Understanding heat transport processes in shallow subground resulting from external and internal impacts

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To my mother,

for teaching me to never give up on my dreams, even though she herself gave up her nursing degree to take care of me. For being with me every day, even from a distance.

To my father,

for teaching me that one can only learn to do things by doing them. For all the stones he broke, all the shoes he shined, and all the cars he washed to make it possible for me to get where I am today.

To my forever boyfriend,

for having supported me in all my dreams. For having picked me up every time I fell down and for making me believe in myself the many times I doubted.

Abstract

Heat conduction in the subsurface environment is the result of internal and external impacts and is governed by different forces in the short and long term. Externally, this phenomenon is related to daily temperature variations, terrestrial, oceanic, and atmospheric tides, and vegetation activity. However, beyond depths of up to 30 meters, thermal conduction is not applied. The transpiration of the vegetation plays a key role in this dynamic by being the connection point between the soil and the atmosphere. The main objectives of this thesis are (1) to identify the variation of groundwater microtemperature at daily and seasonal level, (2) to compare the variation of groundwater microtemperature with different meteorological parameters, (3) with terrestrial tides, (4) with vegetation activities, and (5) to analytically compare the groundwater microtemperature variation with land use changes in the studied area. Daily and annual variations in groundwater microtemperature were compared to variations in meteorological parameters and electrical potential of plants. A decrease of 2 mK was observed in daily subsurface temperature when the surface temperature exceeded 9 ºC. This diurnal temperature variation occurs during the phenological growing season of the vegetation. The same pattern was also observed during summer. However, this relationship does not always occur. At high temperatures (+30 °C) the decrease amounts to just 1 mK. This fact is related to the change in transpiration of plants, decreased or even suspended at high surface temperatures. With an increase in surface temperature an increase in tree electrical potential can be observed. This increase in electrical potential is concomitant with a change in groundwater temperature of approximately 2 mK. A frequency analysis of all data showed a daily frequency of high magnitude in all parameters. The lag time between changes in electric potential and subsurface microtemperature changes amounts to 17 hours, a result of the electrical potential difference between the northern and the southern exposure of the stem (N – S), and 5 hours, the result of the change in electrical potential difference between the southern and the northern stem exposure side (S – N). A comparison between potential changes and the computed change in gravity resulting from earth tidal effects showed that the correlation between the subsurface temperature variation with up to 2 mK and the change in surface temperature variation does not match directly. Atmospheric tides can be correlated with the changes in north and south electric potentials. Annually, a linear decrease of 0.0407 K/year was estimated, and model calculation applying a linear decrease in surface temperature of 2 K as a boundary condition was simulated. Comparing the results with the trend it is realistic to assume that when an apparent thermal diffusivity of 1.8*10-6 m2/s is applied an event starting between 10 and 20 years ago is responsible for the detected decrease in temperature. However, with this thermal diffusivity the conductive annual temperature variation reaches an amplitude of 1.1 mK instead of the measured 5.4 mK at 40 m, showing that the vegetation causes additional convective heat transport triggered by the annual surface temperature.

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Statement of contributions

The presented cumulative dissertation comprises two manuscripts, and the contributions from the author of this thesis are listed below following the standardized contributor role taxonomy (CRediT):

Chapter 3: Pinheiro, M., Buntebarth, G., Polle, A. & Sauter, M. 2021. “Short- and long-term variations in groundwater temperature caused by changes in vegetation cover”. In: International Journal of Terrestrial Heat Flow and Applied Geothermics, 4: 127-34. DOI: https://doi.org/10.31214/ijthfa.v4i1.66

Contributions: Formal analysis, investigation, visualization, writing – original draft.

Chapter 4: Pinheiro, M., Buntebarth, G. & Sauter, M. 2023. “Diurnal variations in vegetation activity affecting shallow groundwater flow identified by microthermal measurements”. In: International Journal of Terrestrial Heat Flow and Applied Geothermics, 6: 1-10. DOI: https://doi.org/10.31214/ijthfa.v6i1.94

Contributions: Formal analysis, investigation, methodology, visualization, writing – original draft.

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1. Introduction

1.1 Motivation

The penetration of temperature variations at the Earth's surface has become significant in the context of discussions on climate warming Čermák and Bodri (1997), and since the beginning of this debate, more attention has been paid to temperature changes at the Earth's surface, their penetration into the subsurface, and their consequences for the environment (Čermák et al. 2000; Hamza and Vieira 2011; Majorowicz, Safanda, and Skinner 2002; Shen et al. 1995).

Heat conduction in the subsurface environment is the result of internal and external impacts, and is governed by different forces, in the short and long term. As internal impacts we can consider time-dependent events such as tectonic activities, seismic effects, and volcanic activity. They are beyond the scope of this work and will not be considered. Externally, this phenomenon is related to daily temperature variations (Buntebarth et al. 1997; Buntebarth 2002; Čermák 1971; Good, Noone, and Bowen 2015; Muncke 1827; Sun et al. 2011; Tautz 1971), to terrestrial, oceanic and atmospheric tides (Harrison 2012; Lanzerotti and Gregori 1986; Meloni, Lanzerotti, and Gregori 1983) and to the activity of vegetation (Beltrami and Kellman 2003; Buntebarth, Pinheiro, and Sauter 2019; Chahine 1992; dos Santos et al. 2017; Feddes et al. 2001; Good, Noone, and Bowen 2015; Griffiths, Madritch, and Swanson 2009; Guiot, Corona, and Escarsel 2010; Kumar, Shankar, and Jat 2014; Kaspar, Zimmermann, and Polte-Rudolf 2015; Korner 2016; McElrone et al. 2013; Pinheiro et al. 2021; Pinheiro, Buntebarth, and Sauter 2023; Prasad 1988; Schlesinger and Jasechko 2014; Sun et al. 2011; Taiz et al. 2015; Zeppel et al. 2008).

The combination of these variables with the geological irregularities at the subground (Bense et al. 2013; Domenico and Palciauskas 1973; Drury, Jessop, and Lewis 1984; Freeze and Cherry 1979; Hamza 1997; Kordilla et al. 2012; Prensky 1992) acts to interfere with heat conduction in the subsurface environment in the short term and is observed daily and seasonally. In the long term, heat conduction in the subsurface medium can vary with land use. The same can be observed with a gradual change, such as the reforestation of an area.

In addition to having great potential to contribute to a more significant fraction of the world's energy needs (Rosen and Fayegh 2017), geothermal measurement has also been applied as a method for assessments of subsurface features in different areas, such as hydrology, paleontology, hydrogeology, earthquake predictions, and climate change (Buntebarth 1997; Čermák and Bodri 2018, 1997; Čermák 1971; Demetrescu and Shimamura 1997; Domenico and Palciauskas 1973; Drury, Jessop, and Lewis 1984; Hamza and Vieira 2011; Hamza 1997; Middleton 1999; Pimentel and Hamza 2013; Prensky 1992). Effects previously considered to be noise, could be studied after the development of high precision equipment in the microKelvin range. The quartz sensors used are very stable in time and do not exceed the resolution in one year.

This dissertation addresses the heat transport process in shallow groundwater influenced by external impacts caused by the transfer of diurnal and seasonal temperature waves at the surface by vegetation activities. It is understood that freshwater movement occurs by heat conduction, from seasonal rainfall regimes to daily variation in plant transpiration (Beltrami and Kellman 2003; Chahine 1992; Griffiths, Madritch, and Swanson 2009; Zeppel et al. 2008). It is a fact that the hydrological cycle is profoundly affected by changes in vegetation cover, causing floods and droughts worldwide (Chahine 1992; dos Santos et al. 2017; Good, Noone, and Bowen 2015; Kumar, Shankar, and Jat 2014; Schlesinger and Jasechko 2014; Sun et al. 2011; Taiz et al. 2015). Moreover, variations at the surface can further affect the dynamics of aquifer recharge, determined, among other effects, by water infiltration into the soil and water percolation through the unsaturated zone (Bense et al. 2013; Kordilla et al. 2012).

The role of vegetation in the water cycle is evident when we see that during the process of photosynthesis, plants retain less than 5% of the water absorbed (McElrone et al. 2013). Water for land evapotranspiration is supplied primarily by the soil, and plant transpiration accounts for 60-80% of evapotranspiration on land, making this component of the water balance equation the most important link between hydrological and biological processes in most ecosystem models (Chahine 1992; Good, Noone, and Bowen 2015; Kumar, Shankar, and Jat 2014; Schlesinger and Jasechko 2014).

1.2 Objectives

The result of this dissertation attempts to explain the influence of vegetation activities on the heat transport process in shallow groundwater influenced by external impacts caused by diurnal and seasonal transfer of surface temperature waves. The main objectives of this thesis are:

- To identify the variation of groundwater microtemperature at daily and seasonal level.
- To compare the variation of groundwater microtemperature with different meteorological parameters.
- Compare the variation of groundwater microtemperature variation with terrestrial tides.
- Compare the variation of groundwater microtemperature with vegetation activities.
- To analytically compare the groundwater microtemperature variation with land use changes in the studied area.

1.3 Format of the thesis

Chapter 2 encompasses the theories of the different scientific communities to address heat conduction and its effects on the hydrogeological cycle. It briefly details the internal and external factors that influence heat conduction into the subground.

To facilitate understanding the **Figure 1.1** shows, in summary form, the internal and external factors that influence heat conduction.

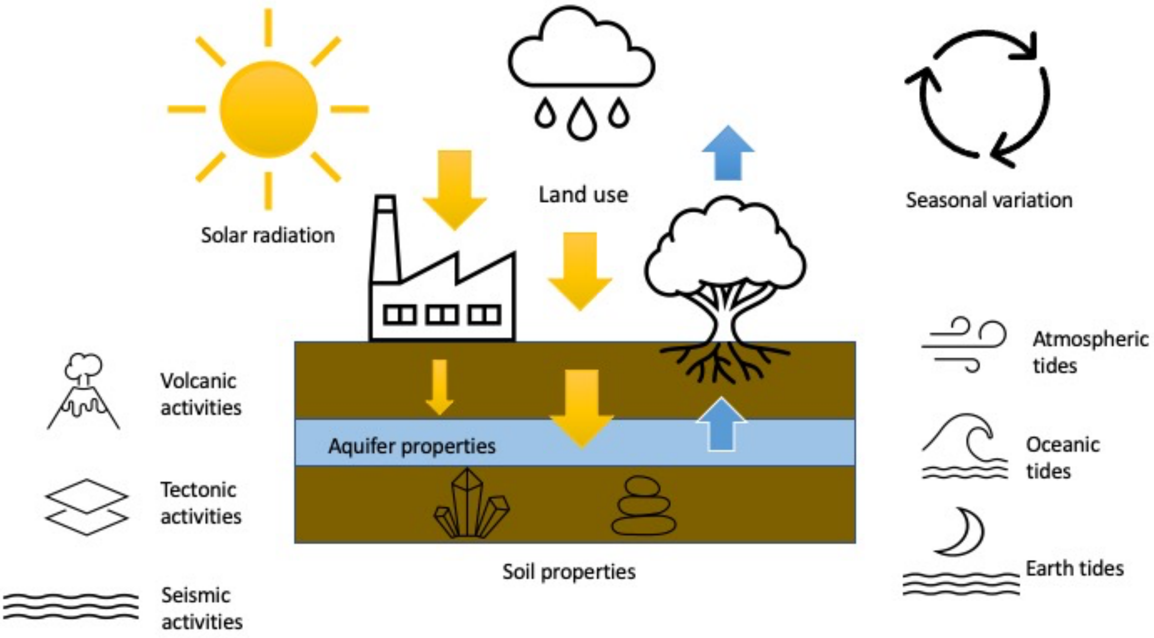

Figure 1.1 External and internal impacts that influence heat transport processes in shallow subsurface

Chapters 3 and 4 encompass the two papers in this cumulative dissertation:

In **Chapter 3** we demonstrate how vegetation cover can be responsible for groundwater temperature variation, as well as how this temperature variation can be related to past events.

In **Chapter 4** we compare groundwater temperature variations with the electrical potential of plants and other meteorological parameters. In addition, we see the relation of atmospheric tides to plants, which is not observed in groundwater.

In both articles we show the relationship with terrestrial tides, which does occur but is not frequent. In summary, in the two chapters we show that there is a direct relationship between the variation in subterranean temperature and the variation in water absorption by plants. We have shown that this relationship leads to similarities with other meteorological parameters and even with the terrestrial and atmospheric tides, but that it is the vegetation that controls this micro-variation. Finally, **Chapter 5** brings a summarized conclusion of the work and suggestions for future studies.

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2. External impacts affecting heat transport processes into the shallow subground

This chapter presents a general introduction to the topic of the dissertation. **Section 2.1** briefly presents the external impacts that influence the heat transport processes in the subsurface: 2.1.1 Solar radiation, 2.1.2 Vegetation, and 2.1.3 Earth, oceanic and atmospheric tides.

Following this, **Section 2.2** presents the Geological characteristics of the area.

Finally, **Section 2.3** introduces the basic concepts of heat conduction processes: 2.3.1 Heat conduction equation and 2.3.2 Temperature measurement methodologies and the analytical heat conduction model.

2.1 External impacts

Externally, heat transfer processes are related to daily temperature variations (Buntebarth et al. 1997; Buntebarth 2002; Čermák 1971; Good, Noone, and Bowen 2015; Muncke 1827; Sun et al. 2011; Tautz 1971), to terrestrial, oceanic and atmospheric tides (Harrison 2012; Lanzerotti and Gregori 1986; Meloni, Lanzerotti, and Gregori 1983) and to the activity of vegetation (Beltrami and Kellman 2003; Buntebarth, Pinheiro, and Sauter 2019; Chahine 1992; dos Santos et al. 2017; Feddes et al. 2001; Good, Noone, and Bowen 2015; Griffiths, Madritch, and Swanson 2009; Guiot, Corona, and Escarsel 2010; Kaspar, Zimmermann, and Polte-Rudolf 2015; Korner 2016; Kumar, Shankar, and Jat 2014; McElrone et al. 2013; Pinheiro et al. 2021; Pinheiro, Buntebarth, and Sauter 2023; Prasad 1988; Schlesinger and Jasechko 2014; Sun et al. 2011; Taiz et al. 2015; Zeppel et al. 2008).

2.1.1 Solar radiation

When we talk globally, the movement of fresh water occurs by heat conduction, from seasonal rainfall regimes to the daily variation of plant transpiration. 94% of the water on our planet resides in the oceans and seas, with a salinity higher than is acceptable for human consumption. Adding this amount to the glaciers, approximately 2% of fresh water remains on the earth's surface. Of this amount, almost 70% resides in the subsurface (Freeze and Cherry 1979). The cycling of water is important to understand its availability. The water that evaporates from the ocean is precipitated there. Only 10% passes to the continent (Gimeno et al. 2012). The earth's surface temperature is clearly affected by solar radiation. Although the percentage of water vapor in the atmosphere is tiny (ca. 0.25%), its importance in climate regulation is indisputable (Held and S. 2000; Trenberth et al. 2003).

The distribution of solar radiative energy flow between the surface and the atmosphere is controlled by the albedo of the Earth's surface. It affects many processes, such as surface temperature and hydrology. The albedo varies with the surface coverage. On the one hand, bright surfaces, such as deserts and snow, have a higher albedo, reflecting most of the incoming solar radiation. On the other hand, darker regions have a lower albedo, meaning that the absorption of solar radiation is greater (Doughty, Loarie, and Field 2012; Wang et al. 2006a). This absorption increases the temperature of the ground.

While most studies conclude that albedo dominates surface energy budgets during land use change (Berbet and Costa 2003), some others demonstrate that while increasing vegetation cover warms the surface, reforestation of a region results in net cooling (Bright et al. 2017; Juang et al. 2007; Kaufmann et al. 2003a). The albedo in vegetated areas will change seasonally and according to both vegetation type and location within the globe. This is because changes in vegetation cover modify not only albedo, but also other variables important for driving climate, such as canopy height and rooting profile, which will affect surface roughness and evapotranspiration rates (Doughty, Loarie, and Field 2012). Trees are rougher surfaces than crops or pastures, and have very deep roots, which allows them to access water reserves deep in the soil and act as better channels for water vapor to the atmosphere (Doughty, Loarie, and Field 2012).

In areas with dense vegetation, a small amount of solar radiation reaches the ground. Compared to the surface temperature variation, these areas will show a low temperature fluctuation in the soil (Bodri and Čermák 2011). The elaborate branched structure of trees greatly increases the interception of sunlight. In addition, the canopy leaves have varied morphology and physiology that help improve light uptake. The result is that very little photosynthetic photon flux density (PPFD) penetrates to the bottom of the canopy; almost all PPFD is absorbed by the leaves before reaching the forest floor. The anatomy of the leaf is highly specialized for light absorption. The outermost cell layer, the epidermis, is typically transparent to visible light, and individual cells are often convex. The convex epidermal cells can act as lenses and focus light so that the amount that reaches some chloroplasts can be many times greater than the amount of ambient light. On average, about 340W of radiant energy from the sun reaches every square meter of the earth's surface. When this sunlight reaches the vegetation, only 5% of the energy is finally converted into carbohydrates by photosynthesis. The ratio of this percentage is so low that a large percentage of the light is of a wavelength too short or too long to be absorbed by the photosynthetic pigments (Taiz et al. 2015).

Vegetation influences the local and global energy balances that are important for climate. It occurs due to both the transpiration process and the vegetation cover. Due to their sensitive reaction to changes in the environment, plants have long been used to reconstruct the climate. Differences such as seasons, precipitation rates, extremely dry and cold periods can be observed in their stem rings.

The process of photosynthesis depends on various physiological and environmental cues to occur. The amount of water transpired by the plant is extremely high, compared to the amount of carbon dioxide assimilated by photosynthesis (Nepstad et al. 1994). For every molecule of CO2 that enters, about 400 molecules of water leave. Considering that plants have enough water and nutrients, the total amount of light received during the growth period will account for the crop's productivity (McElrone et al. 2013; Taiz et al. 2015).

2.1.2 Vegetation

The hydrological cycle is highly affected by changes in vegetation cover. One of the important driving forces in this cycle is transpiration by plants. This process returns approximately 50% of precipitation to the atmosphere, and accounts for more than 60% of the evapotranspiration rate. Vegetation is thus exposed to and governed by different meteorological parameters as well as the availability of water in the soil and subsoil (Burr 1947; Chahine 1992; dos Santos et al. 2017; Good, Noone, and Bowen 2015; Kumar, Shankar, and Jat 2014; Schlesinger and Jasechko 2014; Sun et al. 2011; Taiz et al. 2015; Volkov and Ranatunga 2006). This process can easily explain that woody plants interfere with the groundwater recharge process by altering water infiltration rates, evapotranspiration, interception, as well as changes caused by afforestation or deforestation (Acharya et al. 2018; Antunes et al. 2018; Bense et al. 2013; Kordilla et al. 2012; Le Maitre, Scott, and Colvin 1999). These studies, however, have not addressed the relationship between changes in groundwater microtemperature and plant activity during the growing season (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021; Pinheiro, Buntebarth, and Sauter 2023).

Electrical potentials in plants have been studied for some time and their history was summarized in a review by (Schuch and Wanke 1969). Some studies have shown that despite the periodic daily variation of the electric potential in plants (Ansari and Bowling 1972; Burr 1947; Gibert et al. 2006; Koppan, Szarka, and Wesztergom 2000), there is no direct link with xylem flow (Gibert et al. 2006; Likulunga et al. 2022; Love, Zhang, and Mershin 2008). Other factors are also responsible for triggering these electrical impulses, such as temperature variations, pollination, and variation in water availability (Fromm and Lautner 2007). These factors result in variation in the water content of plants (Likulunga et al. 2022). Soil water taken up by roots contains ions and is therefore electrically conductive. This electrolyte is raised and moves to the top of a tree, creating an electric current that can be determined as an electric potential in the tree trunk (Ansari and Bowling 1972; Volkov and Ranatunga 2006).

The periodic variation in plant electrical potential observed during our study period has been evidenced in other studies (Burr 1947; Gibert et al. 2006; Hao, Li, and Hao 2021; Likulunga et al. 2022). There are periodic daily and annual variations. Studies show that the amplitude of the change in electric potential is greater during spring/summer periods compared to fall/winter periods (Burr 1947; Gibert et al. 2006; Hao, Li, and Hao 2021), consistent with the results presented here and in our previous studies (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021; Pinheiro, Buntebarth, and Sauter 2023).

2.1.3 Earth, oceanic and atmospheric tides

Solar radiation directly influences atmospheric electricity. Therefore, the effect of atmospheric electricity varies, and with it everything that is affected by it. Daily and seasonal variations, depending on the region of the globe, govern climates and biomes. The electrostatic field strength near the earth's surface is about 110-220 V/m and depends on daily weather conditions (Volkov and Ranatunga 2006). Atmospheric electricity has been studied for a long time (Elster and Geitel 1899c, 1899a, 1899b) and exhibits seasonal variation (Harrison 2012). While land and ocean tides are gravitationally controlled, atmospheric tides are mainly thermally controlled (Lanzerotti and Gregori 1986; Meloni, Lanzerotti, and Gregori 1983).

Both, groundwater flow (Acworth and Brain 2008; Allègre et al. 2016; Doan and Brodsky 2006; Hsieh, Bredehoeft, and Rojstaczer 1988; Merritt 1999; Roeloffs 1988; Toll and Rasmussen 2007; Wang et al. 2018a) and plant activity (Burr 1947; Fisahn 2018; Holzknecht and Zürcher 2006a; Zürcher et al. 1998; Zürcher 2006; Zürcher and Schlaepfer 2014; Zürcher 2019) are affected by earth tides. In some studies, the effect of tides must be removed from groundwater monitoring results to be able to better interpret hydrogeologic tests (Toll and Rasmussen 2007). In other studies, hydrogeological parameters can be derived from potential changes induced by land tides (Allègre et al. 2016; Hsieh, Bredehoeft, and Rojstaczer 1988; McMillan et al. 2019; Wang et al. 2018b). In plants, even in the absence of light, some studies relate tree stem growth to lunar phases (Zürcher et al. 1998; Holzknecht and Zürcher 2006a), others report the variation in leaf movement (Fisahn 2018). There are also reports of a change in germination speed with a change in earth tidal forces (Zürcher and Schlaepfer 2014).

Recently, findings demonstrated the relationship between earth tide induced volume strain and changes in microtemperature (Jahr, Buntebarth, and Sauter 2020). The authors related the change in microtemperature to the sub-vertical shift of the groundwater column, +/- parallel to the geothermal gradient, induced by fracture closure or dilation, depending on the magnitude of gravity forces. The effect of groundwater abstraction by vegetation particularly pronounced during growth phases of trees and shrubs, surrounding the monitoring borehole is highlighted as well. Roots of trees exhibit a negative pressure difference compared to the matric potential of the soil at shallow depths, inducing water flow by the root system. Similarly, with shallow groundwater tables, the abstraction of groundwater by trees can be described by the radial flow equation, based on Darcy‘s law, with the flow rate being determined by the hydraulic potential gradient and the hydraulic conductivity of the soil and/or fractured rock system.

2.2 Geological characteristics of the area

The geological characteristics of the area have been described in our previous work (Buntebarth, Pinheiro, and Sauter 2019) and replicated here:

The city of Göttingen is located in the Leinetal graben, part the West European rift zones. The base of the Leinetal valley is formed by folded Variscan units overlain by a discordant Permian Zechstein, the Triassic (Buntsandstein, Muschelkalk and Keuper), and finally Jurassic formation (Lias) (Wunderlich 1959). Its structural geological formation is highly complex due to polyphase tectonic development under various tension forces and pronounced tectonics in the layers. These processes, also termed as “Saxonian folding”, produced a number of folds, faults and fractures.

In this area, a five-spot groundwater well arrangement is surrounded by high scrubland and approx. 20 m high maple and birch trees, which grow at a distance between 15 and 25 m to the boreholes. The five wells of the arrangement, one of which was drilled in 2008, and the other four, including the used North and East well, drilled in 2012 reach to a depth of 78 m and has diameter of 6’’. They are equally configured with alternating permeable and impermeable screens. The permeable screens consist of 3m slotted PE pipe sections that are filled up with filter gravel overlapping 1m. The impermeable screens consist of fully cased PE pipes filled up with high density clay. This configuration achieves hydraulic connection to separated, individual geological strata. The surface construction consists of concrete rings with hydraulic top covers providing room for experimental equipment and easy access to the wells (Oberdorfer et al. 2013).

The Northern well encountered in the upper 12 m of the profile a mixture of limestone, claystone, quartz and feldspars. From 14 m until the bottom, follow predominantly different shades of claystone mixed, in some layers, with siltstones and sandstones in different proportions. Special attention is given at depth of 64 to 68 meters, where there is a layer of gray-colored mudstone, a number of mineralized fractures and is loosely layered, followed by a beige fine sand breccia, possibly indicating mechanical weathering. The matrix of this breccia consists of gray clayey siltstone with fine dark gray mudstone fragments (Werner 2013).

The Eastern well, also used in this study, consists in the initial 14 m of gray limestone, variegated mudstones, quartz, feldspars and calcite mineralization. From 14-24 m, a red-gray partly micaceous silty fine sandstone is present. It contains many calcite mineralizations. From 24 m until the bottom, follow predominantly different mix of siltstones and mudstones in different proportions and colors (Werner 2013).

Other studies in the same area have shown that the complexity of the geology of the region is observed in different hydrogeological tests performed. The connections between wells show to be very heterogeneous, with different zones of higher thermal conductivity (Baetzel 2017; Piecha 2008; Werner 2013).

2.3 Heat transport processes

Subsurface temperature is subject of interest and has been investigated for several years (Buntebarth 2002). There were many attempts to link the history of the earth with subsurface temperature. Buffon tried to simulate the thermal evolution of the earth, even before the theory of heat (Muncke 1827), after he deduced that planets were part of the sun. Kupffer compiled a map of earth temperatures (isogeotherms) and air temperatures and determined that the two quantities do not generally coincide (Buntebarth 2012; Chiasson 2006).

2.3.1 Heat conduction equation

Fourier's work on the theory of heat formed the presently accepted foundation of thermal studies and threw new light on the thermal conditions of the earth's interior.

He considered a cylinder bounded by two flat surface dF perpendicular to the cylinder axis and separated by the distance dn. The cylinder encloses the volume dV. Inside this cylinder, there was considered a homogeneous isotropic heat source A, what generates within volume dV, in unit time dt the following quantity of heat d2q (Buntebarth 2012). Heat conduction equation (1) can be written in many ways, but the usual notation is:

$$\varrho.c.\frac{dT}{dt} = A + \frac{\partial}{\partial x}\left(K.\frac{\partial T}{\partial x}\right) \text{ (1)}$$

2.3.2 Temperature measurement methodologies and the analytical heat conduction model

With the advancement of technology, high precision and high resolution microtemperature measurements have become available, and what were once considered as inconsistent results are now well-defined signals studied and interpreted by different scientific communities (Briciu 2018; Buntebarth et al. 1997; Demetrescu and Shimamura 1997; Drury 1984; Hamza 1997; Jahr, Buntebarth, and Sauter 2020; Richter and Cruiziat 2002; Shimamura and Watanabe 1981; Shimamura et al. 1984). Geothermal measurements in environmental monitoring are known for their ease of installation, stable and long-term monitoring quality, and low interference with the respective environment. Seismic signals, past meteorological events, terrestrial and atmospheric tidal signals, as well as plant activity signals can be correlated with systematic changes in groundwater temperature (Bodri and Čermák 2011; Buntebarth et al. 1997; Buntebarth, Pinheiro, and Sauter 2019; Briciu 2018; Čermák 1971; Demetrescu and Shimamura 1997; Drury and Lewis 1983; Drury 1984; Hamza 1997; Jahr, Buntebarth, and Sauter 2020; Shimamura and Watanabe 1981; Shimamura et al. 1984).

The subsurface temperature variations can be spectrally decomposed into thermal disturbances of different periods, with varying amplitudes and phase relationships. For that reason, the thermal temperature profile can reveal information from past climate events. It occurs because, according to the theory of heat conduction, changes in surface temperature propagate downward as thermal waves or perturbations, with amplitudes decreasing exponentially with depth. Moreover, the rate of propagation of the thermal signal is governed mainly by thermal diffusivity, which is directly proportional to the thermal conductivity of the material. Due to this, temperature changes on the earth's surface propagate slowly downwards, as a consequence of the relatively low thermal diffusivity of rocks (Bodri and Čermák 2011; Carslaw and Jaeger 1992; Čermák 1971; Hamza and Vieira 2011; Harris and Chapman 1997; Majorowicz and Safanda 2005; Pollack and Huang 2000a; Smerdon et al. 2003; Tautz 1971).

Furthermore, the attenuation during propagation depends on the frequency of the waves. Waves with longer periods of time, such as a long-term temperature variation, will have less attenuation, propagating to larger depths compared to short-term temperature variations. Signs of regional climate change may be, however, overshadowed by changes in anthropogenic activity that affect land use or vegetation patterns. For that reason, other possible sources of temperature perturbations must be considered (Čermák and Bodri 2018; Demetrescu and Shimamura 1997; Middleton 1999; Pimentel and Hamza 2013; Prensky 1992).

The penetration of a thermal signal into the subsurface can be calculated in space and time by simple heat conduction models. For this purpose, the steady state background temperatures associated with deep heat flow should be separated. The remaining temperature profile after separation (residual temperature) contains the components of the original observations considered as transient. This transient component, when analyzed, produces a reconstruction of the climatic variations in the surface. By solving the equation of heat conduction with temperature steps as a boundary condition, it can be checked whether any event in the past may have resulted in a spontaneous change in temperature as it occurs after deforestation (Bodri and Čermák 2011; Carslaw and Jaeger 1992; Čermák 1971; Nitoiu and Beltrami 2005; Tautz 1971).

The solution of the heat conduction equation subject to the boundary condition at the surface with $T(z,0) = 0$ and $T(0, t) = \pm T0 \exp(i\omega t)$ is given by (Tautz 1971) in the dependence of the depth z and the elapsed time t after onset with:

$$T(z,t) = 0.5T_0 \exp(i\omega t)\left[\exp\left(z\sqrt{i\omega/\kappa}\right) erfc\left(\frac{z}{2\sqrt{\kappa t}} + \sqrt{i\omega t}\right) + \exp\left(-z\sqrt{i\omega/\kappa}\right) erfc\left(\frac{z}{2\sqrt{\kappa t}} - \sqrt{i\omega t}\right)\right] \quad (2)$$

where κ is the temperature diffusivity and ω is the circular frequency of the temperature wave. After a very long time, i.e., after many cycles, the initialization period changes to a steady-state condition that simplifies eq. (2) to:

$$T(z,t) = T_0 exp\left(-z\sqrt{\omega/2\kappa}\right) cos\left(\omega t - z\sqrt{\omega/2\kappa}\right) \quad (3)$$

Eq. (3) considers a maximum value at a given depth z when the cosine function has its maximum with unity. For an average temperature diffusivity of 10-6 m2/s of the subsurface and a temperature range of ±10 degrees, a variation of T of 10-3 °C is estimated at a depth of 1.5 m. The same variation is calculated at a depth of 29 m for an annual variation.

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3. Short- and long-term variations in groundwater temperature caused by changes in vegetation cover

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Abstract

Several comparative studies of the earth's surface provide evidence that vegetation and other bio-physical processes at the earth's surface can directly affect the atmospheric boundary layer, leading to changes in temperature and precipitation patterns. In this study, we demonstrate how vegetation cover can be responsible for the subsurface temperature variation as well as how this temperature variation can be related to past events. A linear decrease of 0.0407 K/year was estimated, and a decrease of 2 mK was observed in subsurface temperature when the surface temperature exceeded 9 ºC. This diurnal temperature variation occurs during the phenological growing season of the vegetation. The transient temperature shows an annual cycle at a depth of 40 m. Model calculation applying a linear decrease in surface temperature of 2 K as a boundary condition was simulated. Comparing the results with the trend it is realistic to assume that when an apparent thermal diffusivity of 1.8*10-6 m2/s is applied an event starting between 10 and 20 years ago is responsible for the detected decrease in temperature. However, with this thermal diffusivity the conductive annual temperature variation reaches an amplitude of 1.1 mK instead of the measured 5.4 mK at 40 m. In conclusion, beside the vegetation causing additional convective heat transport triggered by the annual surface temperature, the influence of reduced solar incoming heat radiation reaching the ground caused by the increased shadowing effect of vegetation cover might be responsible for a continuous decrease in local temperature of 2 K being active approximately 20 years after plantation.

3.1 Introduction

The consequence of temperature changes at the Earth’s surface as well as its penetration into the subsurface for the environment is of relevance today, especially with regard to the influence of the variation in vegetation cover. Understanding how it has changed through the years is important to predict future changes. The hydrological cycle is deeply affected by those changes, causing flood and drought around the world. One of the important forces in this cycle is transpiration. This process returns approximately 50% of precipitation to the atmosphere, and accounts for more than

60% of the evapotranspiration rate (Chahine 1992; dos Santos et al. 2017; Good, Noone, and Bowen 2015; Kumar, Shankar, and Jat 2014; Schlesinger and Jasechko 2014; Sun et al. 2011; Taiz et al. 2015).

The importance of transpiration for global climate as well as for crop growth is due to the fact that it links both hydrological and biological processes. The rate at which a crop transpires depends on several factors including atmospheric conditions, the shape and properties of the boundary between crop and atmosphere, root system distribution, soil hydraulic properties, and water availability. However, less than 5% of the water absorbed is retained by the plants (Chahine 1992; dos Santos et al. 2017; Feddes et al. 2001; Prasad 1988).

Several comparative studies of the earth's surface provide evidence that vegetation and other properties of the earth's surface can directly affect the atmospheric boundary layer, leading to changes in temperature and precipitation patterns (Beltrami and Kellman 2003; Griffiths, Madritch, and Swanson 2009; Zeppel et al. 2008; Chahine 1992). Such changes can also affect the dynamics of aquifer recharge, determined, among other effects, by water infiltration into the soil and percolation of water through the unsaturated zone (Bense et al. 2013; Kordilla et al. 2012). In this study, we demonstrate how vegetation cover can affect subsurface temperature variations as well as provide information in how far this temperature variation can be related to past events.

3.1.1. Solar radiation and the vegetation cover

The distribution of the solar radiative energy flux between the surface and the atmosphere is controlled by the albedo of the Earth’s surface. It affects many processes such as surface temperature and hydrological processes. Albedo varies with surface cover. On the one hand bright surfaces, such as deserts and snow, have a higher albedo, reflecting most of the incoming solar radiation. On the other hand, darker regions have a lower albedo, implying that the absorption of solar radiation is larger (Doughty, Loarie, and Field 2012; Wang et al. 2006b).

Even though a decrease in albedo results in an increase in ground temperature, reforestation will result in a net cooling. The reason is that the structure of trees as well as the anatomy of leaves are specialized to increase the sunlight absorption. As a consequence, almost all of the photosynthetic photon flux density (PPFD) is absorbed by leaves before reaching the forest floor and it won’t penetrate all the way to the bottom of the forest canopy. Moreover, compared to the variation in surface temperature, these areas will present a low temperature fluctuation in the soil (Berbet and Costa 2003; Bright et al. 2017; Juang et al. 2007; Kaufmann et al. 2003b; Bodri and Čermák 2011; Taiz et al. 2015).

In addition, vegetation influences local and global energy balances important for the climate. The albedo in vegetated areas will vary seasonally with vegetation type as well as with location. Reason being that changes in vegetation cover modify not only albedo but also other important climate- driving variables, such as canopy height and rooting profile, which will affect surface roughness and evapotranspiration rates. Furthermore, crop productivity is directly related to the total amount of light received during the growing season, when it is considered that plants have both enough water and nutrients (McElrone et al. 2013; Taiz et al. 2015; Doughty, Loarie, and Field 2012; Nepstad et al. 1994).

3.1.2. Earth tides and transpiration rates

Recently, findings by (Jahr, Buntebarth, and Sauter 2020) demonstrated the relationship between earth tide induced volume strain and changes in microtemperature. The authors related the change in microtemperature to the sub-vertical shift of the groundwater column, +/- parallel to the geothermal gradient, induced by fracture closure or dilation, depending on the magnitude of gravity forces. The effect of groundwater abstraction by vegetation particularly pronounced during growth phases of trees and shrubs, surrounding the monitoring borehole is highlighted as well.

In temperate climates, vegetation can be considered as a strong sink for soil water during the growing period, while only little water is consumed during the period of dormancy (Davi et al. 2006; Kramer 2012). During the growth phase, water consumption fluctuates between day and night due to the light-driven opening of the stomata and consequently, results in diurnal variation of transpiration water loss (Davi et al. 2006; Dierschke 1991; Schenker et al. 2014). The daily demand of water of a single, large tree can be several liters per square meter of ground surface to maintain plant water supply. Some species grow roots to depths of several tens of meters. Roots of trees exhibit a negative pressure difference compared to the matric potential of the soil at shallow depths, inducing water flow by the root system. Similarly, with shallow groundwater tables, the abstraction of groundwater by trees can be described by the radial flow equation, based on Darcy‘s law, with the flow rate being determined by the hydraulic potential gradient and the hydraulic conductivity of the soil and/or fractured rock system. Moreover, a tidal rhythm has been observed in plants both in an open site and in a controlled environment (Zürcher et al. 1998; Holzknecht and Zürcher 2006b).

In the fractured rock aquifer of the Göttingen North- Campus, fluid flow is believed to be initiated by a change in hydraulic potential, e.g. ambient groundwater flow or groundwater abstraction, or by a change in fracture aperture following a change in volume strain. Both types of mechanisms result in a temperature variation assuming a steady state geothermal heat flux from the centre of the earth and a (sub-)vertical displacement of the groundwater column.

The effect of heat conduction following surface temperature changes is small. Early studies of (Muncke 1827) led to an analytical solution of the heat conduction equation for a temperature wave penetrating into the subsurface. Already in 1837, Lambert-Adolphe-Jacques Quetelet (1796- 1874) described the diurnal and annual temperature variations as sine waves (Buntebarth 2002). Applying the conductive heat conductance, daily temperature variations are attenuated to 0.001 K at a depth of ca. 1.5 m and annual changes reach the same amplitude at ca. 30 m assuming a mean thermal diffusivity of 1 mm2/s and a surface temperature amplitude of ± 10 K (Buntebarth, Pinheiro, and Sauter 2019). These calculations demonstrate the effect of pure conductive heat flow.

The effect of free convective flow due to vertical temperature differences in the observation borehole can be neglected as well, as discussed below.

3.2. Methodology

3.2.1. Study area

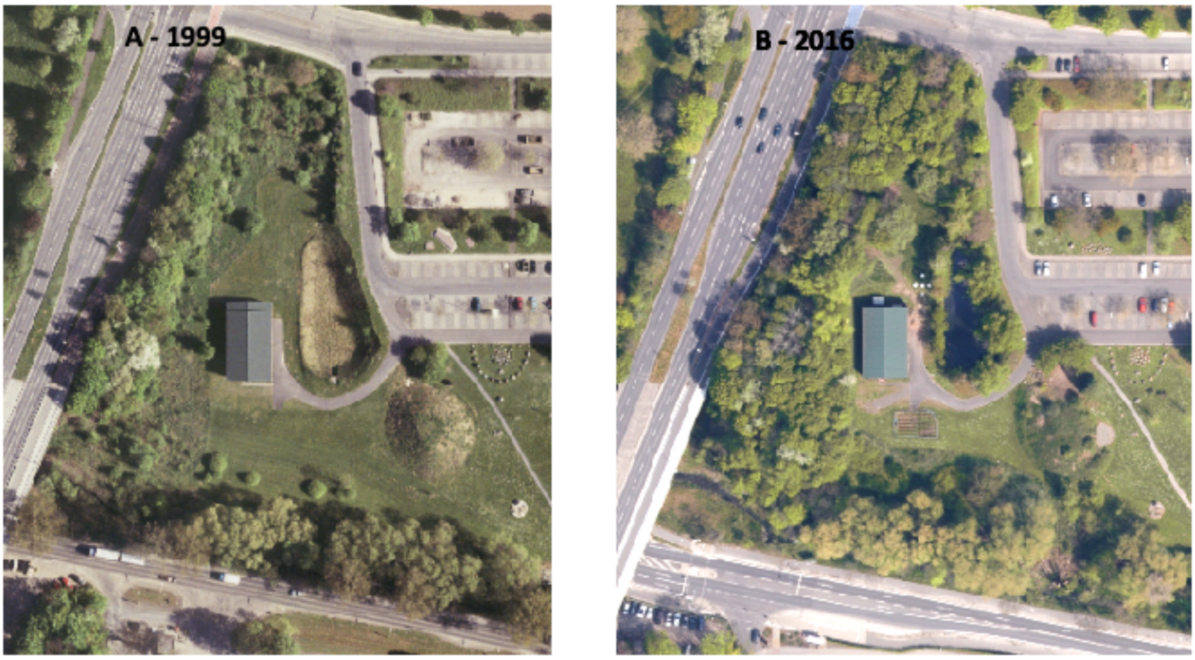

Figure 3.1: Satellite images of the area of investigation of the years 1999 (A) and 2016 (B) by Stadt Göttingen.

The city of Göttingen is located in the Leinetal graben, part the West European rift zones. The geology of this area, as well as the profile of the borehole is detailed by Buntebarth and collaborators (Buntebarth, Pinheiro, and Sauter 2019). From previous works in the study area, it is assumed that the thermal diffusivity ranges from 0.8 to 1.1*10-6 m2/s (Baetzel 2017). At present the area is characterized by high scrubland and approx. 20 m high maple and birch trees, which grow at distances between 15 and 25 m to the boreholes (**Figure 3.1B**). In this image, the five-spot borehole configuration is visible. The first well of the arrangement was drilled in 2008, and the other four, including the Northern well, equipped with the thermal sensors, were drilled in 2012. Compared to the satellite image of 1999 (**Figure 3.1A**) an increase in the vegetation cover can be observed. The trees were most likely planted during the period 1980-1985. In 1999 a shed was constructed in the center of the area and a pond was excavated to the east for fire protection purposes. Previously this region of Göttingen was clear.

3.2.2. The analytical heat conduction model

The subsurface temperature variations can be spectrally decomposed into thermal disturbances of different periods, with varying amplitudes and phase relationships. For that reason, the thermal temperature profile can reveal information from past climate events. It occurs because, according to the theory of heat conduction, changes in surface temperature propagate downward as thermal waves or perturbations, with amplitudes decreasing exponentially with depth. Moreover, the rate of propagation of the thermal signal is governed mainly by thermal diffusivity, which is directly proportional to the thermal conductivity of the material. Due to this, temperature changes on the earth's surface propagate slowly downwards, as a consequence of the relatively low thermal diffusivity of rocks (Čermák 1971; Majorowicz and Safanda 2005; Hamza and Vieira 2011; Smerdon et al. 2003; Harris and Chapman 1997; Pollack and Huang 2000b; Tautz 1971; Carslaw and Jaeger 1992; Bodri and Čermák 2011).

Furthermore, the attenuation during propagation depends on the frequency of the waves. Waves with longer periods of time, such as a long-term temperature variation, will have less attenuation, propagating to larger depths compared to short-term temperature variations. Signs of regional climate change may be, however, overshadowed by changes in anthropogenic activity that affect land use or vegetation patterns. For that reason, other possible sources of temperature perturbations must be considered (Prensky 1992; Čermák and Bodri 2018; Demetrescu and Shimamura 1997; Pimentel and Hamza 2013; Middleton 1999).

The penetration of a thermal signal into the subsurface can be calculated in space and time by simple heat conduction models. For this purpose, the steady state background temperatures associated with deep heat flow should be separated. The remaining temperature profile after separation (residual temperature) contains the components of the original observations considered as transient. This transient component, when analyzed, produces a reconstruction of the climatic variations in the surface. By solving the equation of heat conduction with temperature steps as a boundary condition, it can be checked whether any event in the past may have resulted in a spontaneous change in temperature as it occurs after deforestation (Nitoiu and Beltrami 2005; Čermák 1971; Bodri and Čermák 2011; Tautz 1971; Carslaw and Jaeger 1992).

$$T(z,t) = \pm T_0(1 - erf(\frac{z}{2\sqrt{(at)}})) \qquad (1)$$

T corresponds to the temperature at depth z in a time t with the thermal diffusivity α and the temporal derivative as:

$$(\frac{\partial T}{\partial t})_{z=const} = \pm T_0 \frac{z}{2\sqrt{(\pi a t^3)}} \exp(\frac{-z^2}{4at}) \qquad (2)$$

The application of a continuous surface temperature increase or decrease (±T0) in a specific time in the past (k) as boundary condition can simulate, however, previous events of surface temperature variation.

$$T(z,t) = \pm T_0 \frac{z^2}{ka} [(\frac{at}{z^2} + \frac{1}{2}) erfc(\frac{z}{2\sqrt{(at)}}) - \frac{1}{\sqrt{(\pi)}} \sqrt{(\frac{at}{z^2})} \exp(\frac{-z^2}{4at})] \qquad (3)$$

With the temporal derivative as:

$$(\frac{\partial T}{\partial t})_{z=const} = \pm T_0 \frac{1}{k} erfc(\frac{z}{2\sqrt{(at)}}) \qquad (4)$$

3.2.3. Measurements

Today’s technological advance in the measurement of the groundwater temperature allows to monitor changes in temperature at very high resolution, in the range below Millikelvins. Here, the LogBox microT temperature recording equipment will be used for long-term monitoring of temperatures at the selected depths, a high precision thermometer with a resolution of 0.0002 degrees (www.geotec-instruments.com). The instrument is protected by a waterproof housing and is directly located in the metal protected well head. A waterproof stainless-steel housing protects the calibrated temperature sensor fixed at the depths of 40 m and 78 m. The temperature sensitivity is related to the variation of the resonance frequency (Δf(T)/f0) of the quartz sensor. Its linearized sensitivity which can be applied within a limited temperature variation (T-25) is: Δf(T)/f0= -3*10-5 (T- 25) according to the datasheet of the MicroCrystal sensor MX2T. A temperature compensated frequency counter determines the sensor frequency which must be processed for evaluation of the temperature.

3.3. Results

Long-term temperature measurements were conducted during the period October 2016 to September 2018 at the depths of 40 and 78 m. The greater depth of 78 m might be less influenced by groundwater abstraction by trees and is used for comparison. Based on these measurements, 6 graphs were plotted. Daily mean values are plotted in **Figure 3.2**. The daily average temperature at depth of 40 m shows a continuous decrease, from 11.0091 °C in October 2016 to 10.9258 in September 2018. The annual temperature variation of 0.0407 K/year is observed when a linear trend is applied. The decrease in temperature can be explained by the increased shadowing effect of the growing vegetation cover, decreasing both the local air temperature and the solar radiation reaching the ground.

Comparing temperature records at depths of 40 m with those at 78 m depth, it is possible to extract the raw data series showing different temperature drifts depending on the recording depth. A total increase of 0.04 K at 78 m and a decrease of 0.1 K at 40 m is recorded. The linear trend shows a temperature rise of 0.01 K/year at 78 m and a decrease of 0.02 K/year at 40 m. Applying Equation 4 and assuming a continuous surface temperature increase of 2 K for the last 100 years, an increase of 0.01 K/year in temperature at 78 m can only be observed in 100 years from now. However, if a thermal diffusivity of 1.8*10-6 m2/s is applied, a continuous increase occurring for the last 100 years in the past is realistic.

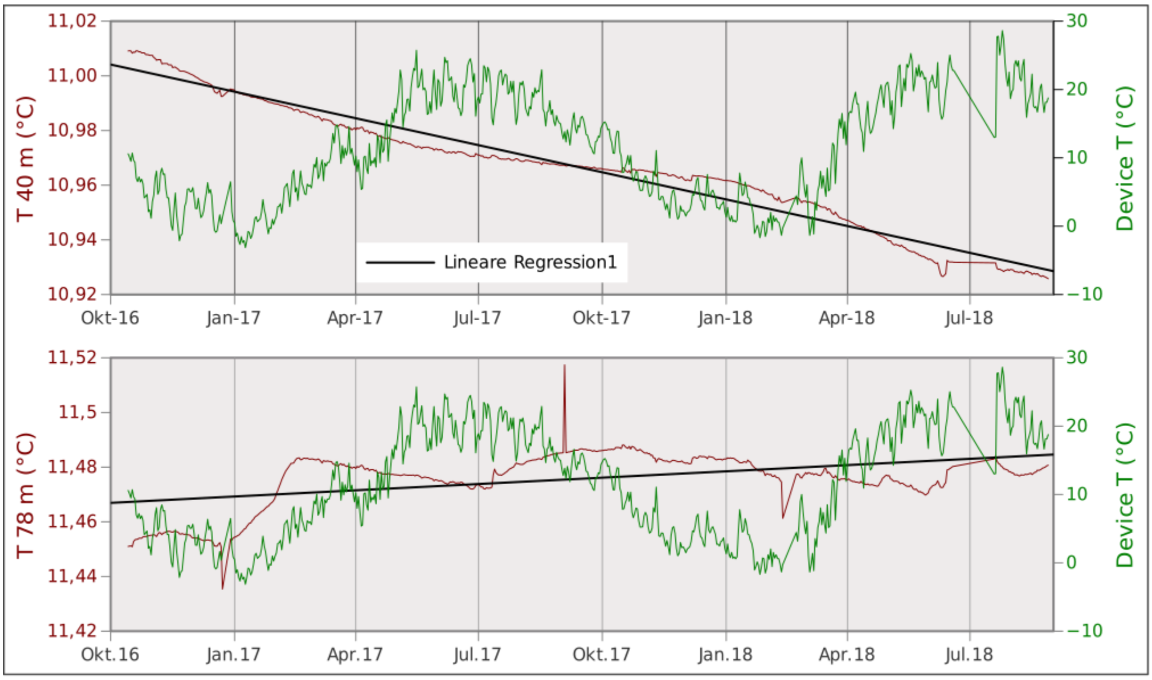

Figure 3.2: Daily average temperatures at depths of 40 and 78 m as well as the device temperature at the field site of the Göttingen North-Campus between October 2016 and September 2018. The black line represents de linear trend of the temperature at both depths.

Periodical variations occur at both depths, but they can be attributed to different types of mechanisms. At larger depths, different types of processes contribute to temperature variations, e.g. hydrological and earth tidal processes, demonstrated by (Jahr, Buntebarth, and Sauter 2020).

Comparing the daily temperature sequence at the depth of 40 m and at the surface in March 2017 and March 2018 (**Figure 3.3**) a decrease in subsurface temperature can be observed when the surface temperature reaches a value of nearly 9 °C. As concluded before (Buntebarth, Pinheiro, and Sauter 2019),a diurnal temperature variation of approximately 2 mK occurs during the phenological growing season of the vegetation. The increase in surface temperature during spring is responsible for the end of the dormant vegetation period. It results in an increase of water abstraction by plants. Observing the daily temperature sequence at 78 m during March 2017 (**Figure 3.4**) it can be noticed that at 78 m depth, as well as at 40 m depth, a relation with the surface temperature variation exists.

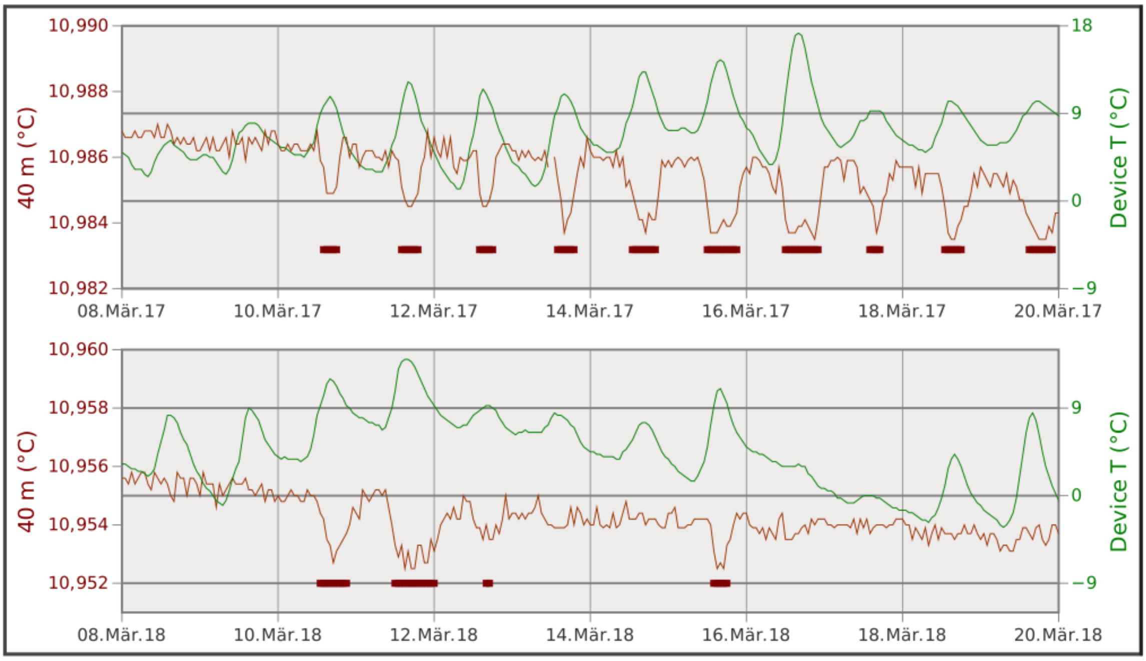

Figure 3.3: *Comparison between daily temperature sequence at 40 m depth and at the surface in both March 2017 and 2018. Solid thick lines illustrate time periods of T >9 °C.*

Apart from the relationship between surface and subsurface temperature variations, the periodical variations can also partly be explained by the influence of earth tides (Buntebarth, Pinheiro, and Sauter 2019; Jahr, Buntebarth, and Sauter 2020) inducing fluid flow variations at daily and half-daily periods. This fluid flow can be explained by changes in volume strain, i.e. opening and closing fractures of the rock mass resulting from changes in gravitational forces of the sun and moon. Consequential variations in porosity and permeability induce fluid flow.

The constant heat flow from the earth's interior which results in a linear temperature increase with depth, i.e. a constant geothermal gradient, is superposed by the transient heat flux component resulting from the above tidally induced fluid flow. Since most fractures are characterized by a sub- vertical geometry, the above fluid flow has a major vertical flow component and therefore contributes to temperature variations at a fixed depth, i.e. at the level of the borehole temperature sensor.

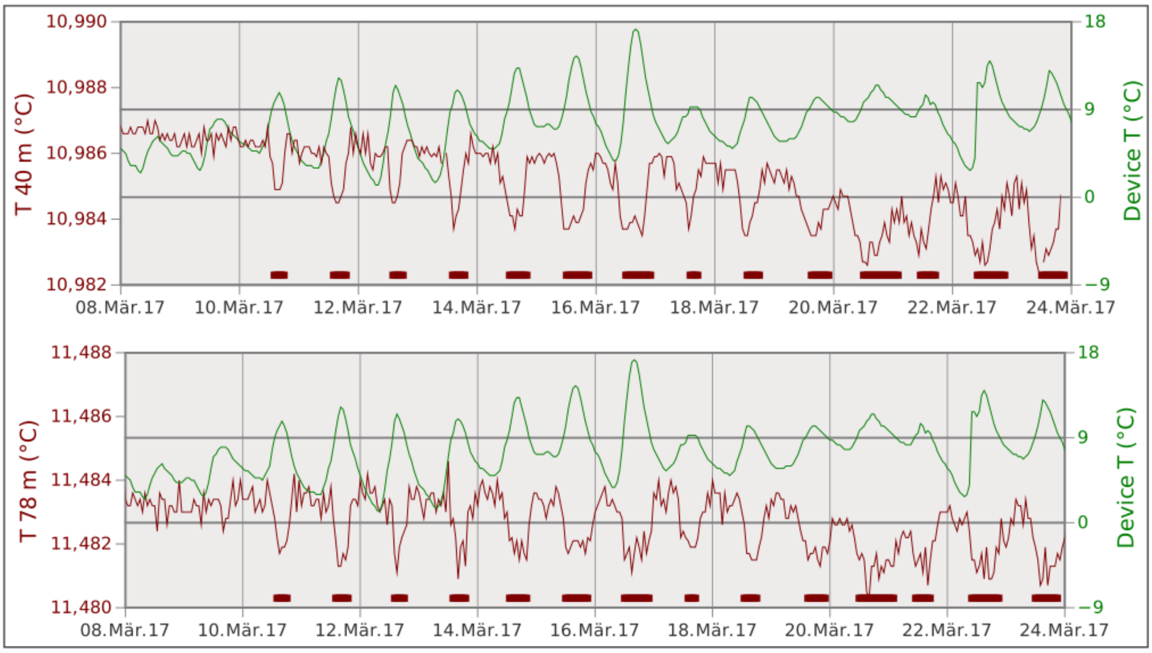

Figure 3.4: Comparison between daily temperature sequence at 40 and 78 m depths and at the surface March 2017. Solid thick lines time periods of T >9 °C.

The constant heat flow from the earth's interior which results in a linear temperature increase with depth, i.e. a constant geothermal gradient, is superposed by the transient heat flux component resulting from the above tidally induced fluid flow. Since most fractures are characterized by a sub- vertical geometry, the above fluid flow has a major vertical flow component and therefore contributes to temperature variations at a fixed depth, i.e. at the level of the borehole temperature sensor.

The main contribution to the change in gravitational force can be attributed to the moon. Its magnitude and the resulting volume strain in the subsurface are determined mainly by the moon phase. **Figure 3.5** demonstrates that the temperature amplitudes are generally larger during days of syzygy, i.e. approximately during times of maximal gravitational force, and lower during times of minimal gravitational force (half- moon). This coincidence between temperature variations and the theoretical changing volume strain is apparent in both temperature records, i.e. at 40 and 78 m depths (Jahr, Buntebarth, and Sauter 2020).

The relationship between volume strain and temperature at 40 m depth is visualized in **Figure 3.6**. The theoretical volume strain at the borehole location coincides, in general, with the amplitude of the recorded temperature. During the time period studied the temperature record in **Figure 3.5** is superimposed by a decreasing trend. In addition to the volume strain, the moon phases are shown in **Figure 3.6**, departing slightly from the corresponding minima and maxima of volume strain. This deviation can be attributed to the complex change in moon- sun-earth gravitational forces (Jahr, Buntebarth, and Sauter 2020).The close relationship between the respective moon phase and the magnitude of the temperature amplitude is apparent except for a few days at the beginning of May 2017.

While during April hardly any precipitation was recorded, an intensive storm event with 23.3 mm of rainfall was measured at the location during the time period of 4. – 5. May 2017. With the availability of sufficient water close to the surface the trees and shrubs did not abstract groundwater from the aquifer, with the consequence of considerably reduced temperature amplitudes. The time of half-moon on May 18 did not coincide with the minimum of volume strain so that the amplitude of temperature change decreased a few days later at the strain minimum.

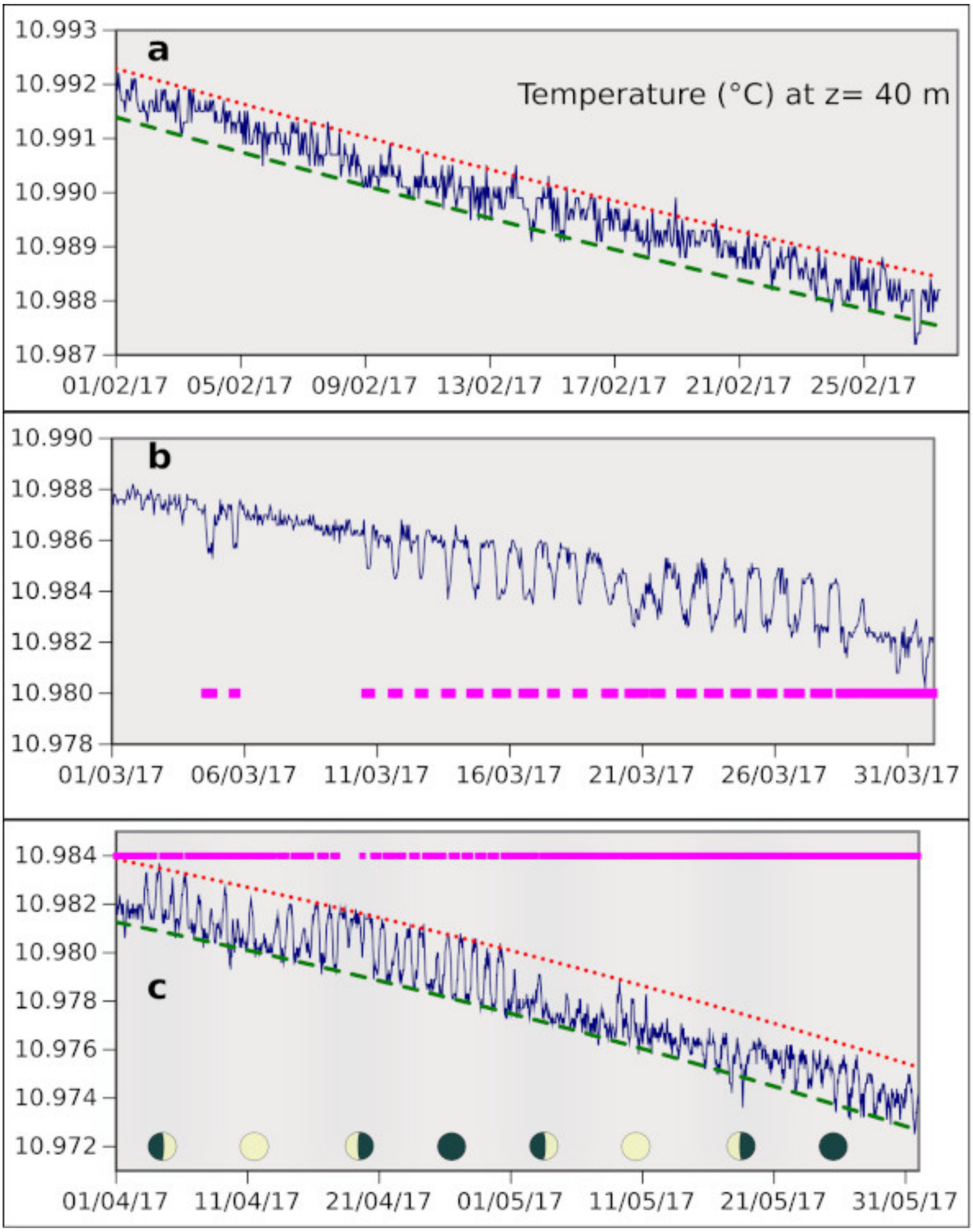

Figure 3.5: Temperature variations at z= 40 m between winter 2016 and during spring 2017; a) Temperature record during February 2017 with upper (dotted red) and lower (dashed green) limit; the surface temperatures are below T= 9 °C; b) Temperature record with increased amplitudes at days with surface temperatures higher than T= 9 °C (Broken solid pink line illustrates time periods of T>9°C and time periods of T<9°C (blank)); c)

Temperature record with upper (dotted red) and lower (dashed green) limit and surface temperatures higher than T= 9 °C. Broken solid pink lines illustrate time periods of T>9°C (solid pink) and time periods of T<9°C (blank) and the moon phase during spring 2017.

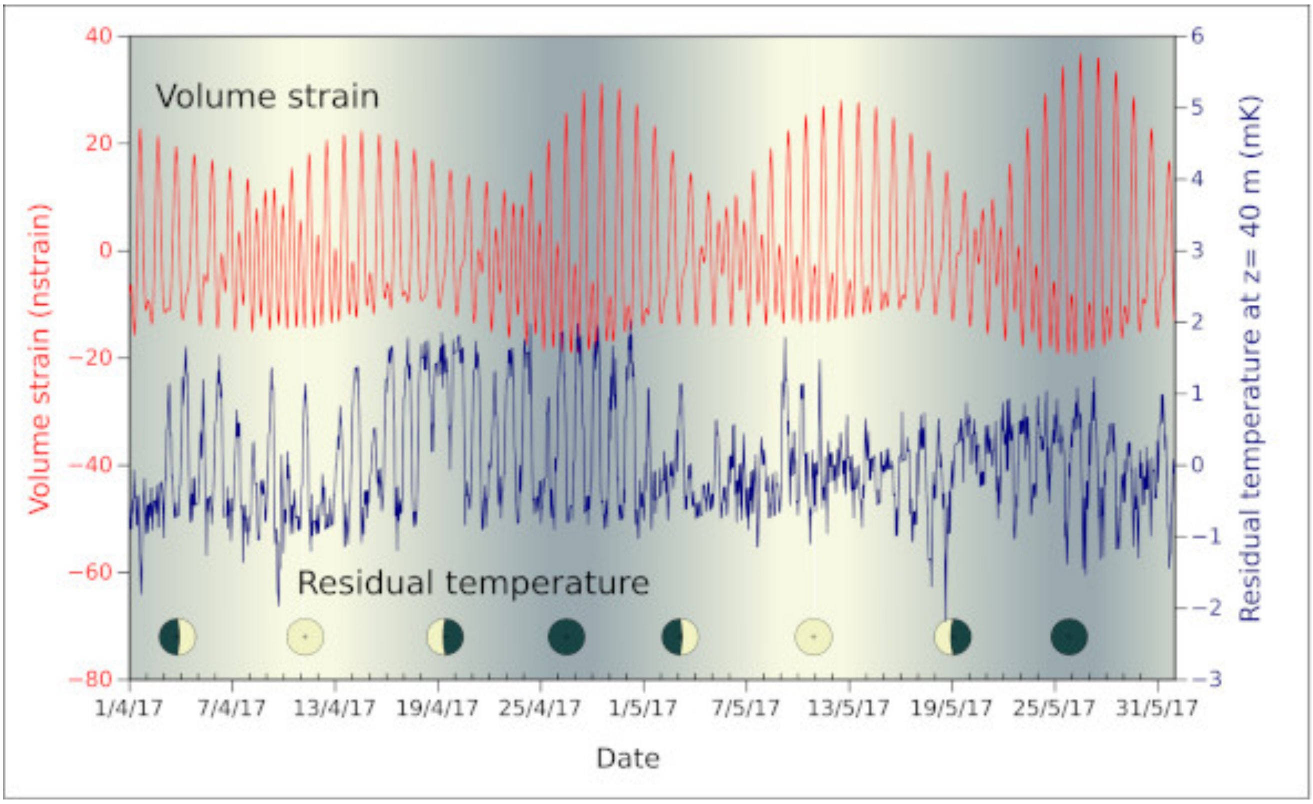

Figure 3.6: Theoretical volume changes (Nano strain) with moon phase and the residual temperature at z= 40 m, i.e. recorded temperature corrected for trend.

Highest temperature variations, i.e., daily and half daily variations, are mainly observed during spring and relate to the moon phases and times of growing vegetation. This phenomenon is also recognized during the years 2016 and 2018 (Buntebarth, Pinheiro, and Sauter 2019). However, the daily and half- daily temperature periods with the change in the moon phases are not apparent during summer and autumn which leads to the conclusion that the trees abstract only small volumes of groundwater during these times.

By separating the residual values from the linear trend to the measured data, it is possible to observe both the steady state background temperature and the transient component.

In **Figure 3.7a**, the transient component is compared with the surface temperature. At the ground surface the temperature amplitude observed was approximately 12 °C while at a depth of 40 m the amplitude of the residual temperature was measured at approximately 0.007 °C. The theoretical heat conduction effect is also presented. In **Figure 3.7b**, the effect of heat conduction was added to the residual temperature. As a consequence, the slope was slightly changed. The transient temperature coincides in phases at the depth of 40 m, showing a phase shift of ca. half a year. It was also observed that the water absorption by trees achieved its maximum ca. 40 days before the maximum of the surface temperature. Furthermore, the slight difference to the annual cycle is an indication that the maximum water consumption occurs before the annual temperature maximum. Interruption of records and reinstallation generated an offset of ca. 2 mK in 2018.

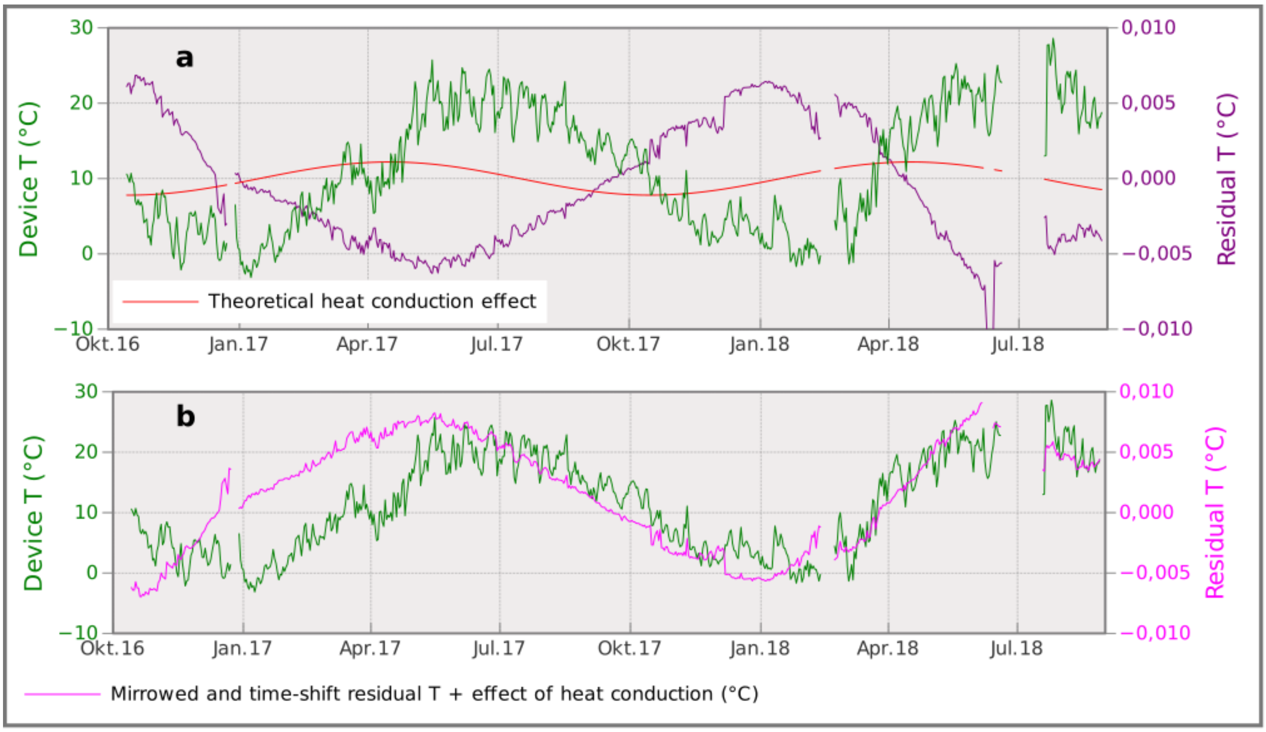

Figure 3.7: a) Comparison between the device temperature and the residual temperature at depth of 40 m. The red line corresponds to the theoretical heat conduction effect; b) The magenta line corresponds to the mirrored and time shifted residual temperature at depth

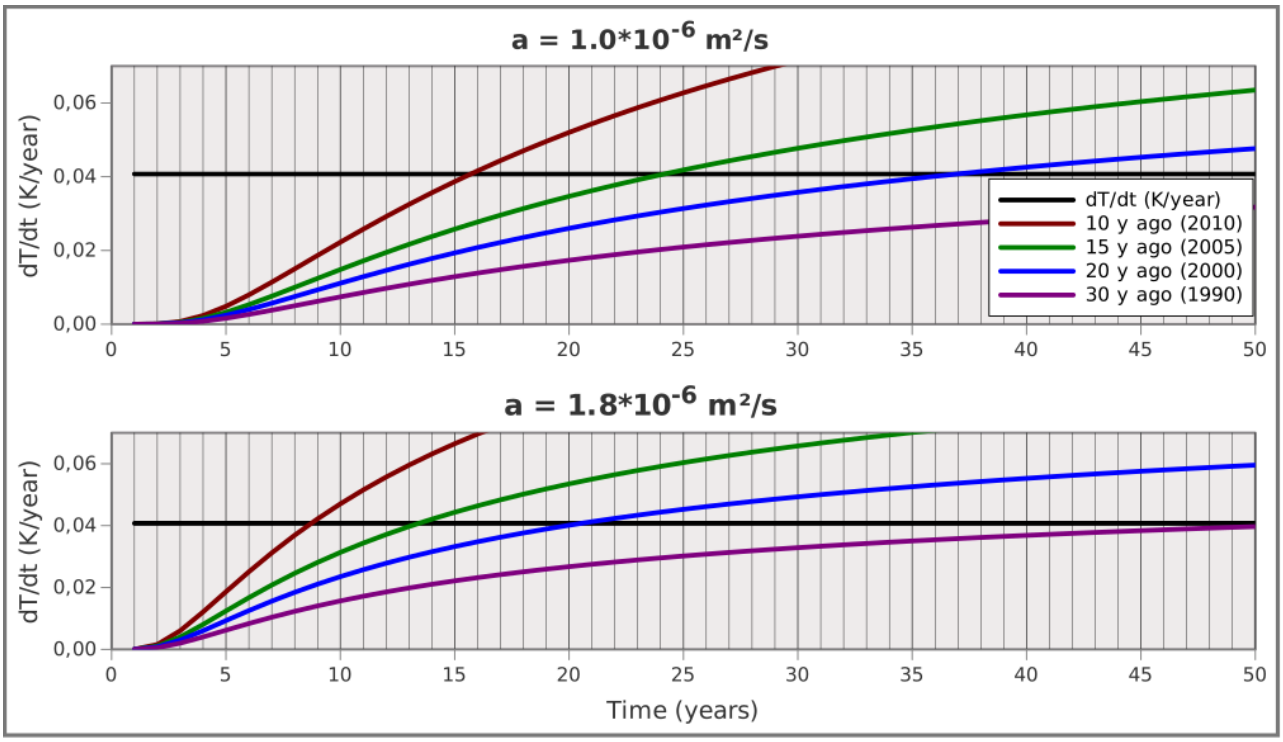

Figure 3.8: Temperature changes with elapsed time at the depth of 40 m after a continuous temperature change starting 10, 15, 20 and 30 years ago. The black line represents the present linear trend of the temperature variation at the depth of 40 m.

This observation can be explained by the activity of vegetation being intensified during spring and summer, when the water potential in plants increases. As a result, the residual temperature of the groundwater decreases. In contrast, when the surface temperature decreases and the vegetation enters into a dormant period, the residual temperature at 40 m depth increases.

Between October and December 2016, the residual value was expected to be higher than that measured. The difference shows an apparent increase in vegetation activity prior to the period expected. The amplitude temperature variation at the surface might have affected vegetation activity during autumnal senescence.

In contrast to a sudden deforestation, accompanied by a spontaneous change in surface temperature, reforestation can be described as a gradual, continuous surface temperature decrease. Considering a continuous decrease in surface temperature of 2 K as a boundary condition, equivalent to the reported temperature step expected after deforestation, equation 4 can be applied. **Figure 3.8** shows the simulation of an event starting between 10 and 30 years ago (from 1990 to 2010), i.e.

the time period of the area of the increasing tree canopy. Considering the expected thermal diffusivity (1.0*10- 6 m2/s) the change in temperature would only be observed in a few years from now. However, when a thermal diffusivity of 1.8*10-6 m2/s is assumed, a continuous decrease in temperature from 10 to 20 years ago is realistic.

3.4. Discussion and conclusion

Subsurface temperature changes can be the effect of a multitude of processes, i.e., the change in surface temperature, convective and conductive geothermal heat flow, hydrological and hydrogeological processes as well as the above discussed crustal deformation and abstraction by vegetation.

The observed microtemperature variations at the Göttingen North-Campus site are suggested to be the result of the superposition of the effects of two main processes and several other factors: The dominating processes are: a) the displacement of the fluid column parallel to the geothermal gradient by earth tide enforced opening and closing of rock fractures, and b) the abstraction of groundwater by the root network of deciduous trees and shrubs. The effects of borehole heat advection, heat conduction from surface temperature variations is negligible and ambient groundwater flow only occurs at shallow depths where considerably higher hydraulic conductivity prevails.

The surface temperature variation signal is attenuated, and phase-shifted with depth and is characterized by an amplitude of 1 mK and a phase shift of 1.5 years at a depth of 40 m, with an apparent thermal diffusivity applied resulting from the effect of the growing vegetation. Frequently, in an environment with high geothermal gradients, the effect of free convection in a borehole is believed to contribute to vertical flow as well, possibly superimposing flow induced by earth tides and abstraction by vegetation. (Luheshi 1983) estimated the minimum temperature gradient in a borehole at 8.5 in. diameter for convection driven flow to occur at 0.06 K/m. At the experimental site in Göttingen the borehole diameter is 15.24 mm (6 in) only and the geothermal gradient amounts to ca. 0.015 K/m (Buntebarth, Pinheiro, and Sauter 2019), i.e. below the critical threshold for free convection.

In our study, we recorded temperature fluctuations that reflect changes in groundwater flow with distinct daily and seasonal patterns. Looking at short-term variations it could be observed that daily as well as annual temperature variations are influenced by fluid flow, i.e. convective heat transport induced by plant activities, and in contrast to heat conduction theory, this variation can be observed at larger depths. During spring and summer, temperature fluctuations can be explained by diurnal changes in water consumption of vegetation, which increases during the day and decreases at night.

Mature, large trees such as the maple trees close to the borehole consume up to several hundreds of litres of water per day. For example, (Pisek and Tranquillini 1951) found that ca. 14 m tall conifers transpired between 80 and 180 l of water per day. Water consumption starts in March and remains high until October. Deciduous tree species exhibit generally larger transpiration rates compared to other species. For beech trees, up to 500 l per day have been reported (https://www.ds.mpg.de/139253/05). However, their seasonal water demand is delayed compared to that of coniferous trees because their above-ground growth activity starts in April and May (Dierschke 1991). In contrast to the above-ground physiology, root growth starts much earlier, when soil temperatures range slightly above the freezing point (Gaul, Hertel, and Leuschner 2008; Hansen, Vogg, and Beck 1996). For maple trees, minimum temperature for root growth is 3 °C (Schenker et al. 2014).

However, at low surface temperatures, vegetation growth activity is considerably reduced. Correspondingly, root water uptake depends largely on temperature. Soil temperatures below 5 to 7 °C inhibit water uptake by herbs and trees because of higher water viscosity and lower membrane permeability (Leuschner and Ellenberg 2017). Our data agree with this threshold considering that residual values of temperature at 40 m depth reached a minimum, when environmental temperatures ranged around 9 °C.

Although roots of some species can reach deep soil layers of up to 10 or 20 m, they do not grow to depths of 40 m. The abstraction of groundwater by plants can be visualized similarly to that of the flow configuration close to a partially penetrating abstraction well, i.e. with considerable vertical flow components. In such type of wells, the hydraulic potential is lowered at shallow depths, inducing fluid flow to the well screen not only as radial horizontal component but also as vertical flow from larger or shallower depths depending on the subsurface geo-hydraulic characteristics and precipitation.

In addition, the periodically changing gravitational forces cause changes in poro-perm rock properties depending on the sun/moon geometric configuration. The continuous change in volume strain causes alternating dilation or closure of subsurface fractures inducing changes in the geometry of flow paths and the magnitude of fluid flux and therefore heat flow. During times of maximum strain, the rock fracture apertures are increased, and groundwater flow is enhanced compared to those periods of minimum strain. The vertical displacement of the fluid column is estimated at ca. 0.18 m based on a geothermal temperature gradient of $\Delta T/\Delta z$ = 0.0135 K/m (Buntebarth, Pinheiro, and Sauter 2019) and a maximum amplitude of ΔT= 2.5 mK.

When the long-term variation is taken into account, vegetation again plays an important role. Changes in vegetation cover will influence not only climate itself, being responsible for i.e. surface temperature variation and precipitation patterns, but also for both changes in distribution of solar radiation and changes in soil layer. Even though vegetation is known to decrease the albedo of the area, radiation will not be absorbed by the soil, but by the plants. As a consequence, the subsurface temperature will decrease.

In this study, with the only variation in land use being the growth of trees around the borehole, the long-term influence starts not at the time the trees were planted (35-40 years ago), but at the time the vegetation cover became of relevance to the albedo (10-20 years ago).

Here, thermal diffusivity is evaluated at a value higher than the expected. The abstraction of water by the roots in shallow layers might be the reason for the additional temperature decrease at 40 m. Additionally, it is important to point out that an increase in vegetation cover might be responsible for a decrease in local temperature of 2 K, expected to have an influence approximately 20 years after plantation. Furthermore, global warming of 2 K in 100 years would have a much lower rate of warming compared to the effect of vegetation described above.

Finally, with the technological advance in groundwater temperature measurements, changes in groundwater temperature seems to be a promising method to understand climate variation as well as the potential impacts of land use change. Currently we are developing a numerical model simulating the hydromechanically controlled heat transport of the fractured rock mass, integrating also the effect of groundwater abstraction by vegetation. This model will allow us to investigate the relative importance of the different drivers and system characteristics.

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4. Diurnal variations in vegetation activity affecting shallow groundwater flow identified by microthermal measurements

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Abstract

Observations of summer microthermal temperature variations suggest, next to hydrological factors, a significant influence of plant activity on groundwater flow in fractured claystone materials. Variations in groundwater microtemperature were compared to variations in meteorological parameters and electrical potential of plants. With an increase in surface temperature, relative air humidity decreases and an increase in tree electrical potential, measured as the difference between the northern and the southern stem exposure (N – S), can be observed. This increase in electrical potential is concomitant with a change in groundwater temperature of approximately 2 mK. This relationship does not always occur. At high temperatures (+30 °C) the decrease amounts to just 1 mK. This fact is related to the change in transpiration of plants, decreased or even suspended at high surface temperatures. A frequency analysis of all data showed a daily frequency of high magnitude in all parameters. Possibly changes in the macro weather situation events were observed in the results of atmospheric pressure, southern electric potential and groundwater temperature. The lag time between changes in electric potential and subsurface microtemperature changes amounts to 17 hours, possibly a result of the electrical potential difference between the northern and the southern exposure of the stem (N – S), and 5 hours, the result of the change in electrical potential difference between the southern and the northern stem exposure side (S – N). A comparison between potential changes and the computed change in gravity resulting from earth tidal effects showed that the correlation between the subsurface temperature variation with up to 2 mK and the change in surface temperature variation does not match directly. Other study shows that the impact of earth tides on subsurface microtemperature variation amounts to ca. 1mK. The effect of groundwater abstraction by mature vegetation is determined at the same range. Atmospheric tides can be correlated with the changes in north and south electric potentials.

4.1. Introduction

With the advancement of technology, high precision and high resolution microtemperature measurements became available, and what were once regarded as incoherent results are now well defined signals studied and interpreted by different scientific communities (Briciu 2018; Shimamura and Watanabe 1981; Shimamura et al. 1984; Jahr, Buntebarth, and Sauter 2020; Buntebarth et al. 1997; Demetrescu and Shimamura 1997; Hamza 1997; Drury, Jessop, and Lewis 1984; Richter and Cruiziat 2002). Geothermal measurements in environmental monitoring are known for their ease of installation, stable and long-term monitoring quality, and low interference with the respective environment. Seismic signals, past weather events, terrestrial and atmospheric tidal signals, as well as plant activity signals could be correlated with systematic changes in groundwater temperature (Briciu 2018; Shimamura and Watanabe 1981; Shimamura et al. 1984; Jahr, Buntebarth, and Sauter 2020; Buntebarth 1997; Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021; Demetrescu and Shimamura 1997; Drury, Jessop, and Lewis 1984; Čermák 1971; Bodri and Čermák 2011).

The hydrologic cycle is highly affected by changes in vegetation cover. One of the important driving forces in this cycle is transpiration by plants. This process returns approximately 50% of precipitation to the atmosphere, and accounts for over 60% of the evapotranspiration rate. Vegetation is thus exposed to and governed by different meteorological parameters, as well as by the availability of water in the soil and subsoil (Burr 1947; Chahine 1992; dos Santos et al. 2017; Good, Noone, and Bowen 2015; Kumar, Shankar, and Jat 2014; Schlesinger and Jasechko 2014; Sun et al. 2011; Taiz et al. 2015; Volkov and Ranatunga 2006).This process can easily explain that woody plants interfere with the groundwater recharge process changing water infiltration rates, evapotranspiration, interception, as well as changes caused by afforestation or deforestation (Le Maitre, Scott, and Colvin 1999; Antunes et al. 2018; Acharya et al. 2018; Bense et al. 2013; Kordilla et al. 2012). These studies however did not address the relationship between changes in groundwater microtemperature and plant activity during the growing season (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al.

2021). Here, we compare short-term, i.e. daily variation of groundwater microtemperature with the ionic flux in a tree.

4.1.1 Vegetation and electric potential

Electric potentials in plants has been studied for some time and has its history summarized in a review by (Schuch and Wanke 1969). Some studies have shown that despite the periodic daily variation of electric potential in plants (Koppan, Szarka, and Wesztergom 2000; Burr 1947; Gibert et al. 2006; Ansari and Bowling 1972), there is no direct link to xylem flow (Gibert et al. 2006; Likulunga et al. 2022; Love, Zhang, and Mershin 2008). Other factors are also responsible for triggering these electrical impulses, such as temperature variations, pollination, and variation in water availability (Fromm and Lautner 2007). These factors result in varying water content of plants (Likulunga et al. 2022). Pathways for the transmission of electrical signals in plants are comparable to those of animals, respecting the different degrees of complexity. This capability can be explained by the need to respond quickly to external signals, for instance, to environmental stressors or damage to the organism (Fromm and Lautner 2007; Volkov and Ranatunga 2006). Soil water abstracted by the roots contains ions and is therefore electrically conductive. This electrolyte is lifted and moves to the top of a tree, creating an electric current that can be determined as an electric potential in the tree trunk (Ansari and Bowling 1972; Volkov and Ranatunga 2006).

4.2. Methodology

To compare plant activity with variations in groundwater temperature and other meteorological parameters, two devices were employed. For the measurement of groundwater temperature a high-precision thermometer with a resolution of 0.0002 degrees (www.geotec-instruments.com) was used. The instrument is protected by a waterproof box and directly located at the well head of an 80 m deep borehole. A stainless- steel waterproof case protects the calibrated temperature sensor attached at a depth of 40 m. In addition to groundwater temperature, air temperature at the tree was recorded as well. The electric potential was monitored in a tree specimen of the Prunus avium species (**Figure 4.1**).

Figure 4.1: Prunus avium with installed LogBox ecoV

The equipment used was LogBox ecoV, manufactured by geeotec (www.geotec- instruments.com). Two pairs of platinum electrodes were placed on two sides of the stem, exposed to the north and south. Vertical distance between the two electrode pairs amounts to approximately one meter, following the protocol of (Koppan, Szarka, and Wesztergom 2000). The horizontal distance measures approximately 41 cm. In addition to the north and south electric potentials, relative humidity, and air temperature close to the electrodes, as well as atmospheric pressure were recorded. Frequency analyses were conducted for the monitoring results, employing a python software.

4.3. Results and discussion

Data for groundwater temperature, air temperature and relative humidity, as well as electric potential are presented in **Figure 4.2**. To eliminate the effect of atmospheric tides the electric potential was presented as the difference between north and south potential. Earlier results (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021) showed a relationship between groundwater microtemperature and surface air temperature, indicating a strong relationship with the onset of the growing season of the plants. In the present data we observe a similar relationship for the summer period (**Figure 4.2**). Further, the increase of the electrical potential in plants is synchronized with an increase of surface temperature and a decrease in relative humidity.

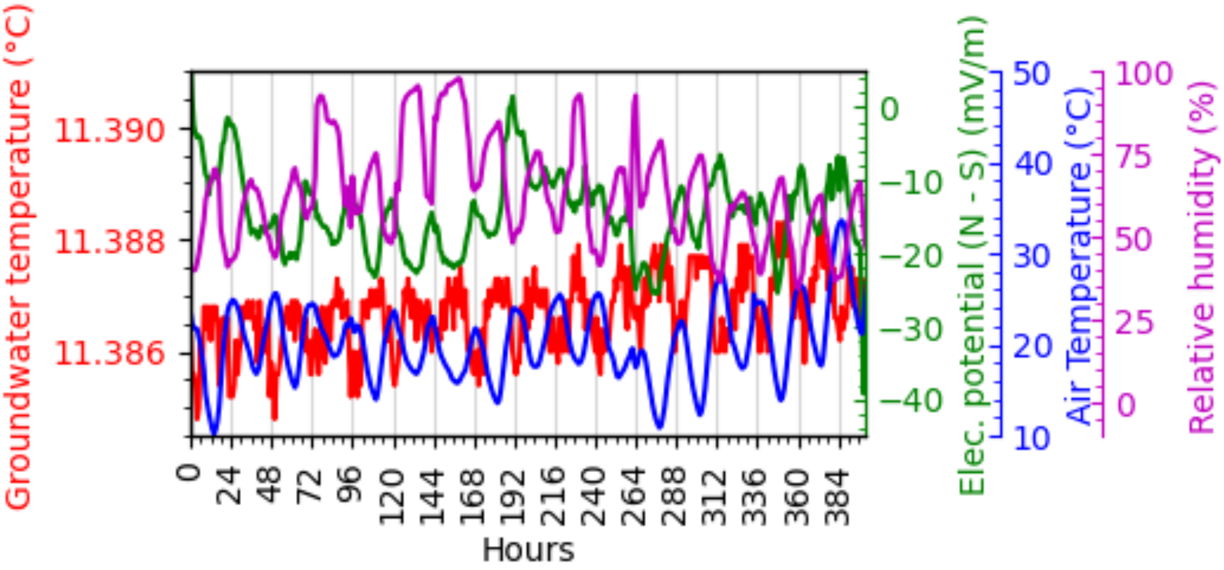

Figure 4.2: Original signals: relative humidity, electric potential (N-S), air temperature and groundwater temperature

A frequency analysis (**Figure 4.3**) revealed a diurnal frequency (24 hours) of different magnitude for all variables. This frequency is directly related to solar radiation. Lower frequencies with larger amplitudes were observed for atmospheric pressure, southern electric potential and groundwater temperature (**Figure 4.3**). These frequencies represent possibly changes in the macro weather situation. North and south electric potentials show a half diurnal frequency (12 hours) and a weak 8-hour amplitude. This frequency is eliminated from the electric potential by subtracting one from the other.

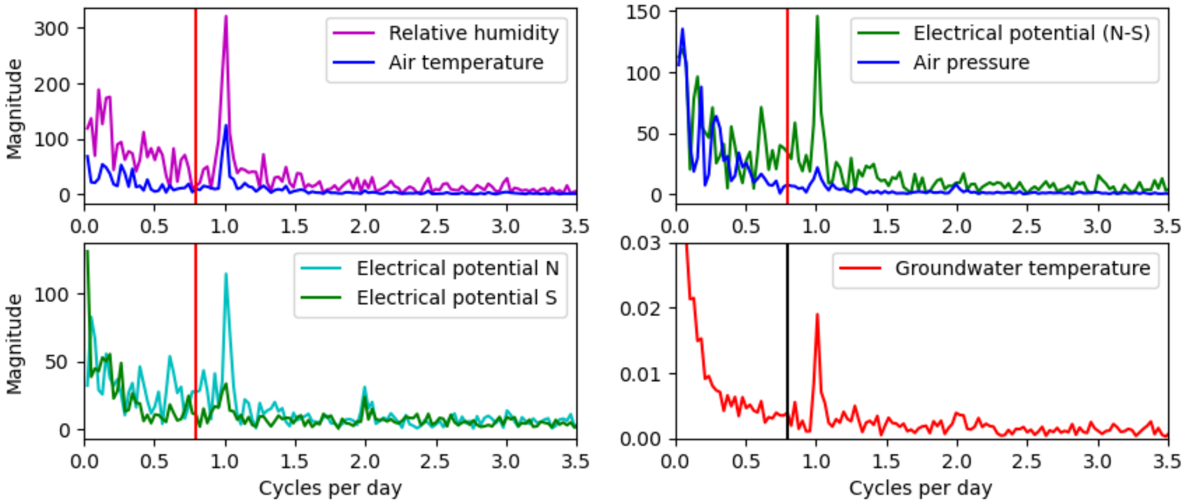

Figure 4.3: Frequency analysis of the different variables: relative humidity, electric potential (N-S), air temperature, air pressure, electric potential North (N), electric potential South (S), and groundwater temperature

4.3.1 Geothermal and surface temperature

The variation of groundwater temperature at depths of up to 30 meters is influenced by the daily and seasonal variation of the temperature at the surface. Beyond this depth thermal conduction is not (Tautz 1971; Buntebarth, Pinheiro, and Sauter 2019) and surface temperature variations are not detectable by techniques available today.

Groundwater is clearly affected by vegetation activities (Le Maitre, Scott, and Colvin 1999; Antunes et al. 2018; Acharya et al. 2018; Bense et al. 2013; Kordilla et al. 2012). Studies show that during the dry season some plants abstract water up to a depth of approximately 6 meters (Antunes et al. 2018). In fractured rock materials with high Hydraulic diffusivities (Buntebarth et al. 2019), this effect can be detected also at large depths of several tens of meters. The review by (Acharya et al. 2018) reports that areas with woody vegetation show higher evapotranspiration and therefore a decrease in recharge. It also suggests that infiltration increases in these areas, when land cover allows it. In this study (Figure 4.2) a temperature decrease of approximately 2 mK with an increase in surface temperature is observed. This relationship does not always apply. In our earlier work (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021) we showed that, with the beginning of the growing season, this relationship applies for surface temperatures above 9 °C. Figure 4.4 shows that with temperatures approaching very high values (> 30 °C) the temperature difference is less than 2 mK. With very high temperatures and/or prolonged exposure to higher temperatures, stomata tend to close, thus reducing transpiration rates to avoid both excessive water loss and cavitation (Richter and Cruiziat 2002; Tibbitts 1979; Taiz et al. 2015). Some studies confirm a higher activity in plants during spring/summer periods compared to that of fall/winter (Burr 1947; Gibert et al. 2006; Hao, Li, and Hao 2021).

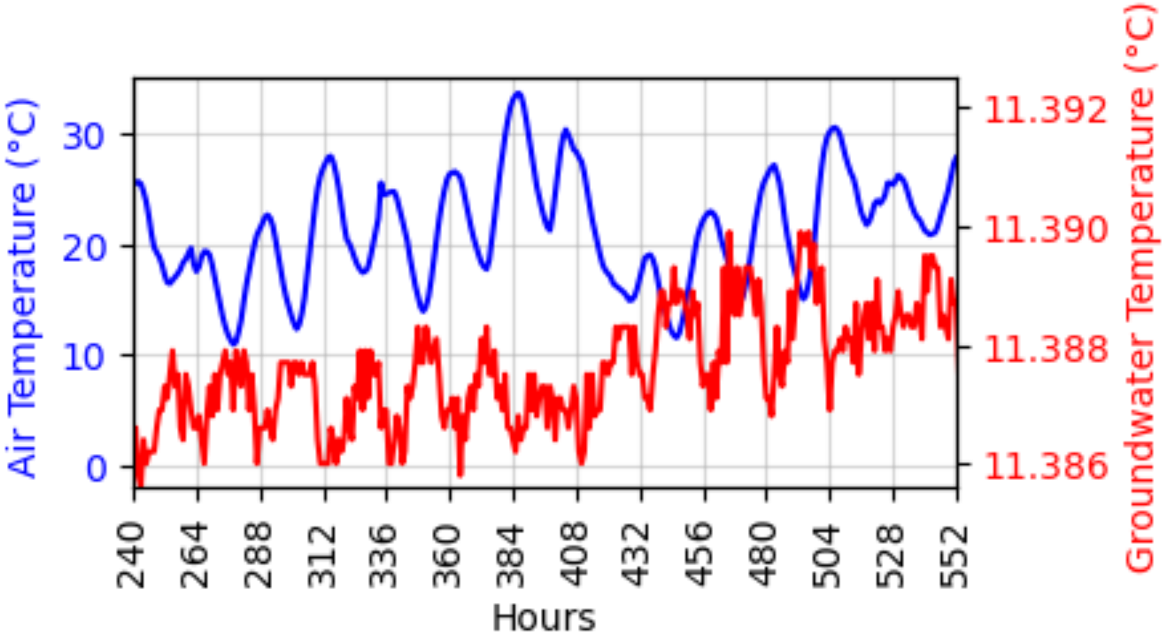

Figure 4.4: Original signal: air temperature and groundwater temperature

4.3.2 Geothermal temperature and electric potential

The periodic variation in plant electrical potential observed during our study period (**Figure 4.2**) was evidenced in other studies (Burr 1947; Gibert et al. 2006; Hao, Li, and Hao 2021; Likulunga et al. 2022). There are daily and annual periodic variations. Studies show that the amplitude of the electric potential change is larger during spring/summer periods compared to those of fall/winter times (Burr 1947; Gibert et al. 2006; Hao, Li, and Hao 2021), consistent with the results presented here and in our earlier studies (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021).

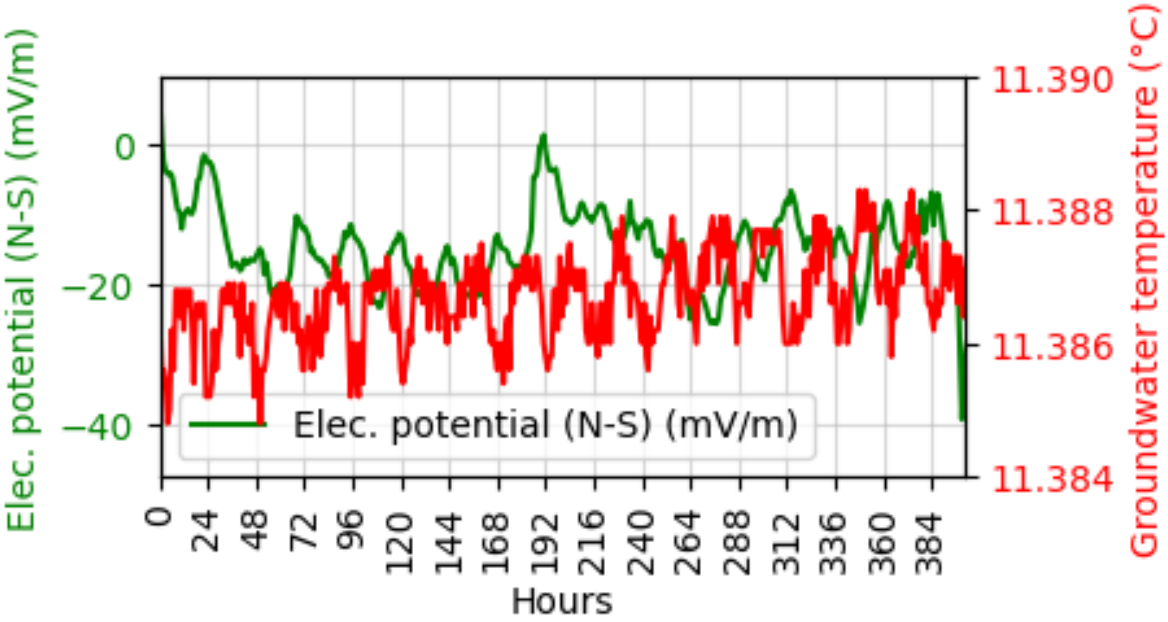

Figure 4.5: Original signal: electrical potential (N-S) and groundwater temperature

Comparing electric potential (N - S) with groundwater temperature, a systematic relationship becomes obvious. This relationship can be observed in both, the original raw signal (**Figure 4.5**) and the frequency analysis (**Figure 4.3**). There is a predominant relationship directly correlated to the intensity of solar radiation. From the phase shift the response time between groundwater temperature and electric potential can be determined at 17 hours (**Figure 4.6**). In this case, there would be a decrease in groundwater temperature caused by the abstraction of water and after 17 hours an increase in the electric potential. Please note that we consider here the difference in electric potential between North and South exposure positions. For a South - North difference, the phase shift becomes 5 hours. Gibert and co-workers (Gibert et al. 2006) report that there is a temporal difference between a change in xylem flux and the change in electric potential. The electric potential returns to its original value after ca. 8 h, while a zero-sap-flow is already reached after ca. 4 h.

The presence of a measurable electrical potential in dead plants, and a zero-change in potential in plants with reduced transpiration rate indicate that sap flow is not the only mechanism explaining electric potential changes (Hao, Li, and Hao 2021). Hao relates the electrical potential of plants direct to water content, which resulted in a good hypothesis, especially when we consider that the changes suffered by plants caused by environmental variations can be observed in the variation of groundwater temperature.

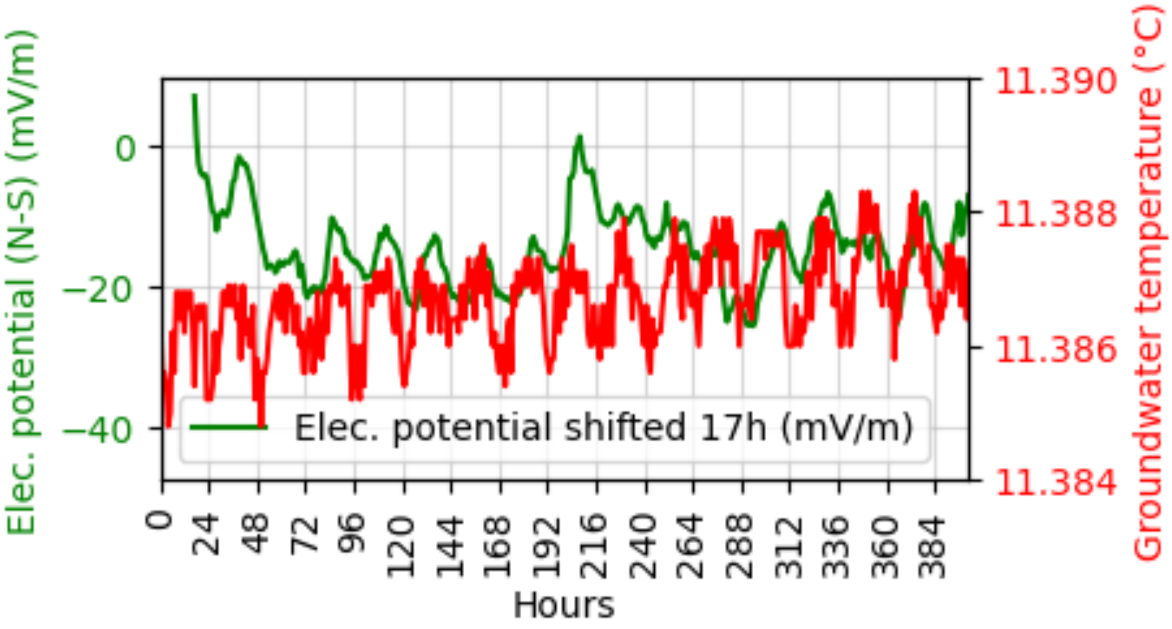

Figure 4.6: Phase shift between the different signals: electrical potential difference (N-S) is shifted by 17h compared to groundwater temperature

4.3.3 Geothermal temperature and terrestrial tides

Both, groundwater flow (Doan and Brodsky 2006; Toll and Rasmussen 2007; Wang et al. 2018a; Merritt 1999; Allègre et al. 2016; Hsieh, Bredehoeft, and Rojstaczer 1988; Acworth and Brain 2008; Roeloffs 1988; McMillan et al. 2019) and vegetation activity (Holzknecht and Zürcher 2006a; Fisahn 2018; Burr 1947; Zürcher et al. 1998; Zürcher 2006; Zürcher and Schlaepfer 2014; Zürcher 2019) are affected by earth tides. In some studies, the effect of tides must be removed from groundwater monitoring results to be able to better interpret hydrogeological tests (Toll and Rasmussen 2007). In other studies, hydrogeological parameters can be derived from potential changes induced by earth tides (Hsieh, Bredehoeft, and Rojstaczer 1988; Wang et al. 2018a; Allègre et al. 2016; McMillan et al. 2019). In plants, even in the absence of light, some studies relate the growth of tree stems to lunar phases (Zürcher et al. 1998; Holzknecht and Zürcher 2006a), others report the variation of leaf movement (Fisahn 2018).

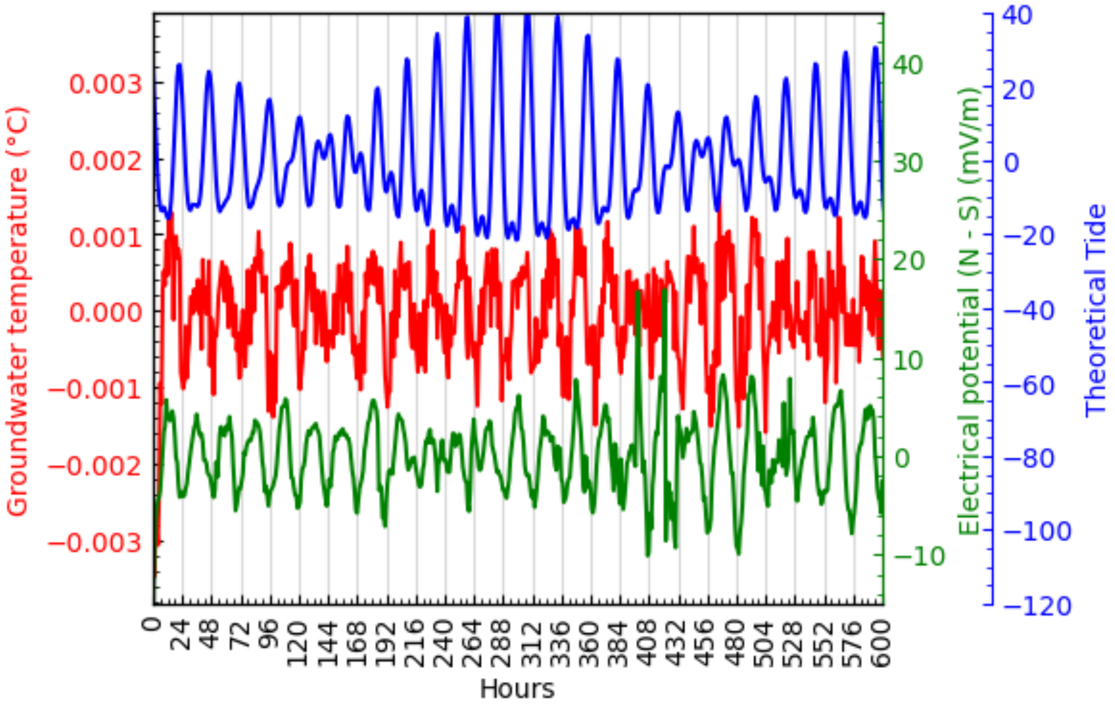

Figure 4.7: Inverse frequency analysis: theoretical tide, electric potential (N-S), and groundwater temperature variation

There are also reports of a change in the speed of germination with a change in earth tidal forces (Zürcher and Schlaepfer 2014).Still, none of these studies can explain our observations concerning to the influence of earth tides combined with vegetation activity and atmospheric electricity.

In our study we observe a relationship between the change in theoretical earth tidal forces and changes in groundwater temperature and electric potential. For better analysis, groundwater temperatures of different frequencies were separated (**Figure 4.3** - vertical line). Temperatures of lowest frequencies representing changes in the macro weather situation, were removed. Just looking at daily groundwater temperature changes (**Figure 4.7**), starting at 15:00, an amplitude of ca. 2 mK is observed, while a variation of about 10 mV/m is reflected in the electric potential changes (**Figure 4.7**). A direct relationship between groundwater temperature change and the change in terrestrial tidal forces could not be detected. Furthermore, a semidiurnal variation (12 hours peak) in electric potential was not observed in the frequency analysis (**Figure 4.3**). (Zhou et al. 2022) used the same geothermometer as employed here and came to the conclusion that the magnitude of the microtemperature variation of groundwater is related to the variation in earth tidal forces amounts to a maximum of 1 mK. This observation is confirmed by our study, showing that the the effect of vegetation and the effect of the tidal are in the same range of variation (Pinheiro et al. 2021; Jahr, Buntebarth, and Sauter 2020; Buntebarth, Pinheiro, and Sauter 2019).

4.3.4 Geothermal temperature and atmospheric tides

Comparing north and south electric potentials with groundwater temperature records (**Figures 4.8 and 4.9**), we observe that there is a clear relationship between both parameters. The south electric potential is however more highly affected by weekly interferences, possibly caused by variations in atmospheric pressure (**Figure 4.3**).

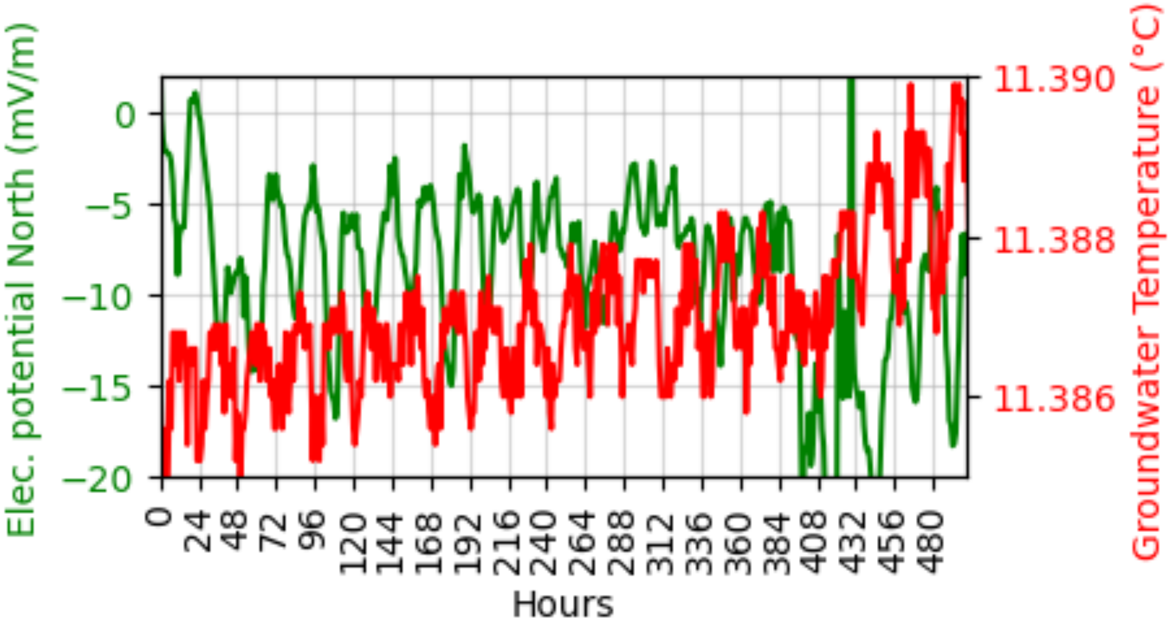

Figure 4.8: Original signal: electrical potential North (N) and groundwater temperature

The surface of the earth is negatively charged. The electrostatic field strength near the earth's surface is about 110-220 V/m and depends on the daily weather conditions (Volkov and Ranatunga 2006). Atmospheric electricity has long been studied (Elster and Geitel 1899b, 1899a, 1899c) and exhibits seasonal variation (Harrison 2012). While land and ocean tides are gravitationally controlled, atmospheric tides are mainly thermally controlled (Lanzerotti and Gregori 1986; Meloni, Lanzerotti, and Gregori 1983). In our study the effect of atmospheric tides is observed in north and south electric potentials changes subjected to frequency analysis (**Figure 4.3**), also observed by (Le Mouël, Gibert, and Poirier 2010).Tides in the upper atmosphere are not mentioned by (Burr 1947), probably because they were not part of the scope of the mentioned work. This semi-diurnal frequency is also present in the atmospheric pressure result (**Figure 4.3**).

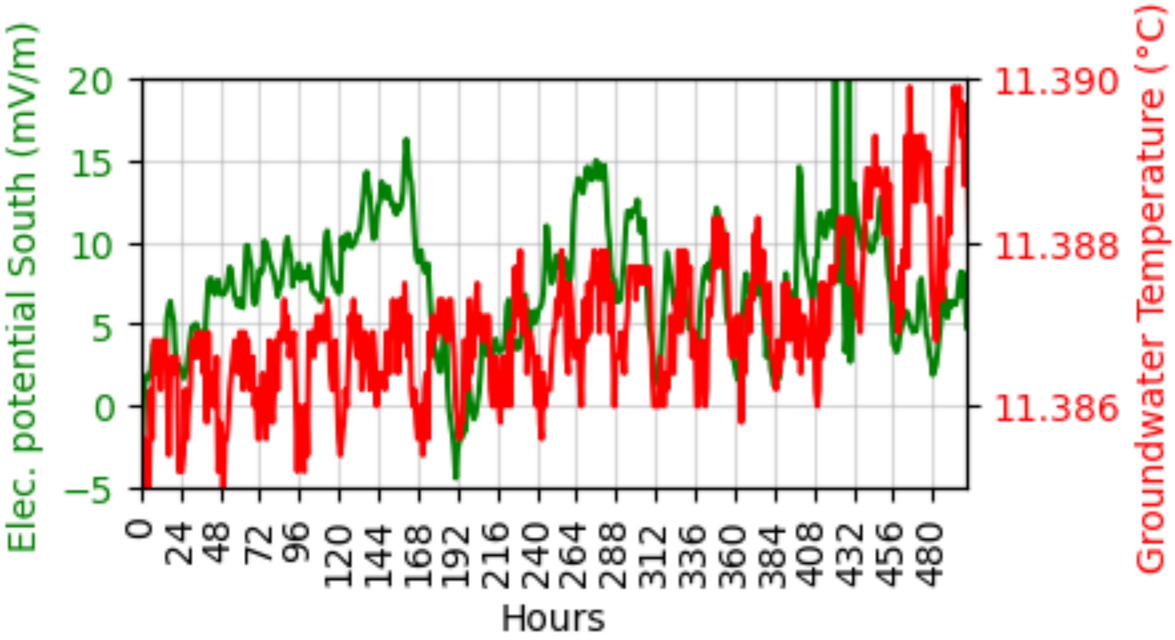

Figure 4.9: Original signal: electrical potential South (S) and groundwater temperature

4.4. Conclusion

Considering that plant transpiration is responsible for most of the water transfer between the subsurface and the surface, we understand that the explanation of a relationship between groundwater microtemperature and plant activity is plausible. We also understand that the advance of technology, in particular geothermal thermometers allows high temperature resolution measurements previously not available. Furthermore, atmospheric electricity can be a plausible force affecting plant activity.

Finally, we do not exclude the presence of other forces acting on natural processes. The use of conceptual models, and especially of boundary conditions, separating, for example, surface and subsurface phenomena, are widely applied and allow to explain the system response to changes in the environmental conditions. However, an interdisciplinary interaction is required to be able to explain the functioning of a system affected.

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5. Synthesis and outlook

This thesis addresses the influence of vegetation activities on the heat transport process in shallow groundwater influenced by external impacts caused by diurnal and seasonal temperature wave transfer at the surface (Pinheiro et al. 2021; Pinheiro, Buntebarth, and Sauter 2023; Buntebarth, Pinheiro, and Sauter 2019). Heat conduction in the subsurface environment is the result of internal and external impacts and is governed by different forces in the short and long term (Bense et al. 2013; Kordilla et al. 2012; Freeze and Cherry 1979; Domenico and Palciauskas 1973; Drury, Jessop, and Lewis 1984; Hamza 1997; Prensky 1992; Shen et al. 1995; Čermák et al. 2000; Majorowicz, Safanda, and Skinner 2002; Hamza and Vieira 2011). Externally, this phenomenon is related to daily temperature variations, terrestrial, oceanic, and atmospheric tides, and vegetation activity variations (Buntebarth et al. 1997; Čermák 1971; Good, Noone, and Bowen 2015; Sun et al. 2011; Muncke 1827; Buntebarth 2002; Tautz 1971; Harrison 2012; Lanzerotti and Gregori 1986; Meloni, Lanzerotti, and Gregori 1983; Beltrami and Kellman 2003; Chahine 1992; Griffiths, Madritch, and Swanson 2009; Zeppel et al. 2008; dos Santos et al. 2017; Kumar, Shankar, and Jat 2014; Schlesinger and Jasechko 2014; Taiz et al. 2015; McElrone et al. 2013; Feddes et al. 2001; Prasad 1988; Guiot, Corona, and Escarsel 2010; Kaspar, Zimmermann, and Polte-Rudolf 2015; Korner 2016; Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021). However, beyond depths of up to 30 meters, thermal conduction is not applied. The transpiration of the vegetation plays a key role in this dynamic by being the connection point between the soil and the atmosphere.

In thermal monitoring, the effects previously considered to be noise could be studied after the development of high-precision equipment in the micro-Kelvin range (Rosen and Fayegh 2017; Čermák and Bodri 2018, 1997; Demetrescu and Shimamura 1997; Hamza and Vieira 2011; Middleton 1999; Pimentel and Hamza 2013; Prensky 1992; Domenico and Palciauskas 1973; Drury, Jessop, and Lewis 1984; Hamza 1997; Buntebarth et al. 1997; Čermák 1971; Buntebarth, Chelidze, and Middleton 2005). Thus, the progress in the resolution of physical properties now allows us to monitor the interaction vegetation x subsoil, presented in this dissertation.

The main objectives of this thesis are (1) to identify the variation of groundwater microtemperature at daily and seasonal level, (2) to compare the variation of groundwater microtemperature with different meteorological parameters, (3) with terrestrial tides, (4) with vegetation activities, and (5) to analytically compare the groundwater microtemperature variation with land use changes in the studied area. This Chapter brings a summarized conclusion of the work and suggestions for future studies.

5.1 Short- and long-term variations in groundwater temperature caused by changes in vegetation cover

Chapter 3 demonstrates how vegetation cover can be responsible for the subsurface temperature variation as well as how this temperature variation can be related to past events. Further, beside the vegetation causing additional convective heat transport triggered by the annual surface temperature, the influence of reduced solar incoming heat radiation reaching the ground caused by the increased shadowing effect of vegetation cover might be responsible for a continuous decrease in local temperature. The studies presented in the Chapter provide the following new insights that are of interest for research on heat conduction in the shallow subsurface environment:

- The sequence of daily subsurface temperatures showed a variation of about 2 mK when the surface temperature reaches a value of almost 9 °C in early spring (Buntebarth, Pinheiro, and Sauter 2019). At lower temperatures this relationship was not observed. The observed variation was related to the growing season of the vegetation, when the increase in surface temperature during spring is responsible for the end of the dormant period of the vegetation (Dierschke 1991; Gaul, Hertel, and Leuschner 2008; Hansen, Vogg, and Beck 1996; Davi et al. 2006; Kramer 2012). This results in increased water uptake by the plants.
- The annual residual temperature in the subsurface showed an increase in winter and a decrease in summer. This observation can be explained by the fact that the activity of the vegetation is intensified during spring

and summer, when the water potential of the plants increases. As a result, the residual groundwater temperature decreases. On the other hand, when the surface temperature decreases and the vegetation enters a period of dormancy, the residual temperature at 40 m depth increases (Pisek and Tranquillini 1951).

- It is understood that although plant roots do not reach depths greater than 20 meters, groundwater uptake by plants can be visualized in a manner similar to the flow configuration near a partially penetrating well, i.e., with considerable vertical flow components. In these types of wells, the hydraulic potential is reduced at shallow depths, inducing fluid flow into the well screen not only as a horizontal radial component, but also as vertical flow from greater or lesser depths, depending on the geohydraulic characteristics of the subsurface and precipitation patterns (Leuschner and Ellenberg 2017; Taiz et al. 2015).
- The periodic variations were also partially explained by the influence of land tides, which induce variations in fluid flow in daily and half-daily periods (Jahr, Buntebarth, and Sauter 2020). This fluid flow can be explained by changes in volume stress, i.e. opening and closing of fractures in the rock mass resulting from changes in the gravitational forces of the sun and moon. The consequent variations in porosity and permeability induce fluid flow.
- The last point analyzed in this work was the influence of increasing vegetation cover in the studied area on the groundwater temperature variation (Nitoiu and Beltrami 2005; Čermák 1971; Bodri and Čermák 2011; Tautz 1971; Carslaw and Jaeger 1992; Prensky 1992; Čermák and Bodri 2018; Demetrescu and Shimamura 1997; Pimentel and Hamza 2013; Middleton 1999). A decrease of 0.04 K/a was observed in the subsurface temperature. The comparison of satellite images between 1999 and 2016 shows an increase in vegetation cover in the studied area. The trees were probably planted during the period from 1980 to 1985. Considering a continuous decrease in surface temperature of 2 K as a boundary condition, equivalent to the reported

temperature step expected after reforestation, the heat conduction equation can be applied. The simulation of an event starting between 10 and 30 years ago (from 1990 to 2010), i.e. the time period of the area of the tree canopy increase was considered. Considering the expected thermal diffusivity (1.0*10-6 m2/s), the temperature change would not be observed for several years. However, when assuming a thermal diffusivity of 1.8*10-6 m2/s, a continuous temperature decrease from 10 to 20 years ago is realistic.

- Here, the thermal diffusivity is evaluated at a higher value than expected. Water uptake by roots in shallow layers may be the reason for the additional temperature decrease at 40 m. Furthermore, it is important to note that an increase in vegetation cover may be responsible for a reduction in local temperature of 2 K, which should have an influence approximately 20 years after planting. Furthermore, a global warming of 2 K in 100 years would have a much smaller warming rate compared to the vegetation effect described above.

In summary, this work has shown a direct relationship of the heat conduction in the shallow subsurface to the vegetation activity at the surface. The depths at which the variations were observed emphasize that heat conduction laws alone cannot be responsible for the anomalies. At the same time, the coincidence with the beginning of the plant growing season and with the surface temperature variation supports the hypothesis presented here.

5.2 Diurnal variations in vegetation activity affecting shallow groundwater flow identified by microthermal measurements

Chapter 4 reinforces how vegetation cover can be responsible for subsurface temperature variation. In addition to the relationship between surface and subsurface temperature, it shows the relationship of these parameters to meteorological parameters and to the electrical potential of plants. The studies presented in the chapter provide the following new insights that are of interest for research on both heat conduction in the shallow subsurface environment and plant physiology:

- Previous results have shown a relationship between groundwater microtemperature and surface air temperature, indicating a strong relationship with the onset of the plant growing season (Buntebarth, Pinheiro, and Sauter 2019; Pinheiro et al. 2021). In the present data, we observe a similar relationship for the summer period. Furthermore, the increase in electrical potential in plants is synchronized with an increase in surface temperature and a decrease in relative humidity. As the surface temperature increases, the relative humidity decreases, and an increase in the electrical potential of the trees, measured as the difference between the northern and southern exposure of the stem (N - S), is observed. This increase in electric potential is concomitant with a change in groundwater temperature of approximately 2 mK. This relationship does not always occur. At high temperatures (+30 °C), the decrease is only 1 mK. This fact is related to the change in transpiration of plants, which decreases or even is suspended at high surface temperatures. At very high temperatures and/or prolonged exposure to higher temperatures, stomata tend to close, thus reducing transpiration rates to prevent excessive water loss and cavitation.
- A frequency analysis of all data showed a high magnitude daily frequency across all parameters (Burr 1947; Gibert et al. 2006; Hao, Li, and Hao 2021; Likulunga et al. 2022). There is a predominant relationship directly correlated with solar radiation intensity. From the phase shift, the response time between groundwater temperature and electric potential can be determined in 17 hours. In this case, there would be a decrease in the groundwater temperature caused by the water uptake and, after 17 hours, an increase in the electric potential. Note that we consider here the difference in electrical potential between the northern and southern exposure positions. For a South - North difference, the phase change becomes 5 hours (Gibert et al. 2006)(Hao, Li, and Hao 2021).
- We could not detect a direct relationship between the change in groundwater temperature and the change in land tidal forces (Doan and

Brodsky 2006; Toll and Rasmussen 2007; Wang et al. 2018; Merritt 1999; Allègre et al. 2016; Hsieh, Bredehoeft, and Rojstaczer 1988; Acworth and Brain 2008; Roeloffs 1988; McMillan et al. 2019). Furthermore, a semi-diurnal variation (12-hour peak) in the electric potential was not observed in the frequency analysis. A comparison between the potential changes and the computed change in gravity resulting from earth tidal effects showed that the correlation between the subsurface temperature change with up to 2 mK and the change in surface temperature change does not correspond directly.

- Finally, this study showed that atmospheric tides can be correlated with changes in north and south electric potentials (Harrison 2012; Volkov and Ranatunga 2006; Meloni, Lanzerotti, and Gregori 1983; Lanzerotti and Gregori. 1986; Elster and Geitel 1899c, 1899a, 1899b). When looking at the frequency analysis of the north and south electric potentials, one notices a mid- day frequency (12 hours) and a weak 8-hour amplitude. This frequency is eliminated from the electric potential with the subtraction of one by the other, which means that it originates from the atmosphere (Le Mouël, Gibert, and Poirier 2010).

In summary, considering that plant transpiration is responsible for most of the water transfer between the subsurface and the surface, we understand that the explanation of a relationship between groundwater microtemperature and plant activity is plausible. We also understand that advances in technology, in particular geothermal thermometers, allow high-resolution temperature measurements previously unavailable. In addition, atmospheric electricity may be a plausible force affecting plant activity.

5.3 Outlook on future research

Developing research considering real data is challenging, to say the least. Nature does not respect boundary conditions defined either by mathematical models or by divisions of the scientific community. Nevertheless, the use of conceptual models and especially boundary conditions, separating for example surface and subsurface phenomena, is widely applied and allows explaining the system's response to changing environmental conditions. However, interdisciplinary interaction is required to be able to explain the functioning of an affected system.

As this is unprecedented work, many questions have arisen along the way. Questions that, no doubt, can be the start of new research on biogeophysics. Although many problems are investigated about the contribution of forest and trees to the Earth's water cycle, not much attention is paid to the fact that roots are a fundamental part of this cycle, connecting the surface with the subsurface. We must first start by investigating more broadly the external variables that affect their functioning, such as the influence of atmospheric tides. What would be the physiological effects caused by them and what changes in the atmosphere of anthropogenic origin can affect the activities of vegetation.

Furthermore, the petrophysical and hydrological properties of the subsoil are sensitive to the water reservoir. Its use by vegetation and recharge by precipitation are links in the chain of the water cycle, which is driven by the sun and moon, resulting in processes controlled by thermal energy and gravitational processes, as demonstrated here. Continuation of this work should include a more detailed study of the water balance, the seasonal effect, and the demonstration of the annual cycle. A mathematical model to calculate the forces involved in this process is also highly recommended.

One of the most current and worrying issues is the effect of climate change on our planet. Here we show that highly resolved temperature measurements underground can provide insight into this topic as well. We understand that further study can lead to promising results for mitigating temperature variations on a local level.

Most groundwater is used globally for agriculture. And another point that this research raises is the variation in the water uptake of the crop when the soil is fertilized. The ion flow in a stem is measured, and by applying this property, an additional effect can be investigated.

Finally, geothermal monitoring shows itself to be an easy-to-install, low maintenance cost, stable technique for long-term monitoring, and of minimal interference to the studied environment. It has already been used in several scientific communities, and this work emphasizes how comprehensive and useful this technique can be.

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