

1 **Observed groundwater temperature response to recent** 2 **climate change**

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14

15 **Abstract**

16 Climate change is known to have a considerable influence on many components of the
17 hydrological cycle. Yet, the implications for groundwater temperature, as an important driver
18 for groundwater quality, thermal use and storage, are not yet comprehensively understood.
19 Furthermore, few studies have examined the implications of climate change-induced
20 groundwater temperature rise for groundwater-dependent ecosystems. Here, we examine the
21 coupling of atmospheric and groundwater warming by employing stochastic and deterministic
22 models. Firstly, several decades of temperature time-series are statistically analyzed with
23 regard to climate regime shifts (CRS) in the long-term mean. The observed increases in
24 shallow groundwater temperatures can be associated with preceding positive shifts in regional
25 surface air temperatures, which are in turn linked to global air temperature changes. The
26 temperature data are also analyzed with an analytical solution to the conduction-advection
27 heat transfer equation to investigate how subsurface heat transfer processes control the
28 propagation of the surface temperature signals into the subsurface. In three of the four
29 monitoring wells, the predicted groundwater temperature increases driven by the regime shifts
30 at the surface boundary condition generally concur with the observed groundwater

1 temperature trends. Due to complex interactions at the ground surface and the heat capacity of
2 the unsaturated zone, the thermal signals from distinct changes in air temperature are damped
3 and delayed in the subsurface, causing a more gradual increase in groundwater temperatures.
4 These signals can have a significant impact on large-scale groundwater temperatures in
5 shallow and economically important aquifers. These findings demonstrate that shallow
6 groundwater temperatures have responded rapidly to recent climate change and thus provide
7 insight into the vulnerability of aquifers and groundwater-dependent ecosystems to future
8 climate change.

9

10 **1 Introduction**

11 Atmospheric climate change is expected to have a significant influence on subsurface
12 hydrological and thermal processes (e.g. Bates et al., 2008; Green et al., 2011; Gunawardhana
13 and Kazama, 2012). While the consequences for groundwater recharge and water availability
14 were scrutinized by many studies (e.g. Maxwell and Kollet, 2008; Ferguson and Maxwell,
15 2010; Stoll et al., 2011; Taylor et al., 2013; Kurylyk and MacQuarrie, 2013), there is still a
16 lack of studies regarding the observation and analysis of the effects of recent climate change
17 on shallow groundwater temperatures (Kløve et al., 2013). Groundwater temperature (GWT)
18 is known to be an important driver for water quality (e.g. Green et al., 2011; Sharma et al.,
19 2012; Hähnlein et al., 2013) and therefore, it is a crucial parameter for groundwater resource
20 quality management (Figura et al., 2011).

21 Furthermore, increasing groundwater temperatures can have a significant influence on
22 groundwater and river ecology (e.g. Kløve et al., 2013). Numerous studies on the impact of
23 recent or projected climate change on the thermal regimes of surface water bodies and the
24 associated impact for coldwater fish habitats have already been conducted (e.g. Kaushal et al.,
25 2010; van Vliet et al., 2011, 2013; Wenger et al., 2011; Isaak et al., 2012; Wu et al., 2012;
26 Jones et al., 2014), but the thermal sensitivity of shallow aquifers to climate change is a
27 relatively unstudied phenomenon (e.g. Brielmann et al., 2009, 2011; Taylor and Stefan, 2009;
28 Kurylyk et al., 2013, 2014a). The thermal response of GWT to climate change is of particular
29 interest to river temperature analysts, as the thermal regimes of baseflow-dominated streams
30 or rivers and hydraulically connected aquifers are inextricably linked (Hayashi and
31 Rosenberry, 2002; Tague et al., 2007; Risley et al., 2010). Furthermore, groundwater sourced
32 coldwater plumes within river mainstreams are known to provide thermal refuge for
33 threatened coldwater fish (e.g. Ebersole et al., 2001; Breau et al., 2007), and questions have

1 arisen regarding the sustainability of these groundwater-dependent ecosystems (GDEs) in a
2 warming climate (Deitchman and Loheide, 2012). The current lack of knowledge regarding
3 the thermal vulnerability of GDEs to the climate change-induced recent warming of shallow
4 GWT has been highlighted as a research gap in several recent studies (e.g. Bertrand et al.,
5 2012; Mayer, 2012; Kanno et al., 2014).

6 Thermal signals arising from changes in ground surface temperatures (GST) propagate
7 downward into the subsurface, causing GWT to deviate from the undisturbed geothermal
8 gradient. Heat transport theory has been applied for inverse modeling of temperature-depth
9 profiles to infer paleoclimates based on measured deviations from the geothermal gradient
10 (e.g. Mareschal and Beltrami, 1992; Pollack et al., 1998; Beltrami et al., 2006; Bodri and
11 Cermak, 2007) and for forward modeling the impact of projected climate change on measured
12 temperature-depth profiles (e.g. Gunawardhana and Kazama, 2011; Kurylyk and MacQuarrie,
13 2014). Such studies are often based on the assumption that long term trends in GST will track
14 long term trends in surface air temperature (SAT), although this has been a matter of
15 considerable debate (e.g. Mann and Schmidt, 2003; Chapman et al., 2004; Schmidt and Mann,
16 2004). For example, decreases in the duration of thickness of the insulating winter snowpack
17 due to rising SAT can paradoxically lead to decreased winter GST (Smerdon et al., 2004;
18 Zhang et al., 2005; Mellander et al., 2007; Mann et al., 2009; Kurylyk et al., 2013), which
19 lead to a decoupling of mean annual SAT and GST trends.

20 Heat advection due to groundwater flow may also perturb subsurface temperature-depth
21 profiles, and it can be difficult to determine if deviations from a linear geothermal gradient
22 have arisen from past climate change or from groundwater flow (Reiter, 2005; Ferguson and
23 Woodbury, 2005; Ferguson et al., 2006). Thus, several analytical solutions have been
24 proposed that account for subsurface thermal perturbations arising from a combination of
25 climate change and vertical groundwater flow (e.g. Taniguchi et al., 1999a, b; Kurylyk and
26 MacQuarrie, 2014). The solutions vary depending on the nature of the surface boundary
27 conditions employed (e.g. linear, exponential, or step trends in temperature), which can be
28 used to match measured or predicted GST trends for a region. These solutions do not account
29 for horizontal groundwater flow, which can also perturb subsurface thermal regimes in certain
30 environments (Ferguson and Bense, 2011; Saar, 2011). Numerical solution techniques can
31 also be applied to account for inhomogeneous subsurface thermal properties, complex surface
32 temperature evolution, and groundwater flow (e.g., Kooi, 2008).

1 Figura et al. (2011) show that temperature variations in Swiss aquifers that are recharged by
2 river water through bank infiltration can be related to changes in climate oscillations systems
3 by applying a statistical regime shift analysis. Characterizing changes in time-series of various
4 climatic, physical and biological parameters with the concept of abrupt regime shifts has been
5 the focus of numerous studies in the last two decades (e.g. Hare and Mantua, 2000; Overland
6 et al., 2008). In this context, a regime is often defined as a period with quasi-stable behavior
7 or with a quantifiable quasi-equilibrium state (deYoung et al., 2004), and accordingly a rapid
8 transition between states with differing average characteristics over multi-annual to multi-
9 decadal periods is referred to as a regime shift (Bakun, 2004).

10 In this study, we demonstrate the direct influence of atmospheric temperature development on
11 shallow GWT at two sites in Germany by analyzing time-series of SAT and GWT with regard
12 to abrupt changes in the long-term annual mean. Compared to previous studies, which used
13 borehole temperature profiles for the analysis of temperature coupling between the
14 atmosphere and the subsurface, the measured time series of annual GWT of the last decades
15 in this study allow for an evaluation of this coupling on a shorter time scale with a higher
16 temporal resolution. Furthermore, we compare different spatially averaged temperature time-
17 series from individual weather stations to global mean air temperature change bringing our
18 observations in the context of global climate change. The magnitudes of the regime shifts and
19 the time lags between the shifts in the chosen time-series are evaluated under consideration of
20 the different thermal processes in the subsurface and the site-specific hydrogeological
21 settings. A standard analytical solution to the conduction-advection subsurface heat transfer
22 equation is applied to investigate the physical thermal processes underlying the observed
23 correlation between SAT regime shifts and GWT rise.

24

25 **2 Data and methods**

26 **2.1 Data and site description**

27 For the analysis of shallow GWT, we use time-series from four observation wells in porous
28 and unconfined aquifers in Germany (Table 1, Fig. 1a and b). Two of the wells are installed in
29 the surrounding area of Cologne outside the small villages of Dansweiler and Sinthern in
30 agricultural areas. The other two wells are located in a rather densely vegetated forest, called
31 Hardtwald, close to the city of Karlsruhe and are therefore named Hardtwald 1 and 2. The
32 proximate surroundings of all four wells were undisturbed over the last decades, so that

1 variations in GWT due to land use changes are unlikely. The distances from the observation
2 wells to the nearest streams are several kilometers (Table 1), thus the influence of river water
3 on the groundwater temperature in the wells can be excluded. The two study areas close to
4 Karlsruhe and Cologne are located approx. 240 km apart from each other and belong to
5 different aquifer systems. Yet, the basic geological and hydrogeological settings of the two
6 aquifers are rather similar (Table 1 and 2).

7 Table 2 lists some basic hydrogeological properties of the studied aquifers and the observation
8 wells. The depth of water table differs considerably between the two well fields, and is
9 approximately 17m for the Cologne aquifer and 7m near Karlsruhe. Variations in the depth of
10 water table during the observation period are within $\pm 1\text{m}$ for the Dansweiler and Sinthern
11 wells and more pronounced in the Hardtwald wells with about $\pm 3\text{ m}$, which are likely caused
12 by a pumping station nearby. However, no statistically significant trend was observed over the
13 last decades in the water level of the observation wells. Both aquifers are recharged by
14 infiltration of meteoric water through the unsaturated zone with estimated recharge rates of
15 $221\pm 45\text{mmyr}^{-1}$ for the Cologne aquifer and $228\pm 45\text{mmyr}^{-1}$ for the aquifer near Karlsruhe
16 (Table 2). A schematic cross-section of the two aquifers near Cologne (left) and Karlsruhe
17 (right) in Fig. 1c and d shows the average depth of the water table below surface level and the
18 depth of the underlying aquitard. Details on the wells' constructions are also depicted with the
19 overall depth and the locations of the filter screens (black areas) that indicate the depth where
20 the pumped water is captured. Furthermore, Fig. 1c and d shows the distance between the
21 wells pairs as well as the distances to the weather stations from which the SAT time-series
22 were obtained.

23 GWT in all observations wells was measured one to six times per year for a period of at least
24 32 years (1974–2006) during frequent water quality assessments by the local groundwater
25 authorities. The measurement protocol, which is standardized by the environmental state
26 agencies to assure data quality and comparability, has undergone no significant changes in the
27 last decades. During the specified procedure, water is pumped from the wells until the water
28 temperature and other on-site parameters are constant. The temperature measurements are
29 thereby conducted with a probe directly at the outlet, to minimize influences by ambient air
30 temperatures. An examination of the time series for seasonal effects revealed that they contain
31 certain minor seasonal effects with annual variations of up to $\pm 0.2\text{ K}$, which indicates an
32 impact of ambient air temperature on the GWT during the sampling. The natural temperature
33 variations due to seasonal GST variations in depths of over 20 m (Table 2) are expected to be
34 less than 0.1 K as can be demonstrated by Stallman's (1965) equation. In most years, at least

1 two measurements per year were available, so that the arithmetic mean was adopted as an
2 annual mean value to minimize such effects. It should also be noted that the measurement
3 accuracy is in the range of ± 0.1 K. Also changes in the measurement procedure, such as
4 variations in the pumping rate or in the placement of the pump within the well, as well as
5 changes in the measurement equipment, can influence the measured GWT and were
6 considered for the evaluation and interpretation of the data.

7 Annual SAT data are available from weather stations operated by the German Weather
8 Service (DWD) outside the cities of Cologne and Karlsruhe in agricultural surroundings (Fig.
9 1a and b). Though located several kilometers from the observation wells, the SAT from these
10 stations is expected to yield a good approximation for the development of SAT at the well
11 sites. Furthermore, for the evaluation of abrupt shifts in the time series of SAT and GWT, the
12 absolute temperature is only of minor importance, while the main focus is on the timing of the
13 shifts and the temperature differences. For the comparison with air temperatures on a larger
14 scale, we use time-series of mean air temperature anomalies based on the reference period
15 1951–1980 from the NASA Goddard Institute for Space Studies (GISS) (e.g. Hansen et al.,
16 2010). Of the spatially averaged temperature data sets available, we evaluate the annual global
17 mean from land-surface air and sea-surface water temperature anomalies and the annual zonal
18 mean for the Northern Hemisphere between 90° and 24°N based on land-surface air
19 temperature anomalies.

20 **2.2 Regime shift analysis**

21 There are several possibilities to statistically evaluate temperature changes in time series with
22 rather simple functional forms. Seidel and Lanzante (2004) compared different approaches
23 (e.g. linear and flat steps models) and revealed that often time-series of atmospheric
24 temperatures can be represented more appropriately by models using breakpoints than by
25 models assuming monotonic functions. Hence, we here apply a sequential t-test analysis for
26 regime shifts (STARS) to detect possible abrupt regime shifts (CRS) in the temperature time-
27 series (Rodionov, 2004; Rodionov and Overland, 2005). The STARS method has been
28 successfully used by recent studies to identify abrupt changes in the long-term mean of
29 environmental time-series (Marty, 2008; North et al., 2013) and GWT time-series (Figura et
30 al., 2011). STARS is a parametric test that can detect multiple regime shifts and needs no a
31 priori assumption for the timing of possible shifts. Identification of a shift is based on the
32 calculation of the Regime Shift Index (RSI), which represents the cumulative sum of the
33 normalized deviations from the mean value of a regime and thus reflects the confidence of a

1 regime shift (Rodionov, 2004). For the regime shift analysis, several test parameters need to
 2 be adjusted to account for specific characteristics, such as the length of the tested time-series.
 3 The target significance level in our analysis is set to 0.15, which corresponds to the p-level of
 4 false positives. The actual p value of an identified shift between subsequent regimes is
 5 calculated separately with a Student's t test. The cut-off length of the test corresponds to a
 6 low-pass filter, so that regimes with a shorter length are disregarded in the analysis (Rodionov
 7 and Overland, 2005). Here, we set the cut-off length to 10 years as atmospheric oscillations
 8 often occur at decadal intervals (Overland et al., 2008). Furthermore, the Huber weight
 9 parameter (set to 1 in our study) included in the STARS procedure improves the treatment of
 10 outliers by weighting them proportionally to their deviation from the mean value (Overland et
 11 al., 2008). As pointed out by Seidel and Lanzante (2004) atmospheric data tend to be highly
 12 temporally auto-correlated, so that especially in short time-series, spurious regime shifts may
 13 be detected due to serial correlation (Rudnick and Davis, 2003). Therefore, we apply a pre-
 14 whitening procedure that removes the red noise component from the temperature time series
 15 prior to testing for a regime shift (Rodionov, 2006). To investigate the potential stationarity
 16 within detected regimes, the non-parametric Mann-Kendall test for the absence of trend is
 17 also applied to the temperature data (von Storch, 1995).

18 **2.3 Analytical solutions**

19 The governing equation for transient subsurface heat transport is the one dimensional
 20 conduction equation for homogeneous media, which equates the divergence of the conductive
 21 flux with the rate of the change of thermal energy in the medium (Carslaw and Jaeger, 1959;
 22 Domenico and Schwartz, 1990):

$$23 \quad \kappa \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t} \quad (1)$$

24 where κ is the bulk thermal diffusivity of the subsurface ($\text{m}^2 \text{s}^{-1}$), T is temperature ($^{\circ}\text{C}$), z is
 25 depth (m), and t is time (s). The governing heat transport equation becomes slightly more
 26 complex when advective heat transport (or 'forced convection') due to groundwater flow is
 27 considered:

$$28 \quad \kappa \frac{\partial^2 T}{\partial z^2} - U \frac{\partial T}{\partial z} = \frac{\partial T}{\partial t} \quad (2)$$

29 where U (m s^{-1}) is the thermal plume velocity under pure advection and a function of the
 30 Darcy velocity q (downwards or recharge is positive, m s^{-1}), the bulk volumetric heat capacity

1 of the soil-water matrix C ($\text{J m}^{-3} \text{ }^\circ\text{C}^{-1}$), and the volumetric heat capacity of water C_w ($\text{J m}^{-3} \text{ }^\circ\text{C}^{-1}$):

$$3 \quad U = q \frac{C_w}{C} \quad (3)$$

4 The governing conduction-advection equation (2) employs several limiting assumptions,
5 including spatiotemporally constant groundwater velocity over the entire domain (including
6 depths below the well screen), one dimensional heat transport, homogenous thermal
7 properties, constant pore water phase, and isothermal conditions between the soil grains and
8 pore water. Here we employ a distinct analytical solution to Eq. (2) to simulate the influence
9 of a climate regime shift on GWT. We assume thermally uniform initial conditions and
10 boundary conditions that are subject to a series of n step increases in GST:

$$11 \quad \text{Initial conditions: } T(z, t = 0) = T_0 \quad (4)$$

$$12 \quad \text{Boundary condition: } T(z = 0, t) = T_0 + \sum_{i=1}^n \Delta GST_i \times H(t - t_i) \quad (5)$$

13 where T_0 is the initial uniform temperature ($^\circ\text{C}$) prior to the beginning of the regime shift,
14 ΔGST_i is the step increase in GST for regime shift i ($^\circ\text{C}$), H is the Heaviside step function, and
15 t_i is the time (s) of the beginning of regime shift i . In this formulation, ΔGST_i refers to a step
16 change in GST in comparison to the GST conditions immediately preceding that change (not
17 necessarily in comparison to initial GST, T_0). We ignore short term (e.g. annual) variations in
18 SAT and GST and rather drive the subsurface heat transport models with temperatures
19 averaged for a given climate regime and then instantaneously increased at the beginning of
20 the next climate regime. The thermally uniform initial conditions is a reasonable assumption
21 given that we begin by considering mean annual GWT at or near the water table following a
22 relatively stable climate regime (i.e. prior to 1988, Fig. 2). Moreover, for the wells observed,
23 the vadose zones and near-surface aquifers are too shallow to realize the influence of any
24 geothermal gradient. The isothermal condition assumption previously noted extends to the
25 surface boundary, which implies that the groundwater recharge entering the semi-infinite
26 domain at the ground surface has a temperature equal to the mean annual surface temperature
27 for that climate regime.

28 The transient conduction-advection heat transport model (TCA model) employed in this study
29 is an analytical solution to the transient conduction-advection Eq. (2) subject to the initial and
30 boundary conditions given in Eqs. (4) and (5). This solution was originally developed by

1 Carslaw and Jaeger (1959) and subsequently employed by Taniguchi et al. (1999b) to study
 2 subsurface temperature evolution due to land cover changes in regions of significant
 3 groundwater flow. Because we assume initially thermally uniform conditions in the
 4 unsaturated zone and shallow groundwater, the resultant solution is simpler than in the
 5 original derivations. Unlike the original derivation, it is also presented here with superposition
 6 principles applied to allow for a series of regime shifts rather than one event. This
 7 superposition approach is valid given the linearity of the governing partial. This superposition
 8 approach is valid given the linearity of the governing partial differential equation and the
 9 boundary and initial conditions (Farlow, 1982):

$$10 \quad T(z, t) = T_0 + \sum_{i=1}^n \frac{\Delta GST_i}{2} \left\{ \operatorname{erfc} \left(\frac{z - U(t - t_i)}{2\sqrt{\kappa(t - t_i)}} \right) + \exp \left(\frac{Uz}{\kappa} \right) \operatorname{erfc} \left(\frac{z + U(t - t_i)}{2\sqrt{\kappa(t - t_i)}} \right) \right\} \times H(t - t_i) \quad (6)$$

11 where $T(z, t)$ is the spatiotemporally varying subsurface temperature (GWT, °C), κ is the bulk
 12 thermal diffusivity of the subsurface ($\text{m}^2 \text{s}^{-1}$), and erfc is the complementary error function.
 13 The Heaviside function indicates that the subsurface thermal influence of each regime shift i
 14 in the boundary condition is not realized until the time t exceeds t_i . Comparisons between the
 15 model results and measured GWT indicate whether these simple analytical solutions are
 16 applicable for modeling the influence of observed and projected climate regime shifts in the
 17 wells considered in this study.

18 It should be noted that it is the GST rather than the SAT that drives subsurface thermal
 19 regimes and thus forms the boundary condition in Eq. (5). However, complete GST time
 20 series were not available for the locations considered in this study. Thus, in the present study,
 21 the magnitude and timing of the regime shifts in GST are obtained from the local SAT data as
 22 follows. In all cases, the timing of the GST regime shifts is assumed to correspond to the
 23 timing of the local SAT regime shifts for that location obtained from the statistical analysis.
 24 This approach is reasonable given the efficient heat transfer that occurs between the lower
 25 atmosphere and the ground surface (e.g. Bonan, 2008). The magnitude of the GST regime
 26 shift was set to be equal to the magnitude of the SAT. Measured SAT and GST data (not
 27 shown) indicate that this approach is valid as the measured magnitude of the climate regime
 28 shift in 1988 was 1.1 C in both the SAT and GST data near Cologne. No GST data were
 29 available for the sites near Karlsruhe (Hardtwald sites, Figure 1 and Table 2), but it is
 30 reasonable to assume that the magnitude of the GST changes track the magnitude of the SAT
 31 changes like in the case of the sites near Cologne.

1 Table 3 presents the assumed subsurface thermal properties for each well for both the
2 saturated and unsaturated zones. A potential range in these values was estimated from
3 literature values taking into account variations in lithology obtained from drilling logs as
4 wells as the variability of water content in the unsaturated zone ranging from dry to saturated
5 conditions (VDI, 2010; Menberg et al., 2013). Because we consider temperature rise at
6 different depths below the water table within the aquifer, the effective thermal diffusivities
7 utilized in the analytical solution for each of the four locations were obtained from a weighted
8 arithmetic average (weighted by zone thickness) of the saturated and unsaturated zone thermal
9 diffusivities. For example, the unsaturated zone thickness was taken as the depth to the water
10 table, and the saturated zone thickness was taken as the distance from the water table to a
11 point along the well screen. Different points in the well screen were considered, as described
12 in the results, because the vertical well capture zone flow dynamics may be complex
13 depending on the nature of the pumping and heterogeneities in near-well hydraulic properties.
14 This is particularly important for the Hardtwald wells, which have longer well screens than in
15 the case of the Dansweiler or Sinthern wells (Fig. 1).

16 Regional recharge rates were extracted from Table 2 with a potential range to reflect the
17 variability of recharge in this region over the last decades (Erftverband, 1995; W. Deinlein,
18 personal communication, 2013). Similar thermal properties and recharge values are assumed
19 for Hardtwald 1 and Hardtwald 2 based on their similar land cover and subsurface properties
20 and the geographical proximity (about 200 m) between the wells.

21

22 **3 Results and Discussion**

23 **3.1 Statistical analysis**

24 **3.1.1 Regime shifts in air and groundwater temperatures**

25 At least two climate regime shifts (CRS) could be detected in the later decades of all analyzed
26 time-series (Fig. 2). The time-series of global mean temperature change and zonal mean
27 temperature change in 90-24° N show significant (STARS, $p < 0.005$) positive shifts in 1977,
28 1987, 1997 and 1977, 1988 and 1998, respectively (Table 4). The observation of shifts in air
29 temperature change in these years is in good agreement with the observation of decadal shift
30 in atmospheric oscillation indices in the late 1970s, late 1980s and late 1990s (Overland et al.,
31 2008). Only the CRS in the late 1980s and late 1990s can be found from examining the time-

1 series of local SAT data from Cologne and Karlsruhe. However, this is not surprising as
2 previous studies observed that the CRS in the late 1970s was most prominent in the North
3 Pacific region (Hare and Mantua, 2000; Overland et al., 2008), and less accentuated in
4 Europe. The same applies to the CRS in the late 1990s (Overland et al., 2008; Swanson and
5 Tsonis, 2009), which is reflected by the differing RSI values in Fig. 2. While the high RSI for
6 the CRS in 1997 in the global mean temperature change indicates a significant shift, the RSIs
7 for the late 1990s CRS in the German SAT time-series are much lower than the RSIs in the
8 late 1980s. Figura et al. (2011) correlated the abrupt increase in SAT in Switzerland with a
9 change in the Arctic Oscillation (AO) that has a strong influence on air temperatures in Europe.
10 However, no such change in the AO Index was found in the late 1990s, suggesting that the
11 CRS in the German SAT is also coupled to the general air temperature increase in the
12 Northern Hemisphere.

13 Two regime shifts were detected in the GWT time-series for the four wells near Cologne and
14 Karlsruhe. These shifts correspond to the CRS in the atmosphere with a certain time lag (Fig.
15 2, Table 4). The regime shifts in GWT time-series are all statistically significant ($p < 0.01$),
16 except for the second regime shift in the late 1990s in Dansweiler. Two prominent outliers in
17 the third regime of the time-series influence the statistical significance for this shift, while the
18 RSI value is calculated under consideration of the outliers according to the Huber weight
19 parameter. Furthermore, the RSI values in Fig. 2 for the second shifts in Dansweiler and
20 Sinthern are not the final values, as the 10-year cut-off length of the STARS test in the last
21 regime has not yet been reached. In general, the time-series of GWT show a more gradual
22 increase than the SAT time-series. In particular, the GWT in the Sinthern well appears to
23 exhibit a linear trend rather than a step increase, which is subsequently discussed. The GWT
24 time-series partly exhibit considerable inter-annual variability, which appears to be more
25 significant in the Hardtwald wells than in Dansweiler and Sinthern. Potential reasons for these
26 rather large fluctuations in annual GWT are related to the uncertainties associated with the
27 measurements as mentioned in the method section. Other possible factors that influence the
28 inter-annual variability could be the pumping station close to the wells in the Hardtwald,
29 where groundwater is extracted at irregular intervals and impacts by undetected land use
30 changes in the close surroundings.

31

1 3.1.2 Statistical analysis of time lags and magnitude of temperature change

2 The time lags between the regime shifts in SAT and GWT are listed in Table 4. The regime
3 shifts in global mean temperature change and the zonal mean in 90-24° N occur
4 simultaneously, except for the regime shift in the late 1980s that has a time lag of one year.
5 However, as annual mean values are used for the analysis, the accuracy of the shift detection
6 is limited to ± 2 year, so that the shifts occur within the uncertainty range. The same applies to
7 the first regime shifts in the local SAT time-series in Cologne and Karlsruhe. Changes in local
8 SAT are also expected to be temporally and spatially highly heterogeneous due to the
9 variability of local climate and the complexity of atmospheric circulation systems (Hansen et
10 al., 2010). The observed CRS in shallow GWT lag behind the abrupt increase in local SAT by
11 1–4 years (Table 4). In Karlsruhe the time lag is generally small with one year for all shift
12 events, while the time lags in Cologne vary between 2–4 years. This difference in the time
13 lags reflects the specific hydrogeological site conditions with the unsaturated zone in Cologne
14 (17m) being significantly thicker than in Karlsruhe (7m, Table 2). The thermal properties in
15 the unsaturated zone differ significantly from those in the saturated zone (Table 3). Thus the
16 propagation of the thermal signal in Cologne is retarded due to the lower thermal diffusivity
17 than in Karlsruhe.

18 The magnitudes of the temperature increase between two subsequent regimes in the zonal
19 mean SAT change are considerably higher than in the global mean SAT change (Fig. 3),
20 because the global temperature data set contains ocean temperature measurements, and ocean
21 temperatures are known to respond more slowly to climatic forcing due to the ocean's large
22 thermal inertia (Hansen et al., 2010). The above mentioned temporal and spatial heterogeneity
23 of the CRS accounts also for the higher increase in SAT in the German time series, which is
24 above the average of the zonal mean in 90-24° N. The significant abrupt increase in the long-
25 term mean of SAT with the late 1980s CRS of close to 1°C was likewise observed in Swiss
26 SAT by Figura et al. (2011).

27 The magnitudes of the increases in the long-term means of GWT are lower and damped by up
28 to 70% compared to the shift magnitude in SAT (Fig. 3). This damping arises from the fact
29 that, due to the thermal inertia of the subsurface, the GWT has not yet fully equilibrated with
30 the GST at the time when the regime shift is observed in the GWT. The magnitudes of the
31 regime shifts in Fig. 3 also reveal that the damping in the time-series from the Hardtwald
32 wells is more pronounced than the damping in Dansweiler and Sinthern. This likely occurs
33 due to depth of groundwater extracted for temperature measurements. For example, the depth

1 to the midpoint of the well screen is higher for the Hardtwald wells than it is for the
2 Dansweiler and Sinthern wells (Table 2). This will be investigated in more detail with the
3 TCA model.

4 3.1.3 Stationarity within the regimes

5 In order to investigate the stationarity within the identified regimes the Mann-Kendall test for
6 the absence of trend was performed for the individual regimes. The resulting p-values are
7 listed in Table 5, in which high p-values close to 1 indicate stationary conditions. No
8 significant trends could be found within the individual regimes of the examined SAT time-
9 series, suggesting that the temperature increase in the last decades can be attributed
10 completely to the detected CRS.

11 In the GWT time series, the p-values of the Mann-Kendall test are generally lower (median of
12 0.20, Table 5) than the p-values of the SAT time series (median of 0.53), indicating that the
13 SAT time-series are more stationary than GWT time series. This more gradual increase in
14 GWT reflects the effects of subsurface heat transport dynamics, which convert the sharp
15 surface temperature signal to a more diffuse subsurface temperature signal. A significant trend
16 ($p < 0.05$) with a slope of 0.13°C was detected in the third regime (2001–2006) in the
17 Sinthern well. However, it has to be noted, that this regime is quite short, and thus the trend
18 analysis may be biased by the last two rather high temperature values in 2005 and 2006. In the
19 regimes before 1991, the p-values of the time-series in Dansweiler and Sinthern are 0.05 and
20 0.06, respectively, and thus close to the critical p-value of 0.05 indicating a more gradual
21 increase rather than abrupt changes. For the wells near Karlsruhe no significant trends were
22 found in GWT within the regimes, which indicates that the temperature increase in the time-
23 series can be linked to the regime shifts.

24 To compare the performance of the regime shift analysis to an approach with linear
25 temperature increase, the RMSE values for the statistical step function model and a linear
26 model were calculated for each time series (not shown). This analysis revealed that the RMSE
27 of the step function fit for all GWT and SAT time series is slightly lower than the RMSE of
28 the linear fit, indicating that the step function model performs slightly better. Thus, it can be
29 stated, that, with the exception of the potentially biased last regime in Sinthern, all regimes in
30 the time series of GWT are statistically stationary, which corroborates the feasibility of the
31 application of regime shift analyses on GWT time-series in addition to the low p-values of
32 STARS (Table 4).

1 **3.2 Analytical model**

2 Predicted GWT were obtained from the analytical solution in Eq. (6) (TCA model) with the
3 thermal properties and recharge rates given in Table 3 and the magnitude and timing of the
4 regime shifts given in Table 4. Due to the availability of GWT data in each well, model runs
5 were started in 1970. Figure 4 shows the measured GWT, assigned GST boundary condition,
6 and predicted GWT for each of the four wells. The range of predicted GWT (shaded area, Fig.
7 4) is derived from the range of thermal properties, well screen depths, and recharge values
8 utilized as input parameters to the model (Table 3). In particular, the upper boundaries of the
9 temperature envelopes in Fig. 4 were obtained with Eq. (6) using depths to the tops of each
10 well screen (Table 2), maximum thermal diffusivities (Table 3), and minimum heat capacities
11 (Table 3, see Eq. 3). The lower boundaries of the temperature envelopes were obtained using
12 depths to the bottom of the well screens, minimum thermal diffusivities, and maximum heat
13 capacities. Finally, the best estimates (red series, Fig. 4) for the predicted GWT data for each
14 well were obtained using depths equal to the midpoints of the well screens and mean thermal
15 diffusivity and heat capacity. In all cases, the thermal properties were taken as the weighted
16 arithmetic average of the unsaturated and saturated zone thermal properties as described in
17 section 3.2.

18 Note that the GST data simulated for the Hartwald wells are characterized by a wider range
19 in the predicted temperature envelopes. This range is primarily due to the longer well screens
20 in the case of the Hartwald wells than for the Sinthern and Dansweiler wells (Table 2).
21 Hereafter, when we refer to the TCA model results we ignore the range in the modeling
22 results and only allude to the specific results obtained using the mean recharge values and
23 mean thermal properties given in Table 3 (i.e. red series, Fig. 4).

24 The TCA model predicted trends in GWT generally concur with the long term trends
25 exhibited in the measured data for Dansweiler, Hartwald 1, and Hartwald 2; however, the
26 TCA model under-predicts the rise in the Sinthern GWT data. These differences suggest that,
27 although they were assumed to be equal, the magnitude of the GST regime shifts in Sinthern
28 may have been greater than those in Dansweiler, or that due to subsurface heterogeneity, the
29 pumped water may be predominantly sourced from above the Sinthern well screen. Modeling
30 results (not shown) indicate that for the mean thermal properties and recharge values, the z
31 value used in Eq. (6) would have to be approximately 9 m for the predicted and observed
32 GWT trends to generally concur. Furthermore, the recharge rates in this well may have been
33 greater than the obtained regional recharge rates for this area. Higher recharge would lead to

1 higher heat advection, which would reduce the lag between a GST signal and its realization in
2 the subsurface (see range in predicted Sinthern GWT, Fig. 4). Similarly, higher thermal
3 diffusivity would generally lead to higher GWT in Sinthern, as the Sinthern GWT is still
4 adjusting to the GST regime shifts in the data shown in Fig. 4. Finally, the last few years of
5 measured GWT data are not available for the Sinthern well. GWT data in the nearby
6 Dansweiler well decreased during this period, thus the visual fit between the measured and
7 predicted Sinthern GWT would likely improve if these data were available.

8 Our approach does not reproduce inter-annual variability in GWT due to the nature of the
9 GST boundary condition, which is constant for a given climate regime (Fig. 4). Inter-annual
10 variability in GWT could theoretically be reproduced by considering a series of “GST
11 regimes” that only last one year; however, the objective of the present study was to examine
12 the subsurface thermal influence of climate regime shifts not inter-annual SAT or GST
13 variability. Finally, it is interesting to note that the abrupt regime shifts applied in the
14 simplified boundary condition manifest themselves as gradual changes in the predicted GWT
15 evolution in the deeper wells due to the influence of the heat capacity and thermal inertia of
16 the subsurface. These findings demonstrate that observed gradual increases in shallow GWT
17 are not necessarily suggestive of gradual trends in GST. The effect of the abrupt GST regime
18 shifts are discernible in the upper edge of the temperature envelopes in Hardtwald 1 and 2
19 (i.e., the GWT signal is diffused but the impact of the piecewise boundary condition is still
20 discernible). This is due to the fact that these particular results were obtained for depths to the
21 top of the well screens of only 10 m (Table 2).

22 With the exception of the anomalous Sinthern data, the general agreement between the
23 predicted and observed trends in GWT data (Fig. 4) indicates that TCA model can produce
24 first-order approximations of the thermal sensitivity of these shallow aquifers to past or future
25 climate regime shifts by conforming the boundary condition to climate model projections. The
26 boundary condition form employed in this study could be matched to future climate
27 projections by considering a series of short GST regimes, or alternatively, a boundary
28 condition that considers a gradual rise in GST could be employed (e.g., Kurylyk and
29 MacQuarrie, 2014). The form of the analytical solution indicates that if a new long term stable
30 climate is achieved, the GWT will eventually rise an equivalent magnitude to the changes in
31 GST, which are often in turn assumed to follow changes in SAT. In the absence of snowpack
32 evolution or land cover changes, any perceived damping in GWT changes in comparison to
33 SAT changes based on statistical analyses likely results from the lagged subsurface thermal
34 response to the boundary condition.

1 There are limitations associated with employing analytical solutions to simple one-
2 dimensional heat transport equations. Several assumptions associated with the conduction-
3 advection equation have been previously noted. For example, the governing equation, and
4 hence the analytical solution, assume that the water phase is constant. This assumption is
5 justified in the present study considering that no significant seasonal freezing of the ground
6 (which retards soil warming, Kurylyk et al., 2014b) is occurring. Also, the solution assumes
7 homogeneous thermal properties; however, we considered heat transport in both the saturated
8 and unsaturated zones. The thermal diffusivity of the unsaturated zone for the wells
9 considered in the present study were up to 30% lower than the saturated zone thermal
10 diffusivities (Table 3). We considered both zones by employing a weighted arithmetic average
11 (based on zone depths) for the effective thermal diffusivity. Also, recharging water may be at
12 a temperature different than the mean annual surface temperature, particularly if the recharge
13 mechanism is snowmelt. However, snowmelt induced recharge is minimal at the observation
14 areas in this study. In general, due to these limitations, the results presented in Figure 4 should
15 be considered first order approximations of the sensitivity of these shallow aquifer thermal
16 regimes to climate regime shifts.

17 3.2.1 Implications for future river temperatures and groundwater-dependent 18 ecosystems

19 Although the wells analysed in this study were not located nearby streams, the timing and
20 magnitude of the measured GWT rise can provide insight into the potential warming of
21 alluvial aquifers feeding ecologically important rivers. Gaining rivers and streams can be
22 strongly influenced by the thermal regimes of surrounding aquifers (e.g. Tague et al., 2007;
23 Kelleher et al., 2012), and this is often particularly true during the dry, warm season when
24 baseflow can provide the majority of the river or stream discharge. Thus, deterministic models
25 of future base-flow dominated rivers temperature should explicitly account for the future
26 thermal regimes of aquifers. Various studies have demonstrated that the thermal regimes of
27 rivers respond to a warming climate, and these studies have generally tacitly ignored GWT
28 rise due to climate change. The results of this study however contradict this assumption by
29 indicating that shallow GWT will respond to SAT warming and that the lag time between
30 SAT warming and the associated increase in shallow GWT can be rather short (< 5 years).
31 Similar results were obtained by Kurylyk et al. (2014a) who employed a numerical model of
32 groundwater flow and energy transport driven by downscaled climate scenarios to

1 demonstrate a potential damping and short lagging of future groundwater discharge
2 temperature rise in response to air temperature changes.

3 Given the expected warming of rivers across the globe (van Vliet et al., 2011, 2013),
4 researchers have rightfully proposed that coldwater fish will begin to increasingly rely on the
5 occurrence and distribution of suitable coldwater refugia (e.g. Brewer, 2013). Our results
6 suggest that GDEs and groundwater-sourced coldwater refugia will also warm in response to
7 climate change. The magnitude and timing of the GWT warming however will depend on
8 several factors, including the timing and magnitude of the SAT warming, changes in
9 precipitation (and thus recharge and advection), the depth of the groundwater table, and the
10 presence or absence of seasonal snowpack.

11

12 **4 Conclusions**

13 By applying a sequential t-test analysis for regime shifts (STARS) to time-series of air and
14 groundwater temperatures, we empirically demonstrated that groundwater temperatures in
15 shallow aquifers show temperature changes that correspond to positive shifts in local SAT in
16 Germany, which in turn can be traced back to increasing global SAT. This observed direct
17 coupling of atmospheric and groundwater temperature development through the unsaturated
18 zone implies that climate warming does not only affect aquifers recharged by river-bank
19 infiltration (Figura et al., 2011), but also a large number of shallow aquifers on a wide spatial
20 scale. The regime shifts in GWT occur with a certain time lag to the CRS depending mainly
21 on the thermal properties and thickness of the unsaturated zone. The magnitude of these
22 regime shifts in GWT compared to the shifts in SAT is damped by the thermal propagation of
23 the temperature signal into the subsurface, leading to a more gradual increase in GWT. This
24 damping perceived in the statistical analyses is predominantly an artifact of the lagged
25 subsurface thermal response. However, despite the extenuation of the temperature signal in
26 the subsurface and the mixing of shallow groundwater during pumping, significant
27 temperature shifts were found in the extracted groundwater.

28 Process-oriented modeling was also performed with an analytical solution to the conduction-
29 advection equation. In three of the four observation wells, the simulated decadal GWT trends
30 generally concurred with the measured decadal GWT trends. However, inter-annual
31 variability could not be reproduced due to the simplistic nature of the boundary condition,
32 which equals the long-term mean surface temperature. This agreement is indicative that the

1 solution to the conduction-advection equation can also be applied to obtain first-order
2 estimates of the influence of future climate change on subsurface thermal regimes.

3 Our results indicate that increasing SATs are prone to have a substantial and swift impact, not
4 only on soil temperatures, but also on large-scale, shallow groundwater temperatures in
5 productive and economically important aquifers. Furthermore, this study has demonstrated
6 that long-term series of pumped groundwater temperature can be analyzed using stochastic
7 approaches to examine the relationship between local and global climate change and local
8 groundwater temperature evolution.

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8

1 **Table 1:** Location coordinates of the observation wells with basic information about the
 2 hydrological setting.

Well	Easting	Northing	Altitude [m asl]	Subsurface material	Distance to nearest stream
Dansweiler	2553462	5646975	88.2	fine to coarse sand, minor contents of gravel and silt ^a	~ 6 km (Erft)
Sinthern	2555310	5648820	64.4		~ 9 km (Erft)
Hardtwald 1	3457460	5435140	112.4	gravel and coarse sand with layers of fine sand and silt ^b	~ 6 km (Rhine)
Hardtwald 2	3457500	5435200	112.1		~ 6 km (Rhine)

3 ^a Klostermann, 1992, ^b HGK, 2007.

4

1 **Table 2:** Hydrogeological data of the four observation wells.

Well	Depth of water table [m bgl]	Depth of well screens [m bgl]	Average hydraulic conductivity [m s^{-1}]	Groundwater recharge rates [mm yr^{-1}]
Dansweiler	18 ± 1	22.5 - 22.6	$1.0\text{-}5.0 \times 10^{-4}$ ^a	221 ± 45 ^c
Sinthern	16 ± 1	21.3 - 21.4	$1.0\text{-}5.0 \times 10^{-4}$ ^a	221 ± 45 ^c
Hardtwald 1	7 ± 3	10 - 36	$1.1\text{-}1.4 \times 10^{-3}$ ^b	228 ± 45 ^d
Hardtwald 2	7 ± 3	10.5 - 38.5	$1.1\text{-}1.4 \times 10^{-3}$ ^b	228 ± 45 ^d

2 ^a Balke, 1973 ^b Wirsing and Luz, 2008 ^c Erftverband, 1995. ^d Deinlein, personal
 3 communication, 2013.

4

1 **Table 3:** Range of thermal properties and recharge values utilized in analytical solutions.

Location	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) (min, mean, max)	Heat capacity ($\times 10^6 \text{ J m}^{-3} \text{ }^\circ\text{C}^{-1}$) (min, mean, max)	Thermal diffusivity ($\times 10^{-7} \text{ m}^2 \text{ s}^{-1}$) (min, mean, max)	Recharge (mm yr^{-1}) (min, mean, max)
Unsaturated zone				
Dansweiler	0.4, 1.2, 2.4	1.3, 2.0, 2.8	3.1, 5.8, 8.4	176, 221, 265
Sinthern	0.4, 1.1, 2.4	1.2, 2.0, 2.8	3.3, 5.6, 7.9	176, 221, 265
Hardtwald	0.8, 1.5, 2.4	1.5, 2.0, 2.5	5.1, 7.4, 9.6	182, 228, 274
Saturated zone				
Dansweiler	1.5, 2.2, 3.1	2.4, 2.6, 2.8	6.2, 8.4, 10.9	176, 221, 265
Sinthern	1.4, 2.1, 3.0	2.3, 2.6, 2.8	6.1, 8.2, 10.7	176, 221, 265
Hardtwald	2.4, 2.9, 3.5	2.5, 2.7, 2.9	9.6, 10.8, 12.0	182, 228, 274

2

1 **Table 4:** Time lags and final p-values of the observed regime shifts in air and groundwater
2 temperature. The specific years indicate the first year of the new regime. Time lags are
3 defined as the period between the occurrence of a regime shift in local SAT and the
4 corresponding successive shift in GWT.

Time-series	Regime shift late 1970s		Regime shift late 1980s			Regime shift late 1990s		
	Year	p-value	Year	Time lag to SAT (years)	p-value	Year	Time lag to SAT (years)	p-value
Global mean ΔT	1977	1.8×10^{-5}	1987	–	4.4×10^{-4}	1997	–	1.8×10^{-7}
Zonal mean ΔT	1977	9.1×10^{-4}	1988	–	4.6×10^{-3}	1997	–	5.7×10^{-5}
SAT Cologne	–	–	1988	–	6.7×10^{-4}	1999	–	5.5×10^{-3}
GWT Dansweiler	–	–	1991	+ 3 (± 2)	1.1×10^{-9}	2003	+ 4 (± 2)	1.0×10^{-1}
GWT Sinthern	–	–	1991	+ 3 (± 2)	9.3×10^{-5}	2001	+ 2 (± 2)	4.3×10^{-4}
SAT Karlsruhe	–	–	1988	–	3.2×10^{-5}	1999	–	3.8×10^{-2}
GWT Hardtwald 1	–	–	1989	+ 1 (± 2)	3.6×10^{-4}	2000	+ 1 (± 2)	1.3×10^{-4}
GWT Hardtwald 2	–	–	1989	+ 1 (± 2)	9.2×10^{-4}	2000	+ 1 (± 2)	1.0×10^{-2}

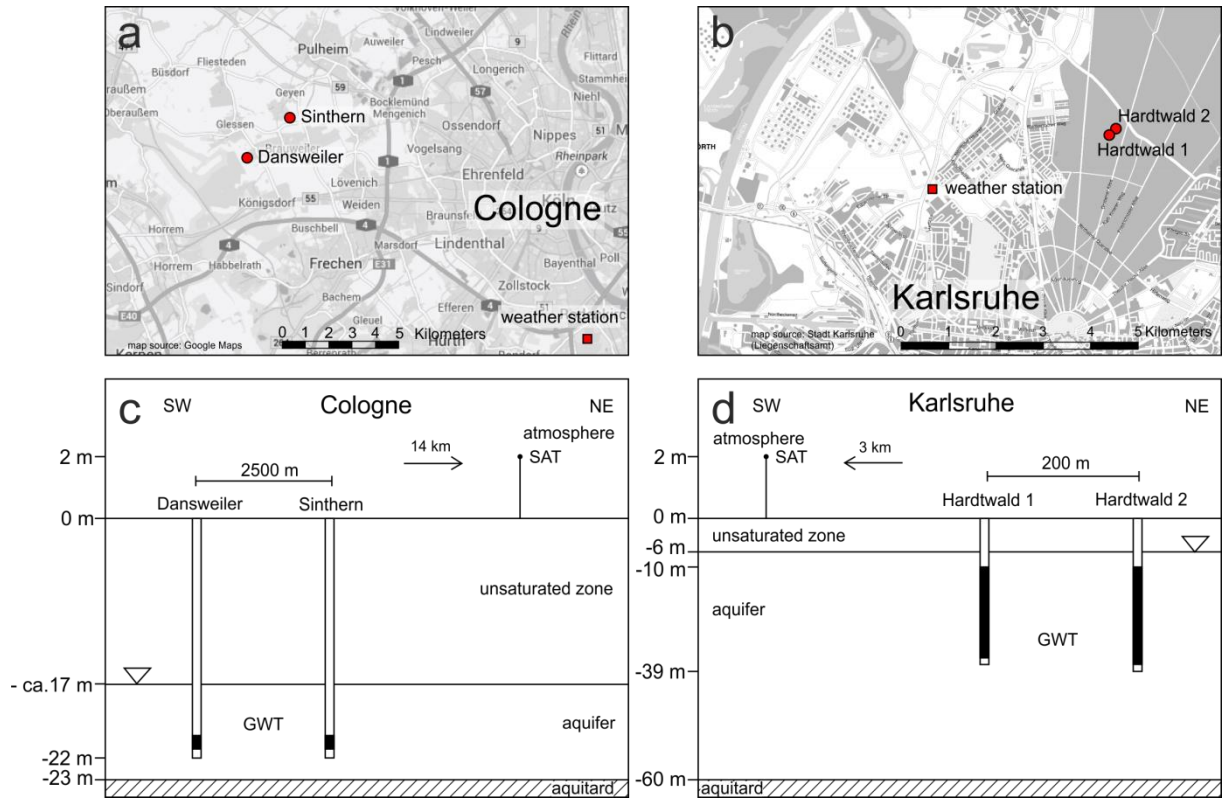
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1 **Table 5:** Results (p-values) of the Mann-Kendall test for the absence of a trend for all regimes
 2 in SAT and GWT time-series.

Time-series	Regime I		Regime II		Regime III		Regime IV	
	Period	p-value	Period	p-value	Period	p-value	Period	p-value
Global mean ΔT	1950-1976	0.62	1977-1986	1.00	1987-1996	0.72	1997-2012	0.26
Zonal mean ΔT	1950-1976	0.30	1977-1986	0.64	1987-1996	0.47	1997-2012	0.72
SAT Cologne	–	–	1962-1987	0.40	1988-1998	0.89	1999-2011	0.46
SAT Karlsruhe	–	–	1962-1987	0.43	1988-1998	0.31	1999-2009	0.76
GWT Dansweiler	–	–	1970-1990	0.05	1991-2002	0.78	2003-2010	1.00
GWT Sinthern	–	–	1974-1990	0.06	1991-2000	0.18	2001-2006	0.01
GWT Hardtwald 1	–	–	1968-1988	0.22	1989-1999	0.14	2000-2011	0.13
GWT Hardtwald 2	–	–	1968-1988	0.43	1989-1999	0.59	2000-2010	0.31

3

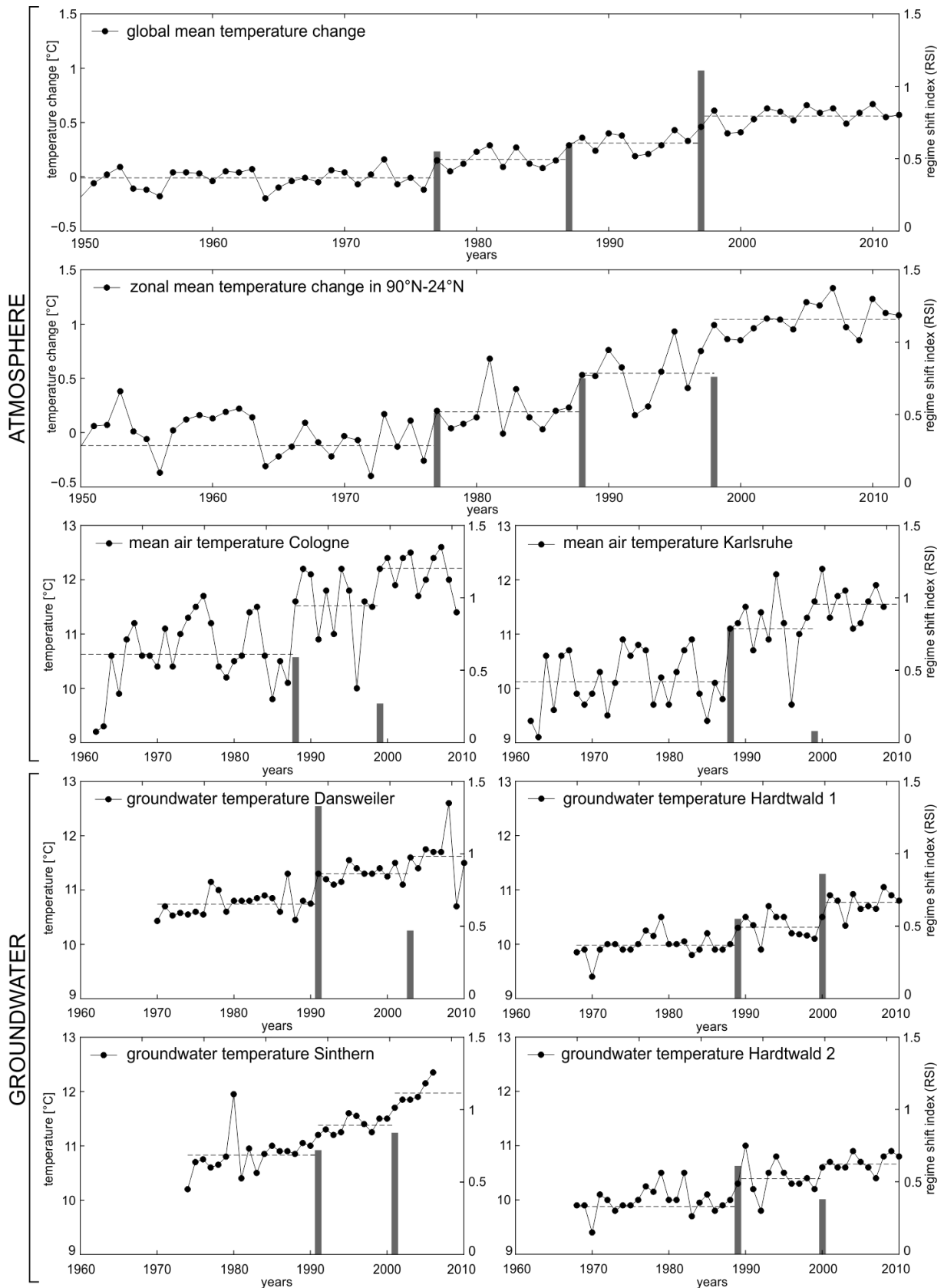
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1

2 **Figure 1:** a, b: Locations of the four observation wells and two weather stations used in the
 3 present study. c, d: Conceptual sketch of the well settings in the aquifers close to Cologne
 4 (left) and Karlsruhe (right). The black zones in the wells indicate the location of the filter
 5 screens. Please note the different scales in the subsurface.

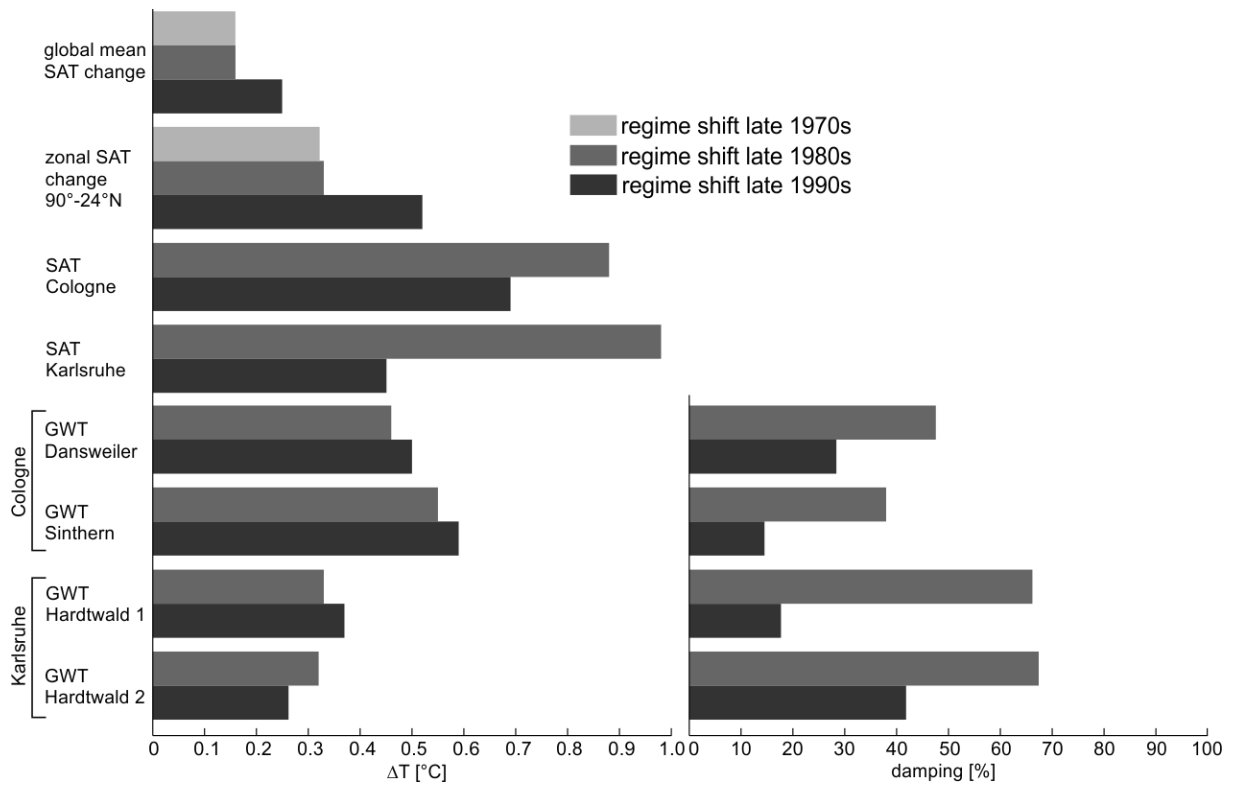
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2 **Figure 2:** Time series of temperature data with long-term means (dashed lines) and observed
 3 regime shift with RSI values.

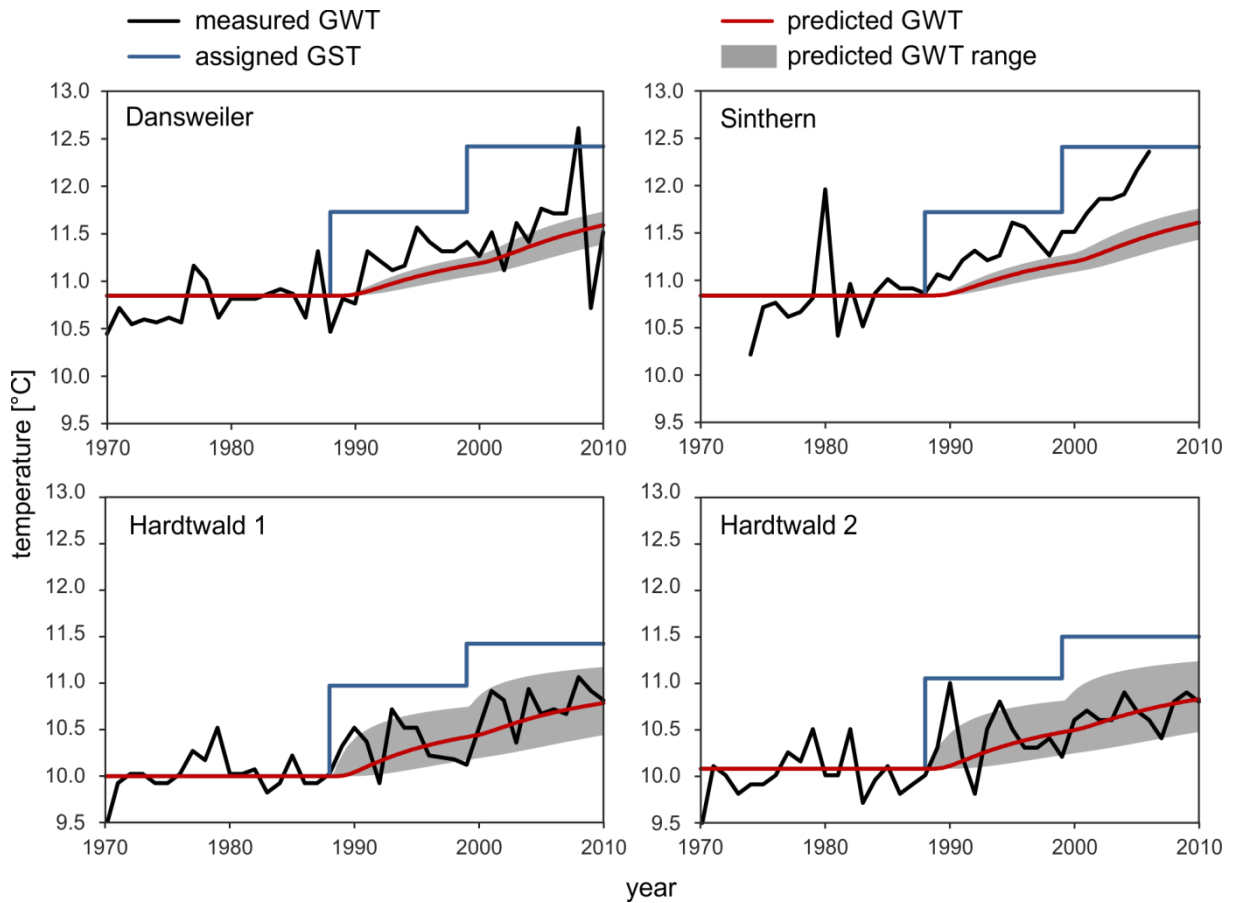
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2 **Figure 3:** Left: Magnitude of regime shifts in time-series of atmospheric and groundwater
 3 temperatures. Right: relative damping of the regime shift magnitude in groundwater
 4 temperatures compared to regional atmospheric regime shift, calculated as 100 minus the ratio
 5 of ΔT in GWT to ΔT in SAT in percent.

6



1
 2 **Figure 4:** Measured GWT, predicted GWT, and assigned GST boundary conditions for the
 3 TCA model (Eq. 6) for each well versus the year. Red lines indicate GWT results obtained
 4 using the mean well screen depth, thermal properties and recharge rates presented in Table 2
 5 and 3. The GWT data at the lower and higher ends of the temperature envelope are obtained
 6 with the ranges in well screen depth, thermal diffusivity, heat capacity, and recharge rates
 7 (Table 2 and 3).