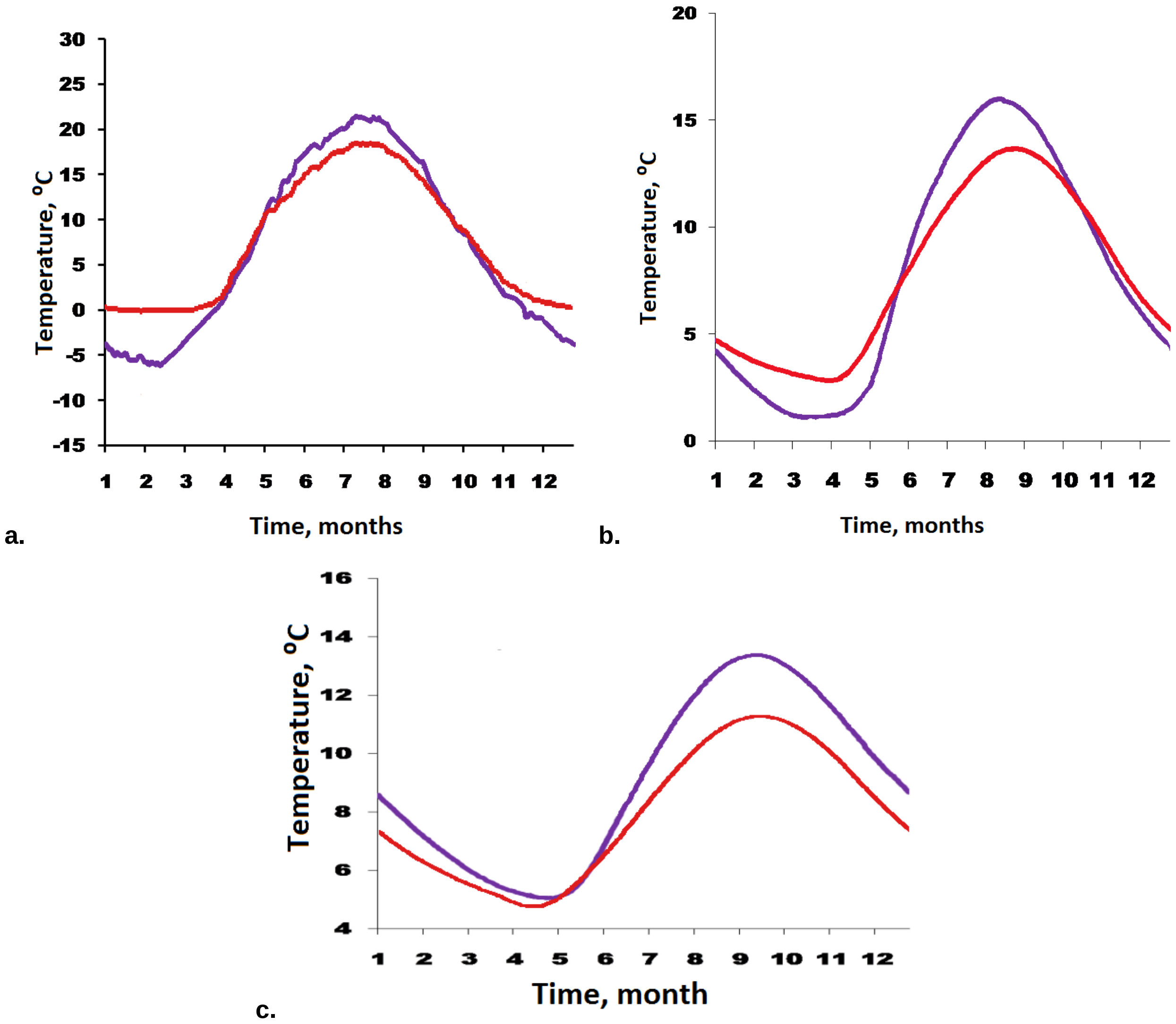

Figure 2. Annual curve of ground temperature under natural cover (red line) and exposed surface (blue line), average values within 1955-2011 at a depth of as follows: a) 20 cm; b) 160 cm; c) 320 cm.

Figure 3 shows annual variations of ground temperature at a depth of 160 cm and mean ambient air temperature throughout the period under review. Each parameter in the graph is used for a trend line to reveal the nature of variations within this years-long period.

It is worth noting that at this depth a steady trend to ground warming is observed. Rate of warming under exposed surface is close to a rate of ambient air temperature rise, while under natural cover a rate of warming is two and a half times slower (Figure 3).

In the study [18], based upon the data of the same meteorological station, similar trends are shown in the ground at a depth of 320 cm.

But this is not something special for Moscow city. The same effect of ground warming was previously observed by other researchers for different cities, for example for Karlsruhe [19], Tokyo, Seoul, Osaka and more [20]. In [19] a conclusion was made that the subsurface heat balance in the urban area in Karlsruhe is obviously dominated by anthropogenic heat sources. Among these heat sources thermal energy input from reinjections of thermal wastewater, sewage leakage and the district heating network together with the heat input from buildings were named. But the most of the ground heat gain is caused by increased ground surface temperature, which is in direct proportion to ambient air temperature.

In practice the fact of ground warming can be used to reduce the length of ground heat exchanger. According to [21], each additional degree of ground temperature could save around 4 m of the borehole length for the same heating power supply.

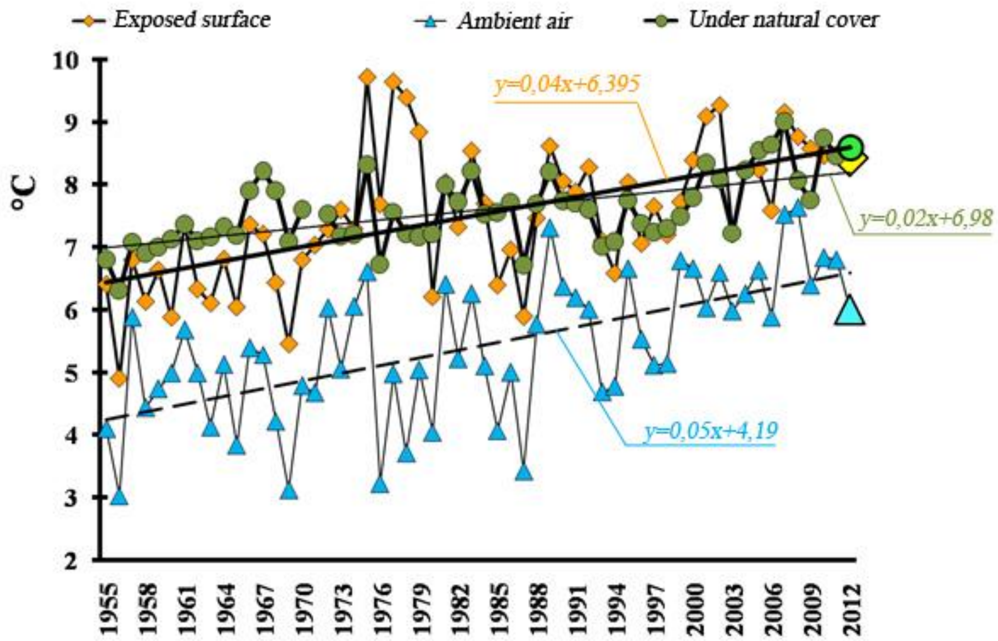

Figure 3. Ground temperature variations at a depth of 160 cm under natural cover and exposed surface, as well as ambient air temperature variations from 1955 till 2012

Horizontal ground heat exchangers of GHPS are often placed at a depth points, close to that of 160 cm. As the type of an underlying surface has a meaningful effect upon variations of the ground temperatures in the annual cycle and dynamics of these long-term variations, while designing the ground heat exchangers it is important to keep in mind, where they are going to be placed: under natural cover or under roads, sidewalks and other surfaces without turf and grass protecting layers in summer and snow cover in winter. [22]

To show long-term trends a temperature curve based upon mean values within consecutive decades (1982–1991, 1992–2001, 2002–2011) at a depth of 400 cm under natural cover and exposed surface (Figure 4) and variations of mean temperature values at the same depth (Figure 5) were examined.

Figures 4 and 5 show that in the last 30 years temperatures at a depth of 400 cm also tend to rise. Within 1992–2001 local fall in temperature under natural cover were observed. It is difficult to explain that fall by ambient air temperature variations because graphs for exposed surface do not reveal a trend like that. On average, a rate of temperature rise at this depth makes about 0.43 °C within 10 years, and this rate is rather uniform.

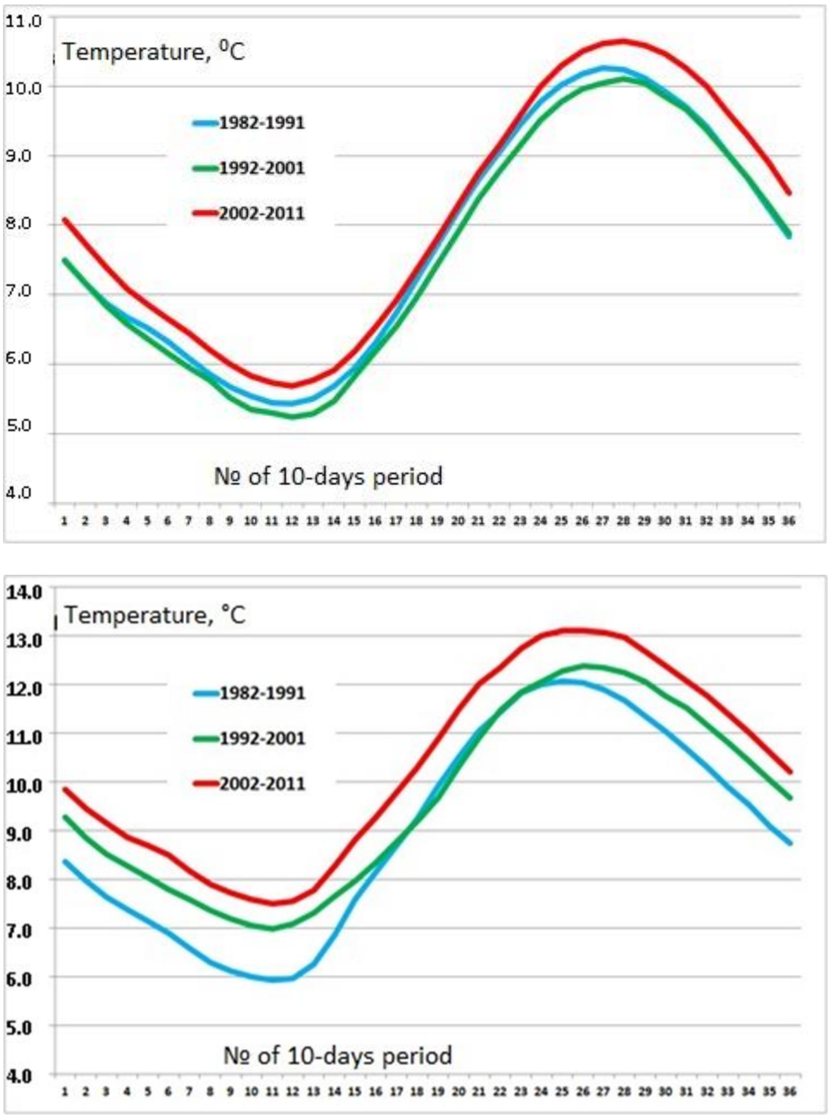

Figure 4. Ground temperature at a depth of 400 cm, by decades in 1982–1991, 1992–2001 and 2002–2011, correspondingly: a) natural cover, b) exposed surface

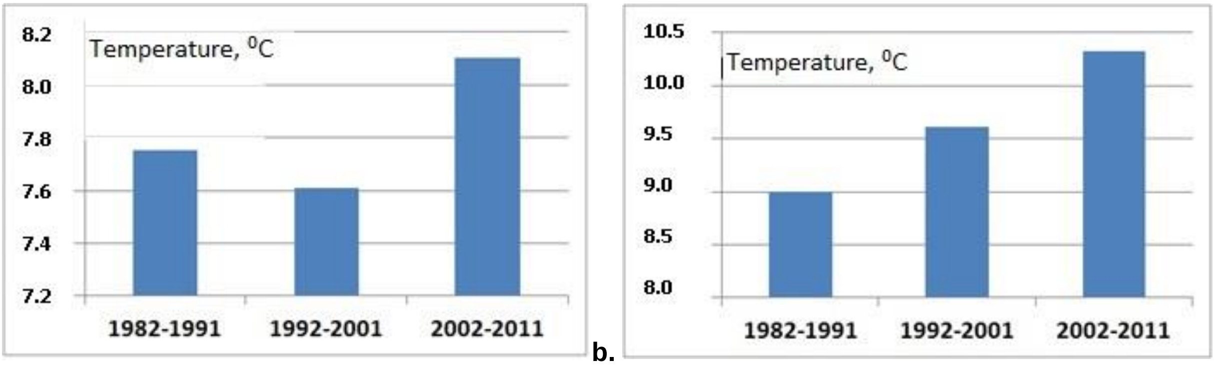

Figure 5. Variations of mean ground temperatures at a depth of 400 cm, by decades within 1982–1991, 1992–2001 and 2002–2011, correspondingly: a) natural cover, b) exposed surface

Conclusions

Data on years-long measurements of variations of ground temperatures in Moscow have been analyzed, at depths of 20 cm, 40 cm, 60 cm, 120 cm, 160 cm, 240 cm and 320 cm in grounds under exposed surface and natural cover. The data were collected from 1982 till 2011. Ground temperatures at a depth of 400 cm and at a depth of 480 cm were obtained using a calculation method.

On the basis of climatic data information has been obtained on a typical temperature curve at depths up to 5 m. These data can be used for ground heat exchangers design and modelling.

As a result of comparison of data for exposed surface and natural cover, impact of an underlying surface upon ground temperature variations in the annual cycle has been demonstrated.

At the depth points under review a steady trend to ground warming has been revealed. At that, a rate of temperature rise under exposed surface is faster than that under natural cover.

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Gregory Vasilyev,
+7(499)1440667; gpvassiliev@mail.ru

Victor Gornov,
+7(499)1440667; insolar-invest@yandex.ru

Pavel Konstantinov,
+7(499)1440667; kostadini@mail.ru

Marina Kolesova,
+7(499)1440667; eco-insolar@mail.ru

Irina Korneva,
+7(916)4354790; comissa@mail.ru

Григорий Петрович Васильев,
+7(499)1440667; эл. почта: gpvassiliev@mail.ru

Виктор Федорович Горнов,
+7(499)1440667;
эл. почта: insolar-invest@yandex.ru

Павел Игоревич Константинов,
+7(499)1440667; эл. почта: kostadini@mail.ru

Марина Владимировна Колесова,
+7(499)1440667; эл. почта: eco-insolar@mail.ru

Ирина Алексеевна Корнева,
+7(916)4354790; эл. почта: comissa@mail.ru

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