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Calculation of Thermal Energy Accumulation from the Behaviour of the Temperature Field in the Near-surface Layers of the Earth's Crust

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1. Introduction

We focused on geomechanics/geophysics and modelling the mechanical behaviour of the Earth's crust (lithospheric plates). The main theme was the investigation of exogenous factors in crustal phenomena. Exogenous factors include e.g. tidal forces, cyclic changes in crustal temperature caused by the Sun, repeated changes in atmospheric air pressure, wave energy transfer from water bodies (seas and oceans) into the crust, etc. This paper (extended abstract of presentation) will show conclusions from models that address the effect of surface temperature changes on the behaviour of the Earth's crust. One of the outputs was a calculation of the temperature field over a time interval of two years.

We then created a similar model focusing only on temperature. It is a recursive algorithm to calculate changes in the temperature field in the Earth's crust based on the surface temperature. The results of both models showing the heat penetration into the deep crust are consistent with the measurements. Based on this recursive algorithm, we estimated the amount of thermal energy stored in the Earth's crust. In this way, the time it takes for half of the stored energy to be released back into the atmosphere can be determined. The most likely value for this parameter $t_{1/2}$ is 270 years, which means that the amount of energy in the entire Earth's crust is now at its maximum. This is due to anomalously high solar activity. The future cumulative solar energy in the Earth's crust is estimated based on estimates of the evolution of solar activity. The results show a small increase in accumulated energy up to 2060 and then a smaller or larger decrease in accumulated energy and hence a decrease in global surface temperature.

2. Model from surface temperature

The most complicated and challenging problem was creating the *"surface temperature model"*. This model will be used as the basis for the future continuation of work on the creation of the above-mentioned geomechanical model. Up to now, the influence of surface temperature changes on stress-deformation states inside the Earth's crust has been considered insignificant in geophysics. The finite element method (FEM) was used for this purpose; the model was created using MSC.MARC/MENTAT software (planar stress, the Earth's crust resting on an elastic foundation). The *"surface temperature model"* is divided into 24 sections. Each section corresponds with one type of material defined via material parameters (the influence of non-homogeneities). Surface temperatures were inserted into the model as limit conditions for a period of two years of real values, measured at meteorological stations. The dissertation also includes statistical calculations for the creation of stochastic models for the process of movement and stress on the surface of the Earth's crust. The model demonstrated that small temperature changes on the surface and at shallow depths below the surface (up to approx. 30 m) influence the variability of stress at depths of over 10 km [1,2].

An acceptable simplification for the calculations can be achieved by replacing the Earth's crust by an infinite hollow cylinder (see Fig. 1), the so-called 'Earthcylinder', and defining the heating or cooling of the Earth's outer surface as a time-varying heat function T=f(φ,t), where φ is the angle /deg/ and t is time /s/ [1].

The Earth's crust is composed of lithospheric plates and is mainly made up of rocks and minerals, where various faults, fractures and other geological formations occur. In addition to rocks and minerals, there are also gases and water. It is, therefore, an inherently highly anisotropic, heterogeneous and inhomogeneous material.

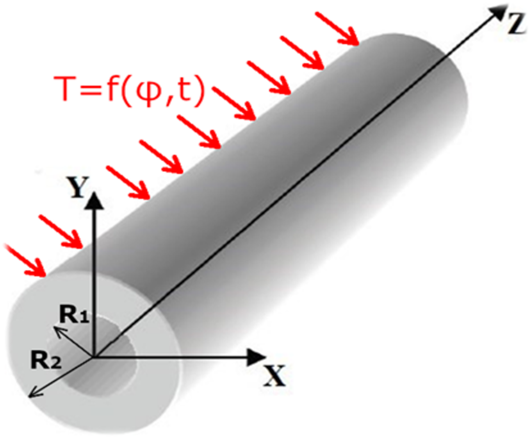

Fig. 1. *Model of the Earth as an infinite hollow cylinder, the so-called 'Earthcylinder' with heating from the Sun (not to scale).*

The model of the Earth's crust is divided into 24 sections with different material properties; it is a piecewise isotropic homogeneous material model, which appears to be anisotropic from the outside. On the surface of each material section, there are temperature functions $T_1, T_2 \ldots, T_{24} = f(\varphi, t)$, which correspond to time-varying temperature values over a two-year period, see Fig. 2 (overleaf) and [2].

For the FEM calculation, the problem is treated as a planar problem with an assumed plane strain. In Fig. 2, the crustal thickness is highly enlarged (for clarity), and the planar model is shown as being divided into 24 sections, with assigned material properties and loading indicated from the temperature. The angular perimeter is divided by 15 degrees, with a different material in each of the 15 degrees.

2.1 Boundary conditions

The temperature boundary condition $T = f(\varphi, t)$ (i.e. $T_1, T_2 \ldots, T_{24} = f(\varphi, t)$, see Figs. 2-4), depends on time t and the angular dimension of the Earth and acts on the outer surface of the crust. This boundary condition simulates the cyclic temperature changes based on the daily cycle of the Earth's rotation and the annual cycle of the planet's orbit around the Sun. An example of T_2 dependence loading for 2 years and 5 days is shown in Fig. 3.

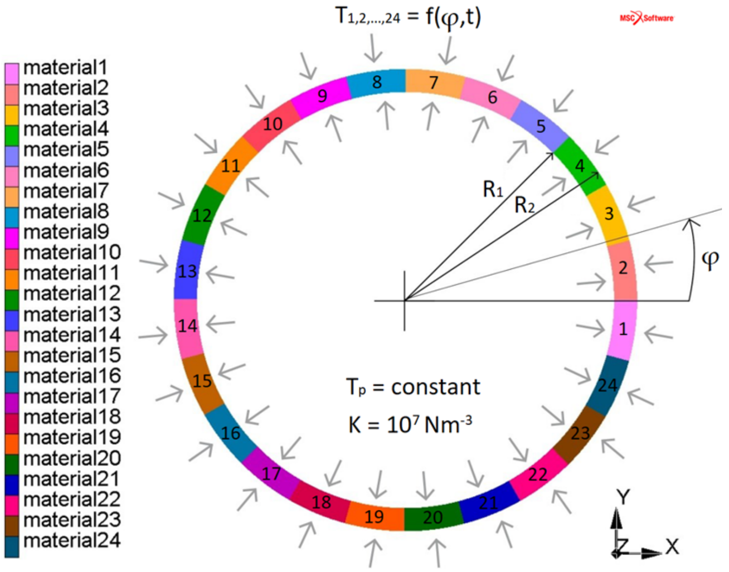

Fig. 2. 'Earthcylinder' with materials and temperature loads (not to scale)

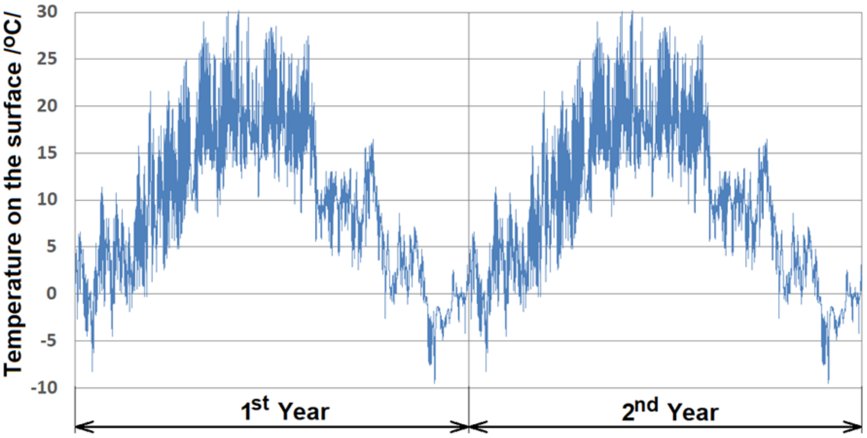

Fig.3. Temperature T2 distribution (a) Boundary condition – for whole 2 years at node 1

The data were then processed for importing into the MSC. Marc Mentat software [42]. The resulting time-dependent temperature series contained 35424 values. For each subsequent section, the time series is shifted by another hour. The different temperature boundary conditions in each section represent a virtual rotation of the model, i.e. the change in temperature simulates the rotation of the Earth around the Sun.

2.2 Results from FEA

Fig. 4 shows that small temperature changes (selected standard deviation) on the surface (depth h=0 m) and at shallow depths under the surface (up to approx. 30 m – approx. annual penetration)

Fig. 5 shows the depth evolution of the equivalent stress σ_{HMH} at the interface of sections 1 and 2 (i.e. $\varphi = 0°$, see Fig. 2). From Fig. 5, the stress attenuation towards depth is evident, as was the case for the other sections. The trend of decreasing σ_{HMH} towards the Earth's interior can also be partly explained by the all-round pressure stress states that characterize matter deep underground or in water.

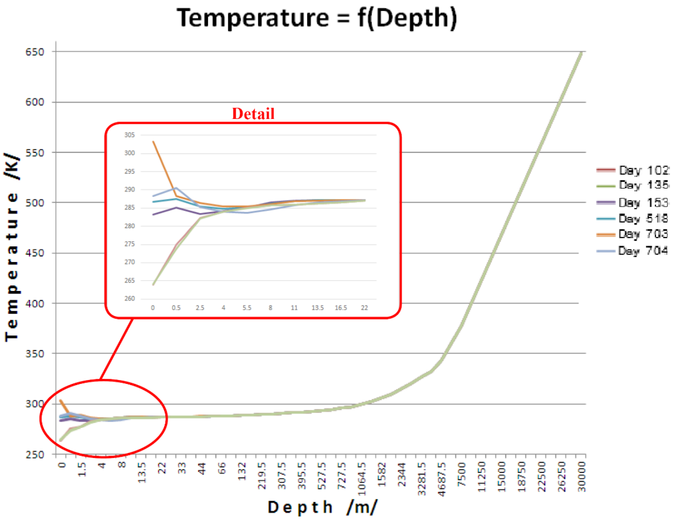

Fig. 4. *Temperature trends in the depth profile at the interface of sections 1 and 2 (φ = 0°) over two years*

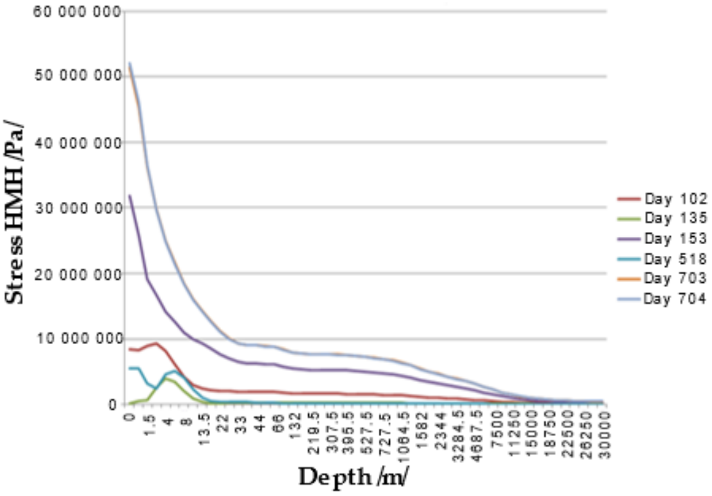

Fig. 5. Plot of depth evolution of the equivalent van mises stress (HMH)/Pa/ at the interface of sections 1 and 2.

Figs. 5 and 6 show that stress fluctuations of the order of 1 MPa occur at a depth of 10 km, even though the thermal wave reached a depth of only 22 m.

3. Model of heat accumulation in the Earth's crust

We developed recursive procedure, which allows estimation of the part of solar energy accumulated in the Earth´s crust and estimation of the half-time of the heat radiation/accumulation parameter. This kind of parameter can show time during which one half of the accumulated energy is released back to space. The theoretical relationships were verified by the long-term paedology measurements.

Let us have a material cube of infinitesimal small dimensions at the depth h below the surface (half-space), which is thermally bonded with the surrounding material (see Fig. 6).

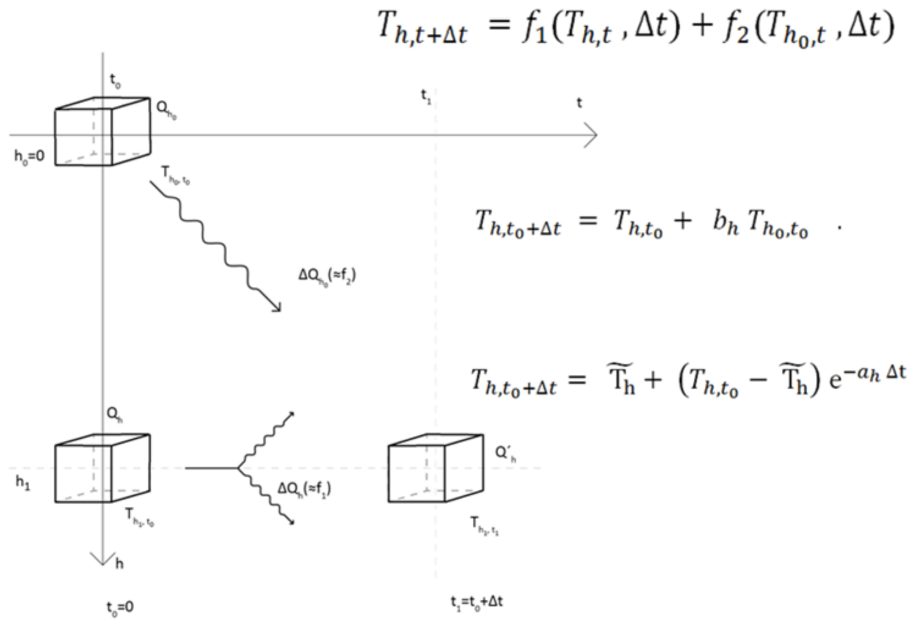

Fig. 6. Scheme of the penetration of heat from the surface to the depth and its radiation from the cube in the depth h

To derive the relationship, we performed a superposition of Newton's law of body cooling and the Fourier-Kirchhoff heat conduction equation. Then we verified the correctness of the relation on measured data (see Fig.7).

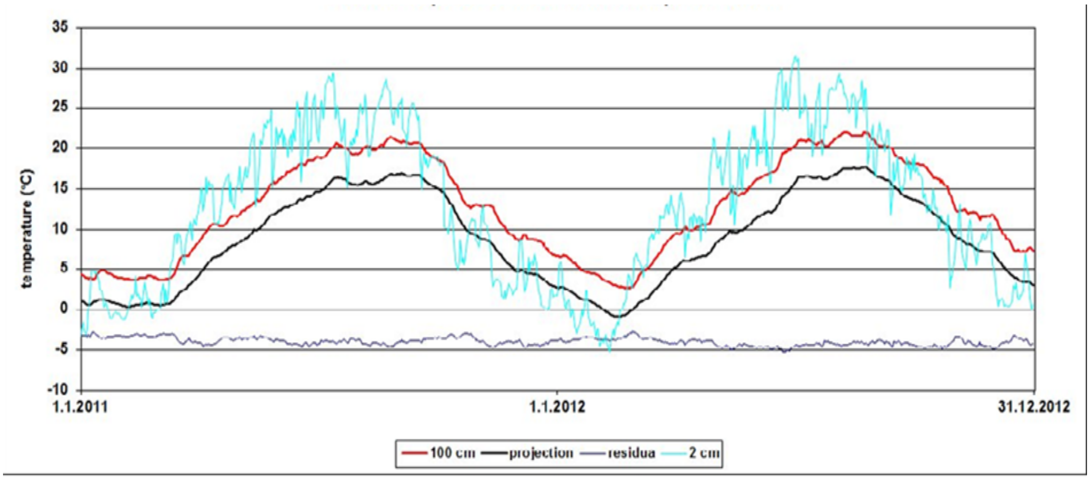

Fig. ***7.*** *Comparison of the temperature development in the depth of 2 cm (turquoise) and 100 cm (red) and recalculated temperatures from the depth of 2 cm to the depth of 100 cm (black). Residuals between measured and recalculated temperatures at a depth of 100 cm are blue.*

Fig. 7 illustrates the recalculated temperature from the depth of 2 cm to the depth of 100 cm using a recursive relation /16/ and the least squares method for the residues of two parameters a_h and b_h

It can be seen that although the temperature at the depth of 2 cm has a phase shift from the temperature measured at the depth of 100 cm (correlation r = 0.88), after conversion it exhibits a high correlation (r = 0.997) where both curves only shifted by the absolute value of 3.75 ° C, which is probably due to a local geothermal gradient or a paleoclimate development. All recalculated temperatures from the depth of 2 cm to the depths of 10 cm up to 100 cm show a high degree of correlation with the correlation coefficient greater than 0.995 with the measured temperatures at these depths.

For the conversion of energy from the Earth's surface to the depth h, it is necessary to know two parameters: a_h and b_h. For the analysis of the correlation between the radiated heat from the depth h to the surface and surface temperatures, it is not necessary to know the parameter b_h, since it only moves the absolute level of temperature at the depth h compared to the surface of the constant value. Therefore, the correlation coefficient is not dependent on it. We therefore used coefficient $b_h = 1$. On the other hand, the coefficient a_h has a real physical meaning and shows how quickly the heat accumulates in the Earth's crust, and/or how quickly it is radiated back to the surface.

3.1 Results of analyses

We calculated for different coefficients a_h the correlation coefficient between the two time series: 1) Of the reconstructed surface temperature by Mann et al. (2008) and 2) volume of the heat release from the depth h to the surface (OLR) according to the relationship shown in Fig. 6. Fig. 8 shows the correlation coefficient between the reconstructed global temperature and the heat released from the Earth's crust.

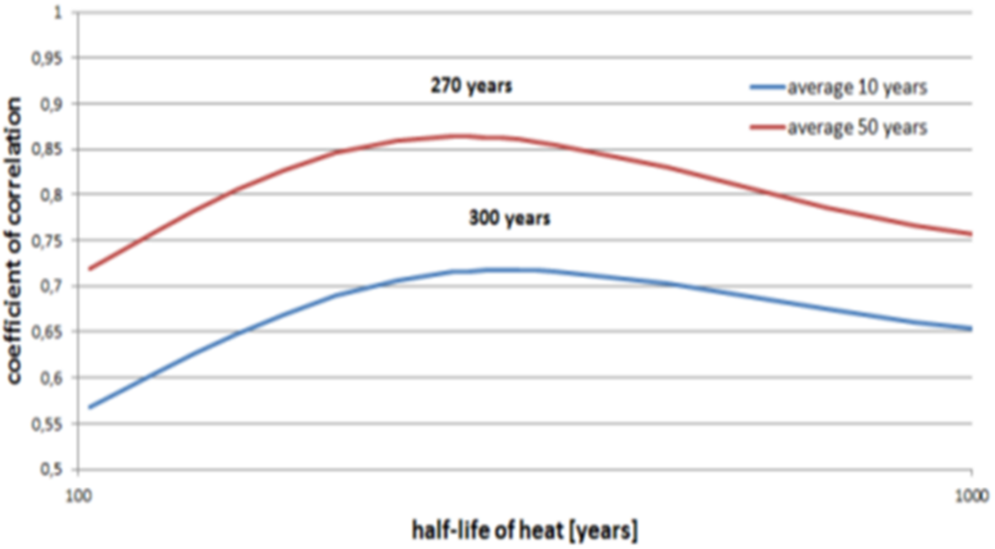

Fig. 8. Correlation coefficient between reconstructed global temperature CRU_composite (Mann et al., 2008) and released heat from the crust for various half-life of heat as a parameter.

It is evident that the correlation coefficient between the smoothed temperatures within the window of 50 years is higher than for the temperature smoothed within a 10-year window, and reaches the maximum r = 0.86, indicating a statistical dependence between the two rows at a significance level of 15 %. The higher correlation coefficient for the longer window shows that the values of the proxy-Wolf numbers in increments of 10 years are physically smoothed, and that the samples did not allow obtaining a higher accuracy either in amplitude or time. Therefore, the smoother curve of the reconstructed temperatures in the 50-year window corresponds better with the primarily smoothed curve of the proxy-Wolf numbers. The resulting curve of heat stored in the continental crust (in relative units) for the maximum correlation coefficient (i.e. the half-time of the heat radiation/accumulation parameter is 270 years) together with the reconstructed temperature curve, is shown in Fig. 9.

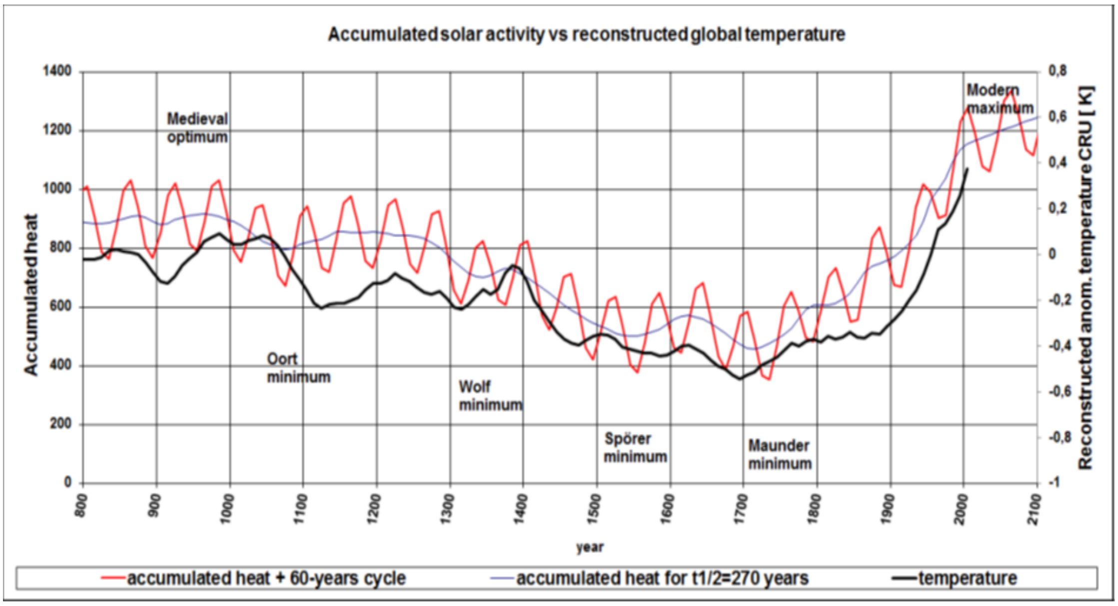

Fig. 9. Comparison between accumulated heat from solar activity and reconstructed global temperature in 50-year time window (according to Mann et al., 2008).

4. Conclusion

The model from surface temperatures showed stress fluctuations on the order of 1 MPa occurring at a depth of 10 km, although the thermal wave reached a depth of only 22 m.

Accumulation of the heat in the Earth´s crust integrates and therefore delays outgoing long wave radiation behind the solar activity. The half-life of the heat coefficient is approx. 270 years.

If we admit that part of the incident energy from the Sun accumulates in the rocks of the continental crust, we can estimate, based on the solar activity and a climatological parameter containing heat or temperature, what the material parameters of these rocks are. The greatest correlation coefficient between the number of the proxy-Wolf numbers [4] and global temperature anomalies in the window of 50 years in the increments of 10 years [5] has been detected for the "half-life of heat" parameter is 270 years. For this parameter, the correlation coefficient between the proxy-Wolf numbers and reconstructed temperature reached r = 0.86, which is a sign of the fact that there is a link between them.

All of solar cycles are close to their maxima. The sudden drop of solar activity can be supposed. Next, the drop of global temperatures can be expected.

The analysis of the development of the heat stored in the continental crust shows that the currently existing climate changes are caused by nature origin, not mankind [6].

The question is What we understand under „**climate changes**". According to our results, it is proportional to the OLR ~ **accumulated heat** in the Earth´s crust.

Guest-Editor: Stein Storlie Bergsmark

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