

The evaluation of global warming's effects on soil temperature – case of Tlemcen (North Africa)

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Abstract: The average temperature of the Earth as a whole is not stable but varies with time, as evidenced by analysis of geological layers. Our planet was colder by ten degrees Celsius 20 000 years ago, during the height of the last ice age. These variations are still very slow, and the temperature has fluctuated by only 0.2 degrees between the year 1000 and the late nineteenth century (ESSLINGER, 2009). The fact that worries the international community at present is the acceleration of the phenomenon, which now occurs at a rate unmatched in the past. Thus, since the late nineteenth century the average global temperature rose by 0.6 degrees. Worse, the computer simulations suggest that warming will accelerate and the average temperature could therefore increase by 1.4 to 5.8 degrees by the end of the century. This phenomenon is called global warming.

In this study, global warming effects on soil temperature of Tlemcen (North of Africa), was evaluated by the analysis of spatial and temporal variations of the soil temperature data. The aim of this study is to set an equation, which introduces the ground temperature field as a function of depth, time, and ground thermal properties in an area where the local warming is known. To achieve this goal, numerical solution of general heat conduction equation and a special programme were used. The integration of derived function could be used to determine the heat accumulation in the ground as a result of global warming.

Key words: depth, global warming, ground thermal properties, soil temperature

INTRODUCTION

Human influence on climate has attained a global scale. This reflects the recent rapid increase in population size, energy consumption, intensity of land use and many other human activities. The increase in surface temperature over the 20th century for the Northern Hemisphere is likely to have been greater than that for any other century in the last thousand years (IPCC, 2007). According to an optimistic scenario in the fourth report of Intergovernmental Panel on Climate Change

(CARSLAW and JAEGER, 1959), temperature will rise by 4.4°C in a century and according to a pessimistic scenario it will rise by 6.4°C , in case the emissions are going to be like now. In the report, it is anticipated that temperature will raise by 0.2°C per decade and even if the concentration of greenhouse gases is fixed at 2000's level, $0.1^{\circ}\text{C}/10$ years increase can't be prevented, because of long life of these gases in the atmosphere. The report indicated that plant productivity would decrease in most regions of the world due to warming beyond a few $^{\circ}\text{C}$.

Global warming means global air temperature increase, and as a result, the ground is getting warmer. In several energy systems, such as ground-coupled heat pump, the ground is used as a heat source or a heat sink or as a medium for thermal energy storage. Consequently, the efficiency of performance of such systems are affected by global warming.

Some works has been done that presented an "index" based on the effect of global warming on soil temperature variations, which is the definitive answer to all probable conditions, KHARSEH (2009) in 2009 described the behavior of the Syrian soil temperature and its variation with global warming.

The annual air temperature varies with time t according to Eq (1) (MASSOUD, 2005), assuming an average air temperature $T_a = 18.55^{\circ}\text{C}$, temperature amplitude $\Delta T = 17.05^{\circ}\text{C}$, during period $t_0 = 1$ year (Fig. 1)

$$T(t) = T_a + A_a \cos\left(2\pi \frac{t}{t_0}\right) \quad (1)$$

where:

A_a – amplitude of air temperature, $^{\circ}\text{C}$.

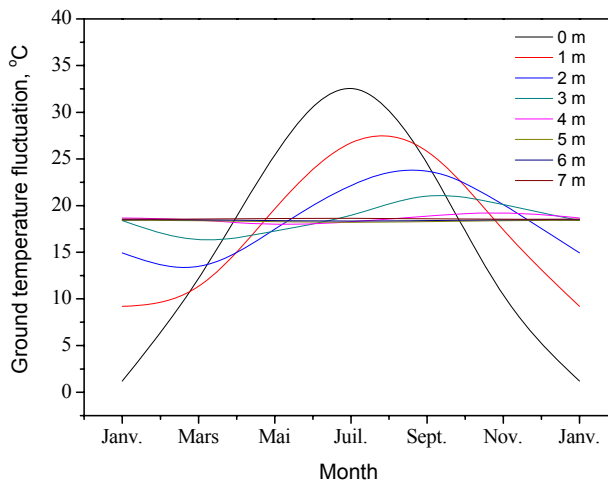


Fig. 1. Temperature fluctuation in Tlemcen at different depth

The ground temperature at depth h (m), thermal conductivity λ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and volumetric heat capacity C ($\text{J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$) varies sinusoidally, but with new amplitude and shifting time T according to Eq. (2) (MASSOUD, 2005) as shown in Fig. (1).

$$T(t, z) = T_a + A_a e^{-\frac{z}{d_0}} \cos\left(2\pi \frac{t}{t_0} - \frac{z}{d_0}\right) \quad (2)$$

where d_0 , the penetration depth, is given by:

$$d_0 = \sqrt{\frac{\lambda t_0}{C\pi}} \quad (3)$$

Generally, the ground temperature amplitude A_g decreases with depth as:

$$A_g = A_a e^{-\frac{z}{d_0}} \quad (4)$$

Comparison of equations (1) and (2) indicates that Earth's crust temperature amplitude is damped. The damped amplitude and shifting time depend on depth, thermal conductivity and volumetric heat capacity of the ground. The shifting time is given by:

$$\phi = t_2 - t_1 = \frac{h}{2} \sqrt{\frac{C t_0}{\lambda \pi}} \quad (5)$$

By knowing the thermal properties of the ground, the depth z_{op} , at which the temperature is the lowest when air temperature is the highest and *vice versa*, can be determined. The optimal depth z_{op} , is the depth, where the shifting time ϕ equal to $t_0/2$, i.e. where the maximum outside temperature is associated, with the minimum temperature at z_{op} . Eq. 5 gives:

$$\phi = \frac{t_0}{2} = \frac{z_{op}}{2} \sqrt{\frac{C t_0}{\lambda \pi}} \Rightarrow z_{op} = \pi \sqrt{\frac{\lambda t_0}{C \pi}} = \pi d_0 \quad (6)$$

After substitution in Eq. 4, the ground temperature amplitude at z_{op} becomes:

$$A_g = A_a e^{-\pi} \Rightarrow \frac{A_g}{A_a} = 4.321\% \quad (7)$$

It follows from Eq. 7 that the temperature amplitude at optimal depth z_{op} is not a function of ground's thermal properties but depends on the temperature amplitude at ground surface. Fig. 2 shows the difference between air temperature (i.e. ground surface temperature) and ground temperature at optimal depth for annual cyclic change of ambient air temperature.

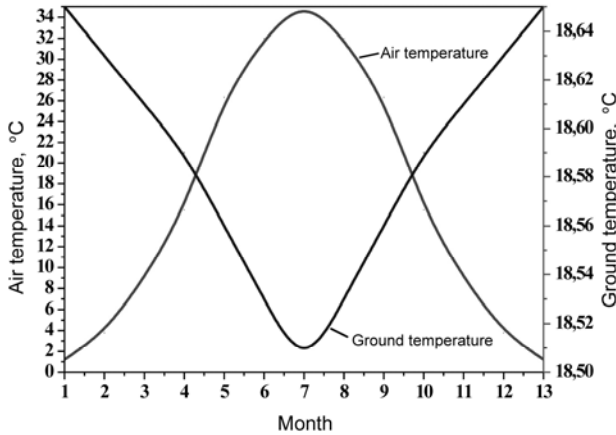


Fig. 2. Temperature fluctuations in air and ground, for $Z_{op} = 8.305$ m

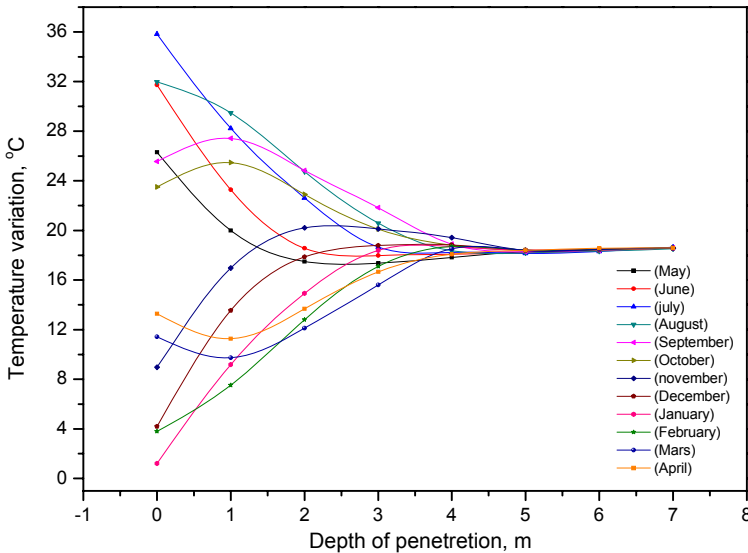


Fig. 3. Temperature field through Ground of Tlemcen without global warming (without considering geothermal gradient) (BOUKLI HACENE, CHABANE SARI, 2010)

Figure 3 shows temperature field through the ground over an entire year. It should be noticed that the ground temperature varies with time and decreases with depth until it “disappears” below approximately 8 m. i.e. the effect of air temperature oscillation at the surface is negligible below a certain ground depth. It should be mentioned, however, that ground temperature generally increases with depth due to the effect of geothermal heat flow.

Taking numerical calculation methods as a starting point and applying the results of KHARSEH and NORDELL (2009), we can calculate the ground temperature development over time due to global warming. However, the aim of current study is to derive an equation that expresses the ground temperature as a function of depth, thermal properties of the ground, geothermal heat flux, and increase of the local air temperature since the start of global warming in 1900.

NUMERICAL SOLUTION OF HEAT CONDUCTION EQUATION

In special cases where thermal properties can be considered constant over the temperature range of interest, in the absence of any internal heat generation, the heat conduction equation can be simplified to obtain the general heat conduction equation:

$$\nabla^2 T = \frac{1}{\alpha} \frac{\partial T}{\partial \tau} \quad (8)$$

Analytical solutions for heat conduction in a homogeneous infinite isotropic medium with a line heat source can be obtained starting from a particular solution of the general heat conduction equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{a} \frac{\partial T}{\partial t}, \quad (9)$$

in the case when the instantaneous point heat source is in the point (x', y', z') (Intergovernmental..., 2001).

The solution for such thermal line source, proposed by Ingersoll, gives the temperature as a function of time (t) at any penetration depth (z) (α in the thermal diffusivity of the soil).

Euler method was used to the numerical solution of this equation. We determine the ground temperature at depth h , and time τ after 1900 in two different region where λ and α are $2.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and $1.10^{-6} \text{ m}^2\cdot\text{S}^{-1}$, respectively. The average air temperature is set to 17.55°C . Global temperature was linearly changed since 1900 to 3 and 6°C . The result of this numerical solution is shown in Figures 4 and 5.

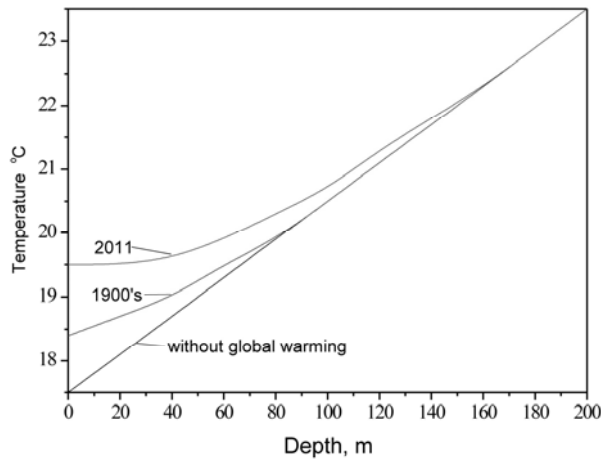


Fig. 4. Development of ground temperature in Tlemcen at different times since 1900 (if GW is 3°C)

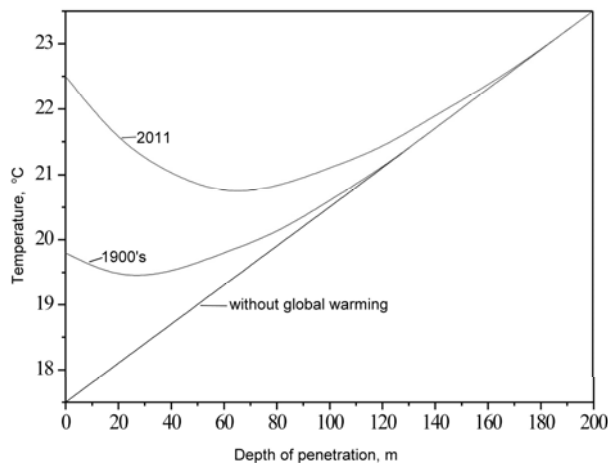


Fig. 5. Development of ground temperature in Tlemcen at different times since 1900 (if GW is 6°C)

GENERAL CONCEPT OF TEMPERATURE FIELD

To find out the primary concept of the equation that gives the ground temperature, Buckingham's π theorem (BUCKINGHAM, 1914; HANCHE-OLSEN, 2004) was applied as a general solution. The basic dimensional variables are given in Table 1. The number of variables used were $n = 7$.

These variables are expressible in terms of $k = 4$ independent fundamental physical quantities (length L , mass M , temperature K , and time S). Buckingham's theorem provides $j = n - k = 3$ independent non-dimensional numbers. It means

Table 1. Basic dimensional variables

∇T	geothermal gradient	$\nabla T = \{\Theta/L\}$
t	time	$\{t\} = \{S\}$
λ	thermal conductivity of ground, $W \cdot mK^{-1}$	$\{\lambda\} = \{ML/S^3\Theta\}$
ΔT	local global warming or air temperature increase, $^{\circ}C$	$\{\Delta T\} = \{\Theta\}$
ρc	volumetric ground heat capacity, $J \cdot m^{-3} \cdot K^{-1}$	$\{\rho c\} = \{M/L\Theta S^2\}$
h	depth below ground surface, m	$\{h\} = \{L\}$
T	ground temperature, $^{\circ}C$	$\{T\} = \{\Theta\}$

that the original expression is equivalent to an equation involving dimensionless variables (π_1, π_2, π_3) constructed from the original variables.

From Table 1 it is obvious that there are four primary dimensions involved: M, L, K and S (BOUKLI HACENE and CHABANE SARI, 2010). Therefore, we can select any set of four dimensional parameters that include all the primary dimensions involved in this problem as explained above. In this case, $\lambda, \Delta T, t$ and h were selected. Dimensionless π groups are set up by combining selected parameters, combined with the remaining parameters ($T, \rho c$) as follows:

$$\pi_1 = \lambda^a \Delta T^b t h^d T \tag{10}$$

$$\pi_2 = \lambda^a \Delta T^b t h^d \rho c \tag{11}$$

$$\pi_3 = \lambda^a \Delta T^b t h^d \nabla T \tag{12}$$

In this group $a, b, c,$ and d exponents are needed to non-dimensionalize the group, which is determined as:

$$(ML/S^3\Theta)^a \theta^b S^c L^d \theta \equiv M^0 L^0 S^0 \theta^0 \tag{13}$$

Similarly, π_2 and π_3 groups can be expressed as:

$$(ML/S^3\Theta)^a \theta^b S^c L^d (M/L\Theta S^2) \equiv M^0 L^0 S^0 \theta^0 \tag{14}$$

$$(ML/S^3\Theta)^a \theta^b S^c L^d \theta / L \equiv M^0 L^0 S^0 \theta^0 \tag{15}$$

Therefore, by finding the constants $a, b, c,$ and d, π_1, π_2 and π_3 can be rewritten as:

$$\pi_1 = \frac{T}{\Delta T} \tag{16}$$

$$\pi^2 = \frac{h^2 \rho c}{\lambda t} = \frac{h^2}{\alpha t} \quad (17)$$

$$\pi_3 = \frac{\nabla T h}{\Delta T} \quad (18)$$

The functional relationship between π_1 , π_2 and π_3 can be written as:

$$\pi_1 = f(\pi_2, \pi_3) = \frac{T}{\Delta T} = f\left(\frac{\lambda t}{h^2 \rho c}, \frac{\nabla T h}{\Delta T}\right) \quad (19)$$

The second π_2 term represents a dimensionless number known as Inverted Fourier Number ($1/F_0$), while the third π_3 in this study will be referred to as Kh .

$$\frac{h^2}{\alpha t} = \frac{1}{F_0} \quad (20)$$

$$\frac{\nabla T h}{\Delta T} = Kh \quad (21)$$

The ground temperature at depth h after time τ from the start of global warming is given as a function of Fourier number and Kh as:

$$T(h, t) = \Delta T f\left(\frac{1}{F_0}, Kh\right) \quad (22)$$

Our goal of determining $f(1/F_0, Kh)$ to express the ground temperature in terms of $T = \Delta T f(1/F_0, Kh)$, is now reduced to finding $f(1/F_0, Kh)$. A numerical solution of heat conduction equation was used to determine the ground temperature at different depths and times since 1880.

RESULTS AND DISCUSSION

Empirically this function i.e. $f(1/F_0, Kh)$ was found (BOUKLI HACENA, CHABANE SARI, 2010), which gives the best correlation with numerical solution of equation 4.

$$f\left(\frac{1}{F_0}, Kh\right) = T_a - \Delta T + \nabla T h + \Delta T \left(\frac{\nabla T h}{\Delta T} + 1\right) \left(1 - \Delta T^{-0.028}\right) \frac{h}{2\sqrt{\alpha t}} \quad (23)$$

As a result, the ground temperature as a function of depth and time was found to be:

$$T(h, t) = T_a - \Delta T + \nabla T h = \Delta T \left(\frac{\nabla T h}{\Delta T} + 1\right) \left(1 - \Delta T^{-0.028}\right) \frac{h}{2\sqrt{\alpha t}} \quad (24)$$

- $T(h, t)$ – temperature through Earth’s crust as a function of depth and time, °C;
- T_a – current average air temperature, °C;
- h – depth, m;
- ΔT – local global warming, °C;
- α – thermal diffusivity, $m^2 \cdot s^{-1}$;
- t – time, s;
- ∇T – temperature gradient ($^{\circ}C \cdot m^{-1}$), that depends on geothermal heat flux and thermal conductivity of Earth’s crust by the use of next equation:
 $\nabla T = q/\lambda$.

The numerical and analytical solutions are compared in Figures 6 and 7 in which the results are exemplified for the following assumptions: mean air temperature $T_a = 17.55^{\circ}C$, local “global” warming was $\Delta T = 3$ and $6^{\circ}C$, respectively, time = 111 years (in seconds), geothermal heat flow $q = 0.038 \text{ W} \cdot m^{-2}$, thermal conductivity $\lambda = 2.2 \text{ W} \cdot m^{-1} \cdot K^{-1}$, and the diffusivity $\alpha = 1.10 \cdot 10^{-6} m^2 \cdot s^{-1}$.

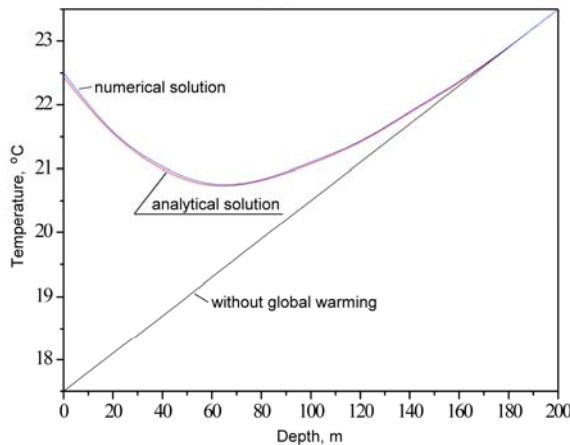


Fig. 6. Comparison of numerical and analytical solutions (ground temperature if GW is 6°C)

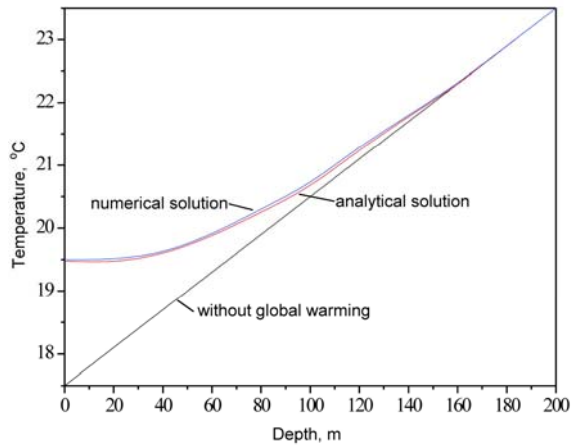


Fig. 7. Comparison of numerical and analytical solutions (ground temperature if GW is 3°C)

CONCLUSIONS

We have applied the derived equation to explain how the ground temperature increases due to the global warming in the case of Tlemcen (North Africa). This function showed excellent agreement when compared with numerical solutions. The equation could be applicable in all situations where the ground temperature is of concern and more generally to understand the effect of global warming.

The study of Kharseh who performed the same work in the Syrian soil can be validated with our results because, even if the soil is not the same and temperatures are different, the resulting figures have the same look.

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STRESZCZENIE

Ocena wpływów globalnego ocieplenia na temperaturę gleby – przykład Tlemcen (Północna Afryka)

Słowa kluczowe: *cieplne właściwości gleby, globalne ocieplenie, głębokość, temperatura gleby*

Średnia temperatura Ziemi jako całości nie jest stała i zmienia się w czasie, czego dowodzą analizy warstw geologicznych. Dwadzieścia tysięcy lat temu, w apogeum epoki lodowcowej, nasza planeta była chłodniejsza o 10°C. Zmiany zachodzą jednak powoli, a temperatura między rokiem 1000 a końcem XIX w. wahała się nie więcej niż o 0,2°C (ESSLINGER, 2009). Obecnie, międzynarodowa społeczność zaniepokojona jest faktem, że zjawisko to nabiera przyspieszenia i osiąga szybkość niespotykaną w przeszłości. Od końca XIX w. średnia temperatura globu wzrosła o 0,6°C. Ponadto, komputerowe symulacje sugerują, że ocieplenie może przyspieszyć, a średnia temperatura może wzrosnąć o 1,4 do 5,8°C do końca bieżącego stulecia. To zjawisko nazwano globalnym ociepleniem.

W przedstawionych badaniach wpływ globalnego ocieplenia na temperaturę gleby w Tlemcen (północ Afryki) oceniono na podstawie analizy przestrzennej i czasowej zmienności temperatury gleby. Celem badań było sformułowanie wzoru, który ujmowałby temperaturę gleby jako funkcję głębokości, czasu i cieplnych właściwości gruntu w obszarze, dla którego znane jest lokalne ocieplenie. Aby osiągnąć ten cel użyto numerycznego rozwiązania ogólnego równania przewodnictwa cieplnego i specjalnego programu. Całka otrzymanej funkcji może służyć do oznaczenia akumulacji ciepła w glebie jako efektu globalnego ocieplenia.