Subsurface Temperature Variations Due to Exponential Air Temperature Model

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Abstract: ***Climate change is expected to increase air temperature and thus to disturb surface energy balance in a complex way. In this study we made an attempt to develop the shallow subsurface thermal model that enables or captures an exponential behaviour of land atmosphere interaction in subsurface thermal evolution. The model uses the one-dimensional heat advection-diffusion equation driven by vertical fluid flow and convective heat flux on the surface. The model solves the equation for given initial and boundary conditions using the finite element method for porous subsurface. The model allows the quantitative analysis of the subsurface thermal structure and evolution for variations of the parameters involved in the model in climate change scenario. This envisages their effect and significance on subsurface thermal environment.***

Keywords: exponential model of air temperature, subsurface temperature, fluid flow, Robin type boundary condition, heat transfer coefficient.

1. Introduction

Energy interaction between the land and atmosphere will propagate into the subsurface and leaves their signatures in subsurface rocks in shallow subsurface. These thermal signatures in subsurface rocks in long time scales are referred as due to climate change and will develop thermal profiles in subsurface. In earth science studies, understanding the influence of climate change on subsurface thermal regime is an important problem.The thermal regimes of shallow subsurface are controlled by the energy flux at the surface and water flux into the subsurface. Shallow subsurface temperatures constitute both heat conduction in porous matrix and advection due to the movement of fluid in the earth's subsurface.

In earlier times the study of subsurface temperatures were based on heat transport by conduction and are influenced by the surface temperatures and heat flow coming from the interior of the earth (Gold and Lachenbruch, 1973). Paleoclimates are inferred by inverting the borehole temperature profiles using analytical solution for transient conduction equation (Mareschal and Beltrami, 1992; Beltrami *et al.*, 1995; Bodri and Cermak, 2007; Lesperance *et al.*, 2010). Bullard (1939) showed groundwater flow also changes subsurface thermal distribution. Then Suzuki (1960) obtained solution to show how upward and downward flow of ground water movement disturb subsurface temperature profiles using transient advection-conduction equation and to infer ground water velocity from temperature profiles (Stallman 1963).

Shallow subsurface temperature profiles are perturbed due to variations in surface temperatures due to changes in land cover or climate, ground water flow (precipitation) and land thermal characteristics thus makes it difficult to distinguish the cause of subsurface thermal anomalies(Ferguson and Woodbury, 2005; Ferguson *et al.*, 2006). Taniguchi et al. (1999) studied the subsurface temperatures for linear increase in surface temperature with ground water flow by modifying the analytical solution given by Carslaw and Jaeger (1959).

Regional and global air temperatures are significantly influenced by the climate changes and in tern it changes the subsurface temperatures. Recent studies have used either Surface Air Temperature (SAT) or Surface Soil Temperature (SST) as boundary condition on earth's surface and with constant vertical ground water movement to get subsurface thermal profiles for climate forcing. However this approach does not consider the potential use of heat flux due to changes in SAT for climate forcing established by combined effect of SAT and SST with heat transfer coefficient. Kumar *et al.*(2012) obtained analytical solution for transient advection-diffusion problem by incorporating robin type boundary condition that enables to prescribe surface air temperature on the surface boundary using Laplace transform technique. Recent warming of climate will describes air temperature as an exponential function with time.

Kurylyk and MacQuarrie (2014)have shown air temperature variation as an exponential function of time using observed data and considered as a boundary condition for obtaining numerical solution for transient advection diffusion problem and verified with analytical results.In this study, numerical solutions for one dimensional advection-diffusion problem with different boundary and initial conditions have established and analysed for land atmosphere processes.

This study is to know the subsurface thermal structure in terms of warming or cooling for future climate change. Robin type boundary condition which relates atmospheric temperatures with land surface temperatures using simple heat transfer coefficient is used instead of taking first type boundary condition for obtaining subsurface temperatures for surface climate forcing.

2. Methodology

The subsurface is the continuum of the solid matrix and the fluid content present in the pore space.Transient one-dimensional advection-diffusion equation is used to calculate temperature profiles for subsurface porous media and is given by

$$\left(\rho C_p\right)_{eff}\frac{\partial T}{\partial t}=K_{eff}\frac{\partial^2 T}{\partial Z^2}-\left(\rho C_p\right)_f\, q\frac{\partial T}{\partial Z}+A(Z,t) \quad (1)$$

Effective volumetric heat capacity and thermal conductivity of the continuum with fluid and solid matrix is given by:

$$\left(\rho C_p\right)_{eff}=\left(\phi\left(\rho C_p\right)_f+(1-\phi)\left(\rho C_p\right)_s\right)$$

$$K_{eff}=\left(\phi(K)_f+(1-\phi)(K)_s\right)$$

Where '$\rho\, C_p$' is the volumetric heat capacity ($M \cdot L^{-1} \cdot t^{-2} \cdot T^{-1}$), '$K$' isthe thermal conductivity of the medium($M \cdot L \cdot t^{-3} \cdot T^{-1}$), 't' is time (t), 'q' is vertical fluid flow ($L.t^{-1}$), 'ϕ' is the porosity of the subsurface, dependent variable 'T' is the temperature (T), 'Z' is the space variable (L) (depth positive downward) and 'A' is the heat source/sink which is neglected in this study. The subscripts 'f', 's' and 'eff' represents the fluids, solid matrix and effective in the above equations.

We calculate the transient numerical solutions to the equation.1 assuming the subsurface as a homogeneous mixture of porous solid matrix and fluid, a time varying surface heat flux on the surface and a constant temperature 'T_b' at the bottom boundary. A linear increase in temperature 'T_0' with constant thermal gradient 'a' represents an initial condition for the subsurface. The ground surface heat flux is used to represent the temporal evolution of the coupling between the air temperature and the ground surface temperature and is given by

Initial Condition

$$T(Z,t)=T_0+aZ \quad at\ \ time\ t=0 \quad \text{——(2)}$$

Boundary Conditions

$$K_{eff}\frac{dT}{dZ}=H\left(T(0,t)-f(t)\right) \quad at\ Z=0 \quad \text{——(3)}$$

$$\text{Where } f(t)=T_0+b*\exp(ct)$$

$$T(Z,t)=T_b \qquad at\ Z=L \qquad \text{——(4)}$$

Where 'b' and 'c' are constants and 'T_b' is the temperature at the bottom boundary,'H' is the heat transfer coefficient, which couples the land and the atmospheric temperatures.

Finite element method is used to calculate subsurface thermal profiles for the above given problem numerically using COMSOL Multiphysics software. It solves the partial differential equation for given set of boundary and initial conditions by discretizing the domain into predefined mesh elements and solves the problem at each element using basis functions. It verifies the solution with iterative techniqueto meet convergence with user bound tolerance.

3. Results and Discussions

Temperature- depth profiles were calculated using equation (1) with initial and boundary conditions. The thermal properties of the porous media are assumed from Ravi *et al.* (2016). The values assumed for thermal conductivity of porous matrix, water, porosity of the subsurface, volumetric heat capacity of the medium and water were 2.5 $W.m^{-1}.^0C^{-1}$,0.56 $W.m^{-1}.^0C^{-1}$, 0.3, $2.7*10^6$ $J.m^{-3}.^0C^{-1}$ and $4.18*10^6$ $J.m^{-3}.^0C^{-1}$ respectively. This giveeffective thermal diffusivity of porous subsurface of $6.1*10^{-7}m^2.s^{-1}$. For initial condition, a geothermal gradient of $0.022^0C.m^{-1}$ is assumed with initial surface temperature of 15^0C which is an average present global surface temperature. The values of constants 'b' and 'c' are 1.16^0C and 0.016 yr^{-1}(Kurylyk and MacQuarrie (2014)).

The fluid flow permits an advective heat transport in porous subsurface solid matrix, a constant fluid flow of $\pm$ 0.5$m.yr^{-1}$ is considered to calculate subsurface temperature profiles. It is observed that for fluid flow of 0.03 m. yr^{-1} (Gunawardhana and Kazama, 2011; Bodri and Cermak, 2007) subsurface temperature profiles mimic for pure conduction. The temperature profiles calculated by solving the advection-diffusion equation with given boundary conditions and given set of parameters shows that, for positive value of fluid flow (figure 1a) surface thermal energy will perturbs downward into the subsurface. The numerical results show increase in surface temperature with time.

For pure conduction (figure 1b) subsurface temperatures comes to join with initial condition after some depth with respect to time. The numerical values for temperature - depth profiles are computed for negative values of fluid flow (figure 1c) the temperatures follow a diffusive trend from the surface into the subsurface. Temperature profiles are parallel to the initial condition for discharge scenario. It exacerbates temperature profiles from deeper part towards surface. It represents an upward flow of heat from the bottom boundary.

Temperature depth profiles over time are best represented in contour plots. Figure 2 shows the temperature contours for reduced temperatures (T(z,t)-T(z,0)) to know the effective propagation of temperatures in subsurface for different fluid flow velocities in time and space. It shows for downward fluid flow the reduced temperatures are propagated more

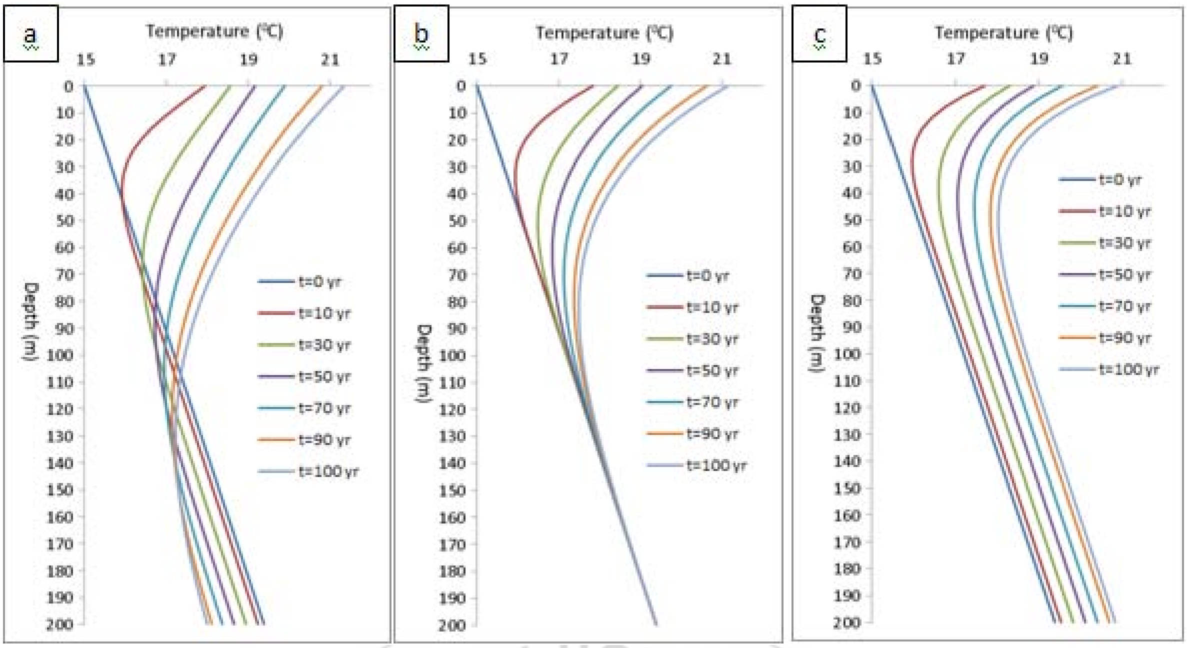

Figure 1: Temperature - depth profiles calculated for (a). Recharge (b). No flow and (c). Discharge for different times.

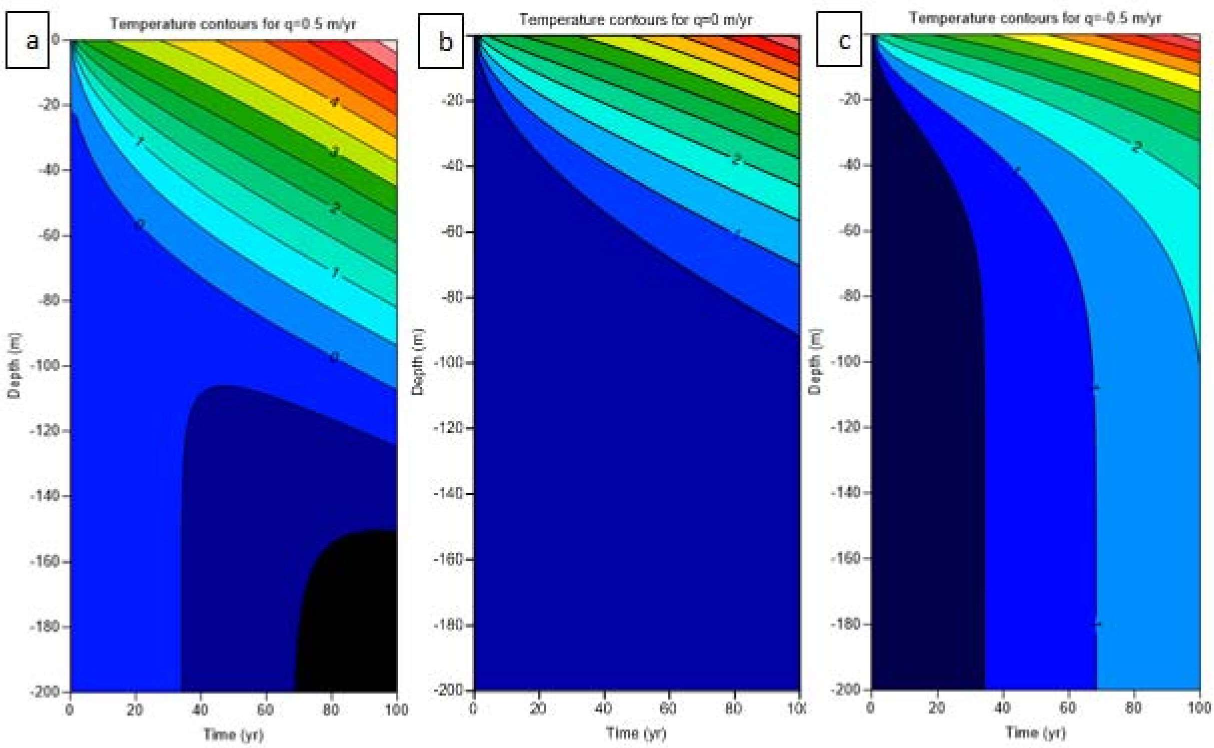

Figure2. Reduced temperature contours for (a) q = 0.5 m/yr, (b) q = 0 m/yr and (c) q= -0.5 m/yr with contour interval of 0.5^0C.

depth when compared to no flow condition while subsurface warming from the deeper portion is observed form the calculated thermal contours.

To see the effect of heat transfer coefficient 'H' on the subsurface features, the numerical values of temperature structure has been calculated for different values of H. The temperature - depth profiles are shown in Figure 3 for H = 0.1, 0.2, and 0.5 at time t = 100 yr in the absence of fluid flow. The results reveal that the surface temperature increases with increase in the heat transfer coefficient. It represents the strength of the coupling between the land surface temperatures and surface air temperatures. Their combined effect on the surface ceases at a depth of approximately 100 m in this case. Figure 4 show the temperature depth profiles for different values of fluid flow velocities to see their effect on subsurface temperatures. It is clear that as the value of ‘q’ increases, subsurface temperatures propagation increases and are more elongated with respect to depth.

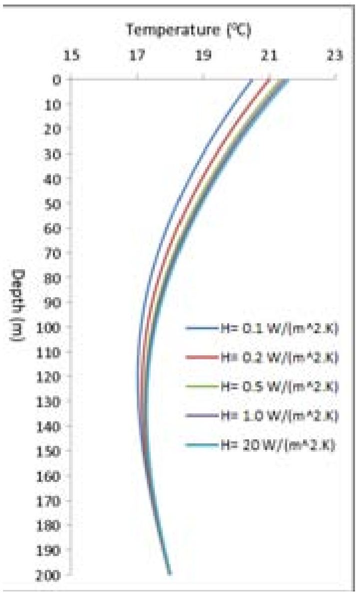

Figure3. Temperature - depth profile for different values of 'H' at time t = 100 yr.

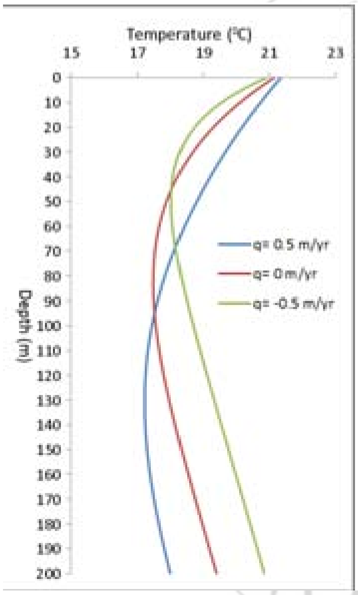

Figure 4: Temperature - depth profiles for different fluid flow velocities at t=100 yr.

4. Conclusions

Numerical solution to the one-dimensional advection diffusion equation with exponential increase of air temperature with time in robin type boundary condition is obtained to know the subsurface thermal environment for surface climate change. The results shows that heat transport in subsurface depends on the direction of the fluid flow and the magnitude of heat transfer coefficient. For downward flow, surface heat propagates into the subsurface for greater depths while for upward flow,as subsurface is warming from deeper geothermal zones it's effect can be seen for shallow depth from the surface. Magnitude of heat transfer coefficient significantly accelerates the surface warming and for higher values(greater than 0.5 W/(m^2K)), the variations in the temperature profile are not significant for this problem. The results are important in understanding the effect of coupled air and land surface temperatures with mass movement (fluid flow) on the subsurface temperatures.

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