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Recent trends of groundwater temperatures in Austria

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Abstract

Climate change is one if not the most pressing challenge modern society faces. Increasing temperatures are observed all over the planet and the impact of climate change on the hydrogeological cycle has long been shown. However, so far we have insufficient knowledge on the influence of atmospheric warming on shallow groundwater temperatures. While some studies analyse the implication climate change has on selected wells, large scale studies are so far lacking. Here we focus on the combined impact of climate change in the atmosphere and local hydrogeological conditions on groundwater temperatures in 229 wells in Austria, which have in part been observed since 1964. A linear analysis finds a temperature change of + 0.8 ± 1.0 K in the years from 1994 to 2013. In the same timeframe surface air temperatures in Austria increased by 0.72 ± 0.04 K displaying a much smaller variety. However, most of the extreme changes in groundwater temperatures can be linked to local hydrogeological conditions. Correlation between groundwater temperatures and nearby surface air temperatures was additionally analysed. They vary greatly with correlation coefficients of -0.36 in central Linz to 0.80 outside of Graz. In contrast the correlation of nationwide groundwater temperatures and surface air temperatures is high with a correlation coefficient of 0.83. All of these findings indicate that while atmospheric climate change can be observed in nationwide groundwater temperatures, individual wells are often primarily dominated by local hydrogeological conditions. In addition to the linear temperature trend a step-wise model was also applied that identifies climate regime shifts, which have been observed globally in the late 70s, 80s, and 90s. Hinting again at the influence of local conditions, at most 20% of all wells show these climate regime shifts. However, we were able to identify an additional shift in 2007 which was observed by 33% of all wells. Overall the step-wise representation gives a slightly more accurate picture of observed temperatures than the linear trend.

1 Introduction

The thermal regime in the ground is coupled with the conditions in the atmosphere, and air temperature variations leave their traces in the ground. While, already at depth of a few meters, the amplitudes of periodic diurnal and seasonal temperature trends are strongly attenuated, long term non-periodic changes of air temperature permanently influence the subsurface down to greater depths of several tens to hundreds of meters. Worldwide, borehole temperature profiles therefore witness the increase of surface air temperature (SAT) due to recent climate change (Huang et al., 2000; Harris and Chapman, 1997). In borehole climatology, focus is set on "dry" boreholes in undisturbed natural areas, that is, boreholes with negligible influence of groundwater flow and no direct human impacts. Borehole temperatures logged in such boreholes can be used to invert vertical conductive heat transport models for deriving the corresponding trend of ground surface temperature (GST). By assuming that GST and SAT are directly coupled or similar, past climate can be reconstructed. Many boreholes, however, are located in urbanized areas and regions with past changes of land cover, where often accelerated ground heat flux and higher GST are observed (Bense and Beltrami, 2007; Menberg et al., 2013; Bayer et al., 2016; Cermak et al., 2017). Moreover, in humid climate regions boreholes are mostly not dry, but drilled for groundwater use or monitoring. When dynamic groundwater flow conditions exist, then advective heat transport can substantially affect the thermal regime in the subsurface (Ferguson et al., 2006; Kollet et al., 2009; Taylor and Stefan, 2009; Stauffer et al., 2013; Westaway and Younger, 2016; Uchida et al., 2003). The interplay of long-term climate variations, land use change and groundwater thus produces a complex transient system, which is difficult if not impossible to accurately understand based on a few borehole measurements (Kurylyk et al., 2017; Kurylyk et al., 2014; Kurylyk et al., 2013; Zhu et al., 2015; Taniguchi and Uemura, 2005; Taniguchi et al., 1999; Irvine et al., 2016; Kupfersberger et al., 2017).

The consequence of climate change on aquifers was illuminated with respect to groundwater recharge and availability of freshwater resources (Moeck et al., 2016; Scibek and Allen, 2006; Holman, 2006; Gunawardhana and Kazama, 2011; Loáiciga, 2003), groundwater quality impacts (Kolb et al., 2017) and effects on groundwater (-dependent) ecosystems (Burns et al., 2017; Jyväsjärvi et al., 2015; Kløve et al., 2014; Andrushchyshyn et al., 2009). Taylor et al. (2013) summarized various connections and feedbacks between climate change and groundwater. A key parameter is the temperature, which is expected to increase in shallow groundwater globally following with some delay following roughly the trends in the atmosphere. However, long-term measurements of temperature evolution in groundwater are rare (Watts et al., 2015; Figura et al., 2015). Instead often well measurements taken at a few different time points are compared to indicate elevated temperatures, such as by Gunawardhana and Kazama (2011) for the Sendai Plain in Japan, by Safanda et al. (2007) for boreholes in the Czech Republic, Slovenia and Portugal, and Yamano et al. (2009) and Menberg et al. (2013) for urban areas in Eastern Asia and Central Europe. Others, such as Kupfersberger (2009) and (Menberg et al., 2014) examine repeated temperature records of single or a few selected wells. The work by Lee et al. (2014) is one of the very studies on long term groundwater temperature (GWT) time series recorded for a larger area. They applied linear regression to hourly temperature data recorded from 2000 to 2010 at 78 South Korean national groundwater monitoring sites. They found a mean increase of 0.1006 K/year and concluded that shallow ground and surface temperature show moderate proportionality. Lee et al. (2014), however, reported that 12 wells revealed decreasing GWT trends without further details on potential factors. Blaschke et al. (2011) applied trend analyses on long term data sets of mean annual GWT of 112 and 255 wells for the time periods 1955-2006 and 1976-2006 respectively in Austria. They found increasing trends of the GWT in shallow porous aquifers related to increasing air temperature. Similar insights from other regions are lacking still, and the contribution of atmospheric warming to long-term GWT evolution is nearly unexplored.

In the presented study, GWT measured over decades in 229 wells in Austria are analysed and regional patterns and temperature anomalies are identified. In contrast to Blaschke et al. (2011) focus here is not only set on linear trends, but also on detection of climate regime shifts in the measured GWT, following the suggestions by Figura et al. (2011) and Menberg et al. (2014). As a relevant mode of global climate variability, long-lived decadal patterns such as the Atlantic or Pacific decadal oscillation have been identified, e.g. (Minobe, 1997; Rodionov, 2004). These control also atmospheric temperatures and can be found as step-wise increases between the regimes. Even if these regime shifts arrive attenuated and delayed in shallow groundwater, they can be detected and thus can offer another hint on the influence of climatic variations. Aside from the statistical analysis of GWT time series, the influence of land cover as well as their correlation to surface air temperature is investigated to scrutinize potential local influences on the measured data.

2 Material and Methods

2.1 Material

Geology, Hydrogeology and Climate of Austria

The Austrian Alps as the main part of the European Eastern Alps are characterized by a complex geology with various lithologies and has been built up during multiple tectonic phases striking now in a West-East direction. The complexity of the tectonic and geologic settings of the European Alps and in particular of the European Eastern Alps is described and discussed by numerous authors (Schmid et al., 2004; Linzer et al., 2002). Active tectonic evolution resulting in high topography and uplift rates coincide largely with high stream power (Robl et al., 2017; Robl et al., 2008) and thus, have an impact on the drainage system of the Alps. During the Pleistocene the Alps were affected by glaciations with a strong impact on the morphology in particular on the inner alpine valleys and the foreland. Due to sedimentation during the Holocene these areas now contain quaternary porous aquifers. The herein analysed wells are located in shallow aquifers representing these quaternary sediments in the inner alpine valleys and foreland basin. Based on a compiled geology a hydrogeological overview as a hydrogeological map of Austria is provided by Schubert et al. (2003).

Climate and climate trends during the last two century (1800-2000) of the Great Alpine Region (European Alps and their surrounding foreland, GAR) was intensively investigated during last decades yielding in the HISTALP data set (Auer et al., 2007). This data set left its mark on the regional classification of climate zones by Köppen-Geiger where Austria is mainly divided into three climate zones, warm temperate, boral and alpine.

Groundwater Temperatures

In Austria, GWTs are monitored by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, Directorate-General IV. - Water Management (BMLUFUW). In this study, monthly mean data of 229 individual wells from all over the country (Fig. 1a) are analysed. The average measurement depth in the wells is 7 ± 4 m below the ground surface (Fig. S1a). All wells are located in the Cfb climate zone of the Köppen-Geiger classification, warm temperate climate with warm summers and no dry seasons (Rubel et al., 2016). They are monitored since at least 1994, and some already since 1966 (see Fig. S1b for more information). From 1994 to 2013, the recorded GWT time series of all wells are continuous without major breaks (> 3 month). The annually averaged spatial median GWTs and 90 % percentiles for all wells are displayed in Fig. 1b. Here, we focus on annual averages in order to minimize any seasonal bias, which depends on measurement depth and thermal properties of the aquifer. The obtained temperature in Fig. 1b increases from around 10 °C in 1966 to 11.2 °C in 2013.

Surface Air Temperatures

Surface air temperatures (SATs) within Austria are monitored by the Central Institution for Meteorology and Geodynamics (ZAMG), Austria. In this study data from 12 individual weather stations is being analysed, each one is located within 5 km of at least one analysed well and in the same climate zone (Cfb). Their location is displayed in Fig. 1a. Again monthly mean data was available for a time period of 1966 to 2013. The time series of annual mean temperatures is shown in Fig. 1b. As expected and as previously shown in Benz et al. (2017b) for SAT and Benz et al. (2017a) for land surface temperatures, above ground temperatures are generally lower than GWTs.

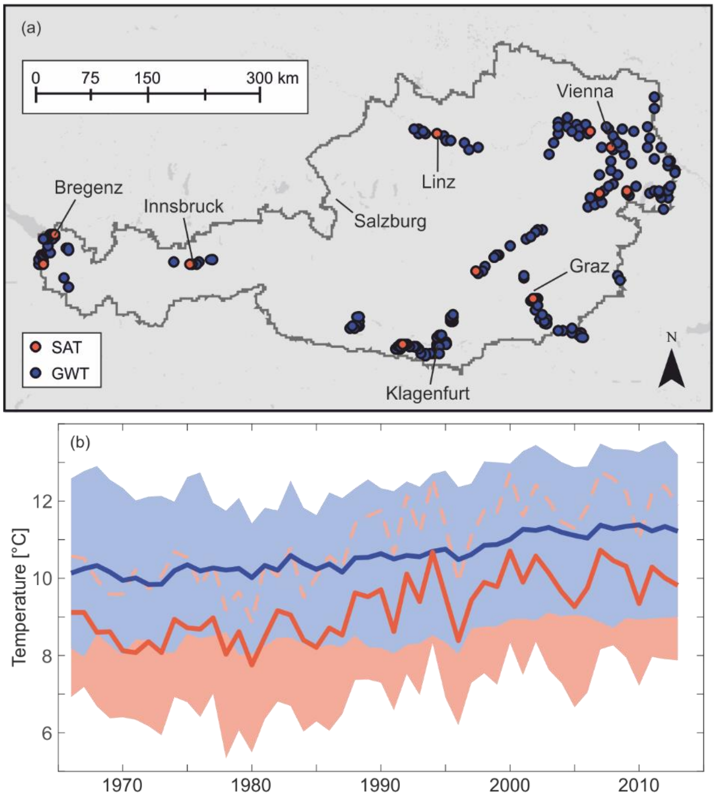

Figure 1. (a) Location of all analysed groundwater temperature (GWT - 229 wells) and surface air temperature (SAT - 12 weather stations) measurement points; (b) temporal evolution of the spatial median, annual mean temperatures for groundwater (blue) and air (red). The inner 90 percentile are marked in lighter colours.

Land Cover

Within this study we worked with the CORINE Land Cover (CLC) data with a resolution of 100 m × 100 m (Fig. S2a). The level-1 nomenclature was used, which divides Austria into three classes: (1) artificial surfaces, (2) agricultural areas, and (3) forests and semi natural areas, which from now on will only be revered to as forest. A map of the CLC 2012 using this classification is shown in Figure S2a. In addition CLC 1990 was consulted, however, no land cover changes near any of the analysed wells and weather stations are observed. All 12 analysed weather stations are located in areas classified as artificial surface, whereas only 45 % of all wells are under artificial surfaces, 46 % agricultural areas, and 9 % under forest following the 100 m × 100 m classification.

2.2 Method

Linear analysis

Equivalent to the work by (Lee et al., 2014), a linear temperature change between January 1994 and December 2013 was determined for all 229 wells. To do so a linear fit of the monthly mean temperature data was determined in Matlab 2016b.

Correlations

Spearman correlation coefficients are determined for annual mean GWT and SATs. Mean values are only determined for a year if more than 8 months of data are available. If there are breaks in the annual mean time series, the corresponding years are ignored. Next to the correlation between GWT and SAT, correlation between all individual wells and weather stations are determined in order to create a plot similar to a (semi)variogram that shows the correlation between two measurement stations depending on their distance to each other.

Climate regime shifts

Climate data is often thought not change linearly, but in form of a step function, dividing a time series into individual climate regimes of a constant mean (Andrushchyshyn et al., 2009; Minobe, 1997). These regimes are changed when so-called climate regime shifts (CRS) occur and mean values change. While several methods to model these shifts have been in use (Easterling and Peterson, 1995), in recent years the method by Rodionov (2004) became standard. This sequential analysis is data driven and requires no prior knowledge of the timing of possible shifts. It was updated to further include prewithening in order to reduce background noise (Rodionov, 2006) and is available online as a Microsoft Excel add-in (NOAA, 2017). In this study we applied the method to all analysed temperature time series using annual mean data. Breaks within that data were filled using a linear fit. All parameters were set to the same values as in the work by Menberg et al. (2014), who applied the method to four GWT time series in Germany. A target significance level of 0.15 was used by Menberg et al. and in our analysis, the cut off length was set to 10 years and the Huber weight parameter was set to 1.

3 Results and Discussion

3.1 Correlations

Figure 2a displays the correlation between different wells or rather different weather stations in relation to their distance to each other. Shown is the distance between two wells/weather stations on the x-axis and the corresponding spearman correlation coefficient between them. For the weather station each individual pair is shown by a red point, for GWTs, as there are so many possible pairs of wells, the lines gives the moving median (± 25 km) correlation of all pairs at the corresponding distances. As expected correlation decreases with distance. This decrease is more extreme in the GWT

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than in the SAT and GWT correlate less than SAT overall. This agrees with the observations in Benz et al. (2017b) that showed that annual mean GWTs show greater variations than SAT over the same distances.

Additionally the correlation between two wells seems to be anisotropic: the distance in the north-south direction of two wells has more influence on the correlation between both temperatures than the distance in west-east direction (Fig. 2b). This is also the cause of the jump in correlation at 600 km that can be observed in Fig. 2a. Due to the shape of Austria from this distance on wells must both be located at a similar latitude. The anisotropic behaviour of correlations can be explained by the orientation and morphology of the Alps, where valleys generally run from west to east. Hence, larger rivers typically follow this direction and wells at the same latitude observe same or similar temperature signals.

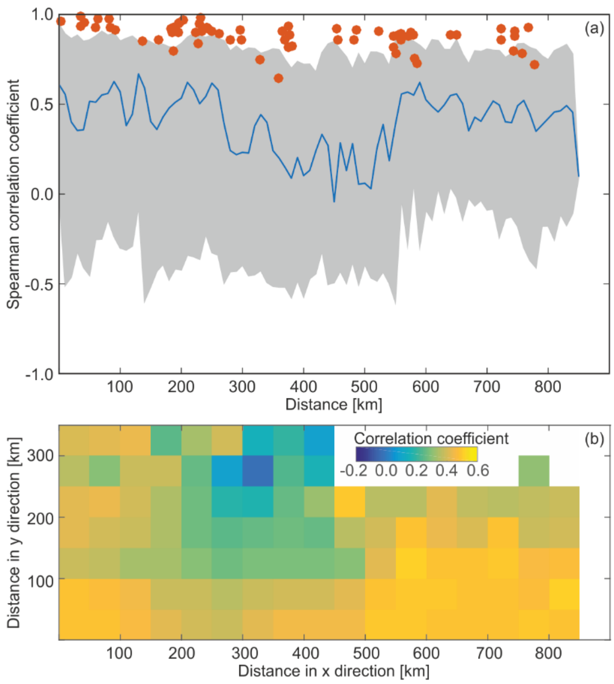

Figure 2. Influence of distance on the correlation between the annual means of two measurement points. a) Correlation between SAT time series is given in red, median correlation between GWT time series is given in blue. The inner 90 percentile are coloured in grey. b) The colour gives the median correlation between GWTs of two wells in relation to their absolute distance to each other in east-west direction (x-axis) and in north-south direction (y-axis).

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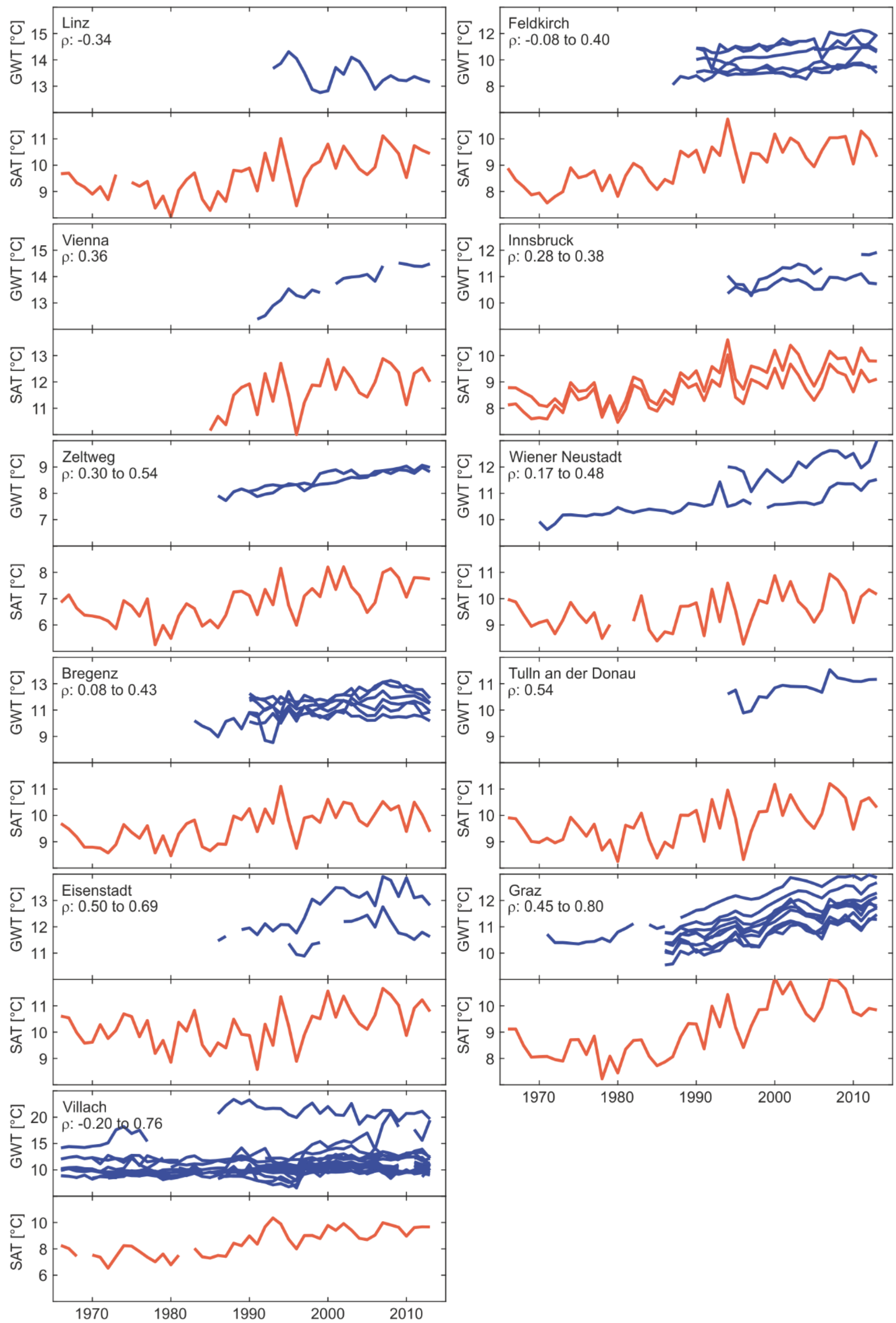

Figure 3. Surface air temperature (SAT) and groundwater temperatures (GWTs) of all wells within 5 km of the analysed weather station. See Fig. S3 for an overview of the locations. Minimum and maximum correlations between individual wells and weather stations are given.

In a next step, correlations between weather stations and wells within 5 km of them are being analysed. All locations are displayed in detail in Fig. S3, and time series of SAT and GWTs are shown in Fig. 3. Correlations vary greatly, however are < 0.5 for about half of the individual pairs of wells and weather stations. This indicates that GWTs are often influenced by local causes and not necessarily solely by surface temperatures. The lowest correlation is determined in Linz (Table 1) where the groundwater is intensively used for cooling and heating (Krakow and Fuchs-Hanusch, 2016). The studied well is located within the city centre next to train tracks and office buildings. Hence, it is very likely that the thermal properties of the groundwater are dominated by anthropogenic influences from heated buildings and underground structures as often the case in subsurface urban heat islands (Menberg et al., 2013; Benz et al., 2015b; Attard et al., 2016; Benz et al., 2015a), which would also explain the high GWTs with average 3.3 K warmer than the local annual mean SAT. Like the well, the weather station is also located within the city centre.

The best correlations between individual pairs of a well and a weather station can be observed in the southern part of the city of Graz, where all wells and the weather station are again located close to or within the Graz airport, respectively. The well with the highest correlation of 0.80 to SAT is located less than 1 km from the weather station and is continuously monitored since 1970 and shows the longest time series in the area. The well with the lowest correlation (0.45) to the weather station here is located slightly to the east near a dog-park. Here observations started in 1994, it is the shortest time series in this area. All other wells here began measurements in 1986 and show correlations between 0.6 and 0.7 to the weather station. However, while the duration of the measurements play a significant role for local comparisons, it is not significant when comparing data on a countrywide scale. For example the long time series in Wiener Neustadt (Fig. 3), which started measurements in 1970 has a correlation of 0.48 and is therefore comparable to the short time series in Graz.

Table 1. Correlation between spatial median SAT and spatial median GWT for all analysed SAT locations and additional information.

Location	Number of wells	Number of weather stations	Spearman correlation	p-value	Population[a)]
Linz	1	1	-0.34	10^{-1}	192,000
Feldkirch	6	1	0.24	10^{-2}	31,000
Vienna	1	1	0.36	10^{-1}	1,740,000
Innsbruck	2	2	0.40	10^{-2}	123,000
Zeltweg	2	1	0.49	10^{-3}	7,000
Wiener Neustadt	2	1	0.51	10^{-4}	42,000
Bregenz	6	1	0.51	10^{-3}	28,000
Tulln an der Donau	1	1	0.54	10^{-2}	15,000
Eisenstadt	2	1	0.71	10^{-5}	13,000
Graz	9	1	0.71	10^{-7}	266,000
Villach	19	1	0.80	10^{-11}	60,000

[a)] Register-based Labour Market Statistics 2014, municipality level, Statistik Austria (Austria, 2017).

Table 1 displays the correlations between spatial median GWT and spatial median SAT for each of the SAT locations in Fig S2. For all locations with at least two wells besides Zeltweg and Graz correlation does improve when spatial median GWT is analysed instead of the individual locations. In all likelihood the spatial median GWT provides a more general temperature trend that is not influenced by local influences on temperatures such as construction work, plant development and shading, and are therefore more closely related to surface air temperatures. This is also shown by the higher correlation of spatial median GWT and SAT for all of Austria (Fig. 1b) with 0.83 and thus higher than any pair of individual well and weather station.

In addition, the data indicates that city size or rather population of the city does not necessarily influence the correlation between GWT and SAT. For example, the correlation in Vienna, Austria's largest city with a population of 1.7 Million, is slightly larger than the one in Feldkirch, a town with approximately 30,000 inhabitants. Similar both locations Graz (population of more than 250,000) and Eisenstadt (population of 13,000) have the same correlation of 0.71 despite their vastly different population. However, it is important to note that not all wells analysed here are located in the city centre, still all of them are within close proximity (< 250 m) of build-up, urban areas (see Fig. S2).

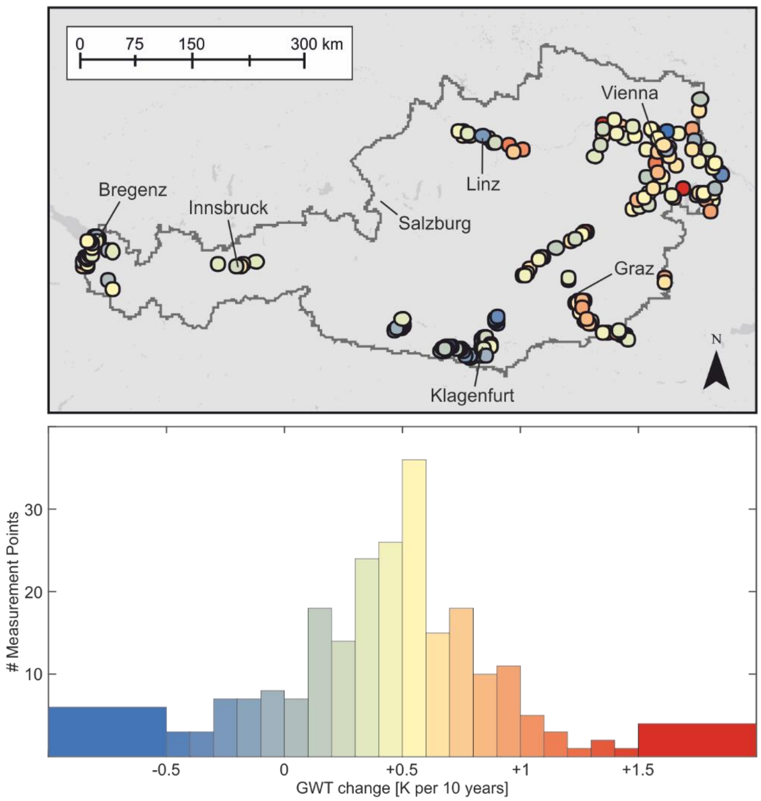

Figure 4. Increase in temperature for all individual measurement points for the 20-year timeframe 01/1994 to 12/2013. The mean change in groundwater temperature is +0.4 ± 0.5 K per 10 years.

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3.2 Linear temperature change

During the time between 01/1994 and 12/2013, GWTs have changed on average by +0.45 ± 0.49 K per 10 years and SAT on average by +0.36 ± 0.02 K per 10 years. The increase of GWT is in good agreement with results of a former study considering data sets of Austria from 1976-2006 (Blaschke et al., 2011). This is more than double the global air temperature increase determined by Jones et al. (1999) for the timeframe 1978 to 1997 with +0.32 K in 20 years and slightly less than the numbers given in the work by Ji et al. (2014). In their global study they give an air temperature increase of more than 0.4 K for the timeframe 2000 to 2009 for the northern mid-latitudes including Austria. Fig. 4 displays a map and a histogram of all determined GWT changes. There appears to be no influence of land cover on the observed temperature change (Fig. S2b). However, for the time period from 1990 to 2012, which does not include a major land cover change at any of the well locations, GWTs under artificial surfaces are on average 1.4 ± 0.3 K warmer than GWTs under forest; and GWTs under agricultural areas are on average 0.6 ± 0.2 K warmer than GWTs under forest (Fig. S2c). This validates previous findings by Benz et al. (2017b) for GWTs in Germany, who identified even larger differences of up to 3 K between the individual land cover classes.

No obvious spatial pattern for temperature changes is visible. However, most wells with temperature changes lower than the 5th percentile are located close to the river Drava in Ferlach, Villach, and Kleblach-Lind in the very South of Austria (Fig. 5 and Fig. S4). Although they are up to 80 km away from each other, all of these wells show a sudden drop in temperatures in the year 2007 (wells Ia, Ib, IIa, IIb, Va, and Vb marked blue in Fig. 5). This temperature reduction can be seen in most of the 27 wells that are less than 1 km from the Drava away (Fig. S5), for 24 of them temperatures in 2006 are more than 0.6 K warmer than temperatures in 2008. However, temperatures (as well as additional parameters such as water level) within the river do not indicate any connection between this sudden temperature reduction and the Drava river (Fig. S5). It is however possible, that the flood event in July 2007 might have caused a change in the river and aquifer interaction along the Drava river and consequently the change in the GWTs. Either way, further research is necessary to identify the cause of this temperature anomaly.

Additionally, three other wells in the lowest 5 percent of temperature change are all located less than 10 km from each other near the village Kappel am Krappfeld (wells IVa, b and c marked orange in Fig. 5). They and also additional surrounding wells show a steep decline in temperatures in 2006 before temperatures start to increase steadily again. These wells seem to be affected by the new drinking water supply (four wells with a total pumping rate of about 100 l/s) located about 1 km in the south brought on line during this time. In general, most of the extreme changes in temperature appear to be caused by local causes and do not change gradually, but in one sudden drop or rather rise in temperatures. Another example of this can be seen in wells with temperature changes higher than the 95th percentile (Fig. 5 and Fig. S6). While these highest five percent of all wells do not show local clusters to the same extend as the lowest 5 percent and can be observed all over the country, three wells (6a, 6b and 6c, marked dark blue in Fig. 5) are located in Villach in the South of Austria. The latter are influenced by ascending thermal water via a fault system, which is related to the Periadriatic Lineament (Zojer, 1980) showing a temperature increases of up to 3.7 K per 10 years. Some wells in Villach are also close to the river Drava and are in the lowest 5 % regarding temperature change, however a drastic increase in temperature cause by the local hot springs can be observed in earlier years (Fig. 5, wells IIb and IIc marked dark blue).

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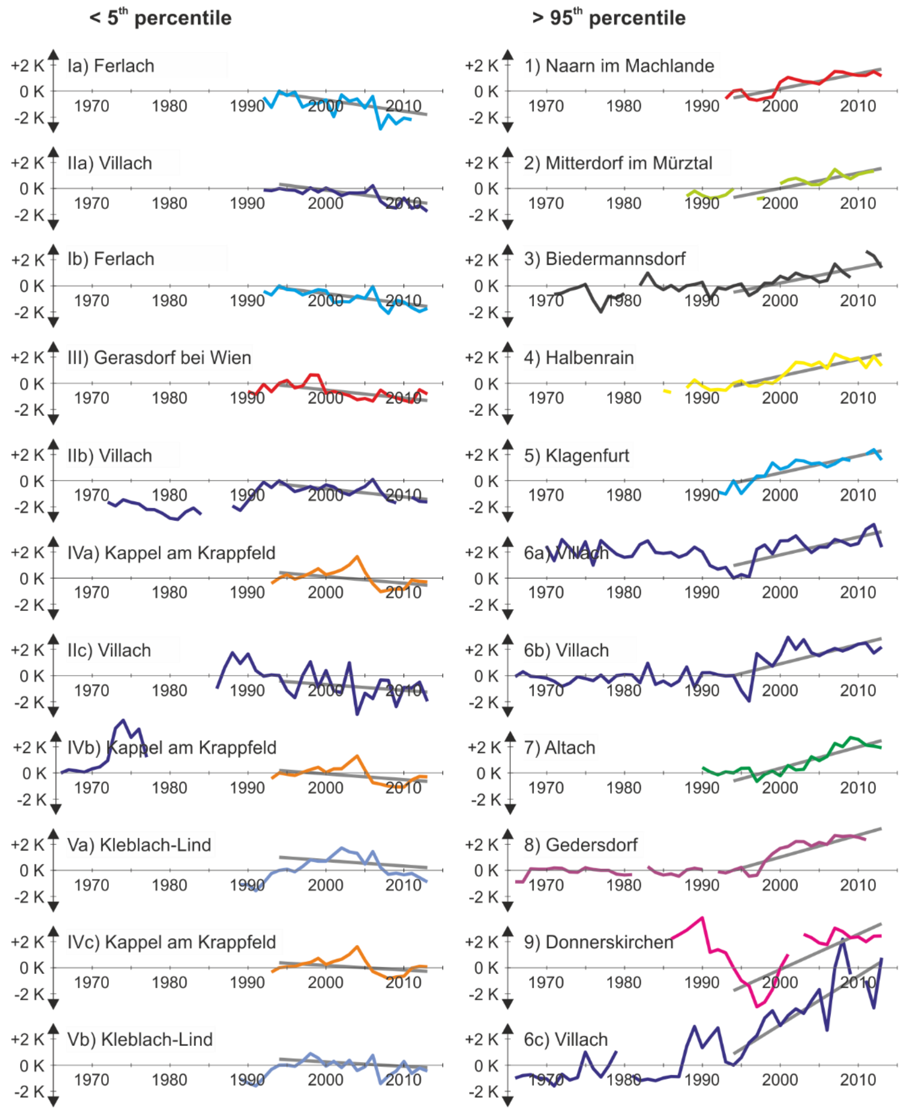

Figure 5. Annual mean time series and linear fit (in grey) of the wells with the lowest (left side, numbered with roman numbers) and highest (right side, numbered with arabic numbers) temperature changes in the time frame 01/1994 and 12/2013. See Fig. S4 and S5 for an overview of the locations. They are placed in ascending orders with the highest temperature change at the bottom.

To evaluate the goodness of this linear approach when representing climate change, RMSE of the fit was determined for each well on the basis of annual mean GWT data for 1994 to 2013. We found an average RMSE of 0.4 ± 0.2 °C. By far the worst fit, with an RMSE of 1.4 °C is determined for the well in Villach that has the highest temperature increase of 3.7 K per 10 years is caused by the local thermal hot spot (Fig. 5, plot 6c).

3.3 Climate regime shifts

Global climate regime shifts (CRS) in air and also groundwater were detected for the late 70s, the late 80s and the late 90s by Menberg et al. (2014). Using the same algorithm spatial median annual mean GWT and SAT in Austria show shifts in the late 80s and 90s (Fig. 6a). GWTs show additional shifts in 1981 and 2007. While the shift in the late 80s is observed during the same year (1988) in GWT and SAT, the shift in the late 90s appears earlier and is more significant in GWTs. As temperature signals from the surface can be observed in the GWT with a time lag and not early on, this indicates that the CRS method cannot be used to determine the precise time lag between GWT and SAT. Accordingly the detected time shifts in wells within 5 km of a weather station do generally not indicate the same CRS as the weather station: Of 45 CRS observed in at least one well only 7 are also observed in a nearby weather station no more than year before (Fig. S7). For this analysis, the weather station in Villach was excluded, as GWTs here are dominated by local hot springs and not by surface temperature changes. It is also important to note that some of the analysed time series only span over a 20 year time period and are thus on the shorter end for a statistically relevant analysis of climate regime shifts (Rodionov, 2006).

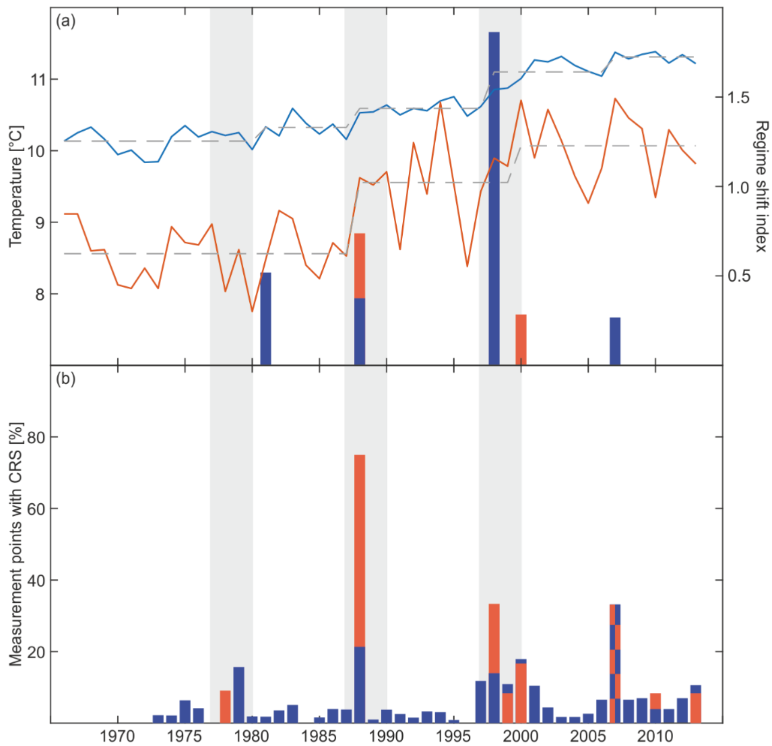

Figure 6. (a) Spatial median annual mean groundwater temperature (blue) and surface air temperature (red) as well as the corresponding climate regime shifts (CRS) in form of the regime shift index. (b) Percentage of measurement points in GWT (blue) and SAT (red) that show a CRS in each year. The analysis of global temperatures data indicates a regime shift at the end of the 70s, the 80s and the 90s which are shown here in as grey bars.

Overall GWTs increase by 1.8 K between the first and last analysed CRS and SAT increased by 1.5 K. If the individual wells and weather stations are analysed (Fig. 6b), we found that at most 33 % of all wells show a CRS at the same time (in 2007), during the global shifts only 20 % of all wells indicate them. However, these are not the same 20 % for each individual shift. Additionally the dimension of the shifts do not always agree. For example, wells experiencing a shift observed in 2007 include all wells along the Drau observed in Fig. 5 and S5, which show a sudden drop in temperature for this year. In contrast, the countrywide time series in Fig. 6a indicates a positive shift in temperatures.

Results show that the shift in the 90s is temporally more spread out than the shifts in the 70s and 80s in both GWT and SAT. This indicates that this shift is less well defined and temperatures of the globe became more variable in their temporal evolution. In accordance to this interpretation there is a higher percentage wells with a CRS in the years after 1996 than before. Furthermore, one third of all weather stations and wells detect a shift in 2007, which was not observed by Menberg et al. (2014) whom studied shorter time series than here. These include wells along the river Drau (see Fig. S5) which show a negative shift in that year. If these wells are excluded 24 % of the remaining wells indicate 2007 as the start of a new climate regime within Austria. This year was also identified by Litzow and Mueter (2014) as the start of a new regime for both climate and biological indicators within the North Pacific Ocean.

Like with the linear approach, the goodness of the CRS and corresponding statistical step model was evaluated by determining the RMSE for the time period 1994 to 2013. We determined a mean RMSE value of 0.3 ± 0.2 K, which is slightly better than the RMSE for the linear fit as determined above (0.4 ± 0.2 K). Only 15 of the 229 analysed wells provided a better fit using the linear approach than the statistical step model of the CRS approach. Hence, we conclude that the CRS method is more appropriate to simulate temperature changes in groundwater than a linear approach even for time periods as short as 20 years.

4 Conclusions

Temperatures in 229 shallow wells and 12 weather stations in Austria, monitored in part since 1966, were analysed in this study. Linear temperature change was determined and revealed a general increase in temperature between the years 1994 and 2013 of approximately 0.4 ± 0.5 K per 10 years in the groundwater and on average 0.36 ± 0.02 K per 10 years in the air. Most extreme changes in groundwater temperatures, especially temperature decrease, could be linked to local causes such as the instalment of a new drinking water supply that influences nearby groundwater wells. This reveals the extent in which groundwater temperatures are dominated by local events and the thermal properties of the surrounding. Accordingly correlation between annual mean groundwater temperatures and nearby (< 5 km) air temperatures varies greatly from -0.36 in Linz to 0.80 near Graz. However, if spatial median groundwater temperatures and surface air temperatures of all of Austria are compared, we found a significant correlation of 0.83 demonstrating once more that groundwater temperatures are closely linked to surface temperatures and therefore experience climate change. However, globally observed climate regime shifts in the late 70s, 80s and 90s could only be identified in approximately 20 % of all wells. Nevertheless, we were able to observe another shift in 2007 in 33% of all wells and weather stations indicating this year as the possible start of a new climate regime within the alpine region. However, further research studying other climate parameters such as permafrost and snowfall is necessary to validate these findings. Overall climate regimes represent measured temperature slightly better (RMSE: 0.3 ± 0.2 K) than the linear fit (RMSE: 0.4 ± 0.2 K).

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