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Regime shift in groundwater temperature triggered by the Arctic Oscillation

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[1] Groundwater is the world's most important source of raw drinking water. However, the potential impact of climate change on this vital resource is unclear because of a lack of relevant long-term data. Here we statistically analyze over 20 years of groundwater temperature data from five Swiss aquifers fed predominantly by river-bank infiltration. The results reveal an abrupt increase in annual mean groundwater temperature centered on 1987–1988 that can also be observed in air and river temperatures. We associate this temperature increase with the Northern Hemisphere late 1980s climate regime shift (CRS), which itself is related to an abrupt change in the behavior of the Arctic Oscillation. Because temperature affects redox conditions in groundwater, groundwater biogeochemistry in aquifers fed by river-bank infiltration is likely to depend on large-scale climatic forcing and will be affected by climate change. **Citation:** Figura, S., D. M. Livingstone, E. Hoehn, and R. Kipfer (2011), Regime shift in groundwater temperature triggered by the Arctic Oscillation, *Geophys. Res. Lett.*, *38*, L23401, doi:10.1029/2011GL049749.

1. Introduction

[2] Climate change is expected to have a strong impact on the hydrological cycle [*Bates et al.*, 2008]. However, owing to the paucity of relevant long-term data, little is known about its effects on groundwater [*Bates et al.*, 2008], which accounts for about half of global drinking water production [*Connor et al.*, 2009]. In a recent review paper, *Green et al.* [2011] emphasize that existing studies on this topic focus on variables that are associated primarily with groundwater quantity, such as water table levels and recharge rates. Scarcely anything is known about the impact of climate change on groundwater quality [*Bates et al.*, 2008; *Green et al.*, 2011].

[3] Temperature is an important determinant of groundwater quality. Based on current knowledge of heat transport in groundwater [*Anderson*, 2005], an increase in groundwater temperature driven by climate change is likely. A few studies on this topic have tried to describe and predict the magnitude of the groundwater temperature increase by applying simple heat transport models [e.g., *Taylor and Stefan*, 2009; *Gunawardhana and Kazama*, 2011] or by analyzing vertical borehole temperatures [*Taniguchi et al.*, 1999, 2007]. However, to the best of our knowledge no empirical studies exist which demonstrate in detail the direct effect of recent climate change on groundwater temperature. Higher groundwater temperatures may affect biogeochemical processes such that groundwater is rendered less suitable as a source of raw drinking water [*Von Gunten et al.*, 1991; *Sprenger et al.*, 2011; *Green et al.*, 2011]. During the heat wave that occurred during summer 2003 in much of Europe [*Schär et al.*, 2004], reducing conditions in groundwater were reported at study sites in Germany [*Eckert et al.*, 2008] and Switzerland [*Hoehn and Scholtis*, 2011]. At the Swiss study site, the reducing conditions led to the precipitation of iron and manganese in the pumping wells in response to re-aeration in the open pumping station [*Hoehn and Scholtis*, 2011]. Knowledge of the response of groundwater temperature to climatic forcing may therefore be crucial for future groundwater resource quality management.

[4] Large-scale climate modes, such as the El Niño Southern Oscillation, the North Atlantic Oscillation, and the Pacific Decadal Oscillation, appear to affect groundwater level and recharge [*Hanson et al.*, 2006; *Gurdak et al.*, 2007; *Holman et al.*, 2011], suggesting that large-scale climatic forcing might also affect groundwater temperatures. Here, we analyze statistically several long time-series (at least 20 years of regular measurements) of Swiss groundwater temperatures with a view to detecting the impact of one clear, recent feature of large-scale climate change. This feature is the now well-documented climate regime shift (CRS) that occurred over large areas of the Northern Hemisphere in the late 1980s as a result of an alteration in atmospheric circulation patterns associated with an abrupt change in the behavior of the Arctic Oscillation [*Rodionov and Overland*, 2005]. The late 1980s CRS is known to have had a substantial effect on physical and biological processes in seas [*Hare and Mantua*, 2000; *Reid et al.*, 2001; *Alheit et al.*, 2005; *Rodionov and Overland*, 2005; *Tian et al.*, 2008; *Conversi et al.*, 2010], lakes [*Gerten and Adrian*, 2000; *Anneville et al.*, 2004; *Temnerud and Weyhenmeyer*, 2008], and rivers [*Hari et al.*, 2006], but an effect on groundwater has not yet been demonstrated.

2. Data and Methods

[5] We analyzed time-series of water temperatures measured in the pumping wells of five granular, unconsolidated aquifers on the Swiss Plateau (Figure 1). These aquifers have thicknesses of 15–30 m and are recharged predominantly from four rivers by river-bank infiltration (auxiliary material).[1] The temperatures were measured in

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[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2011gl049749. Other auxiliary materials are available in the HTML.

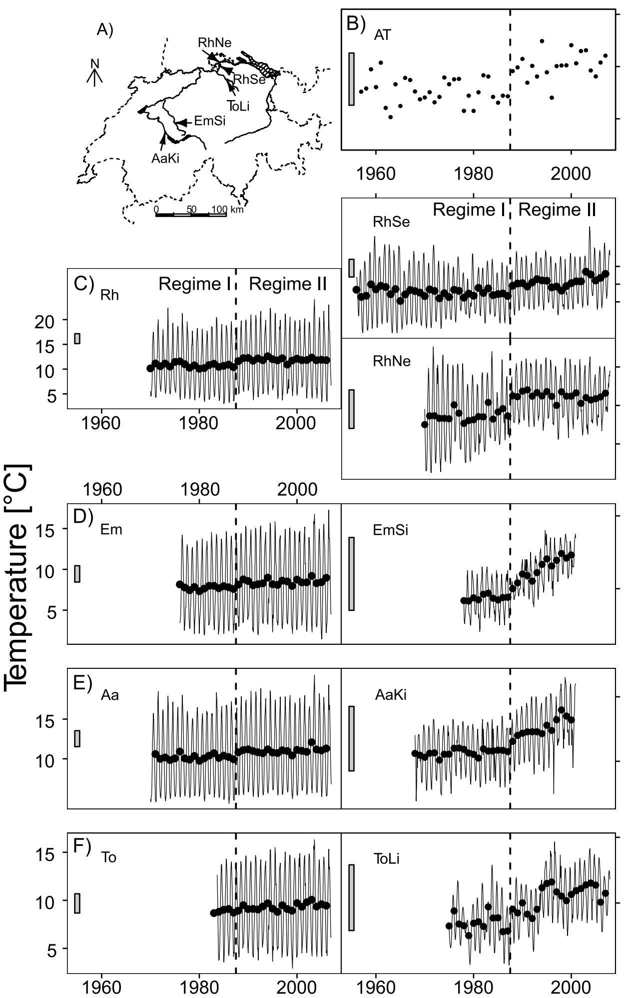

Figure 1. Temperature data. (a) Map of Switzerland showing locations of rivers and aquifers. (b) Annual mean regional air temperature. (c–f) Monthly means (lines) and annual means (dots) of measured (left) river water temperatures and (right) groundwater temperatures. The vertical dashed lines separate Regime I (1978–1987) from Regime II (1988–2000). Note the different scales on the y-axes. To facilitate comparison, a gray rectangle located on the left-hand side of each panel illustrates a temperature difference of 2 K.

tubes within the pumping wells before the water came in contact with the atmosphere and are likely to be broadly representative of groundwater temperatures in the aquifers. The rivers feeding the aquifers are the Rhine (Rh), Emme (Em), Aare (Aa), and Toess (To). The aquifers are abbreviated here as RhSe, RhNe, EmSi, AaKi, and ToLi, where the first two letters designate the river feeding the aquifer. For the first four of these aquifers, groundwater temperature time-series were available from one pumping well per aquifer. For the fifth aquifer (ToLi), a groundwater temperature time series was obtained by combining the temperature time-series from five individual pumping wells (auxiliary material). Time-series of the water temperatures of the four rivers feeding the aquifers were also analyzed, as was the time-series of the Swiss Plateau regional air temperature (auxiliary material).

[6] The air and river water temperature data had been sampled at intervals of at least one day and did not require interpolation; the daily data were aggregated to obtain monthly and annual means. The groundwater temperature data had been sampled at irregular intervals. The raw data were first interpolated at daily intervals using a cubic spline, and the interpolated data were then aggregated to yield estimates of monthly and annual means (auxiliary material).

[7] Rodionov's sequential t-test analysis of regime shifts (STARS) [*Rodionov*, 2004] was employed to identify abrupt shifts in the time-series. The STARS results were cross-checked using the non-parametric Pettitt change-point test [*Pettitt*, 1979] and the parametric Bayesian change-point test of *Barry and Hartigan* [1993]. The former computes the location of a change-point and assigns it a significance value; the latter computes the posterior probability that any given point in the time-series is a change-point. Whilst STARS and the Barry-Hartigan test can detect multiple

Table 1. Results of the Regime Shift and Change-Point Tests[a]

	Annual	Winter	Spring	Summer	Autumn
			STARS		
AT	87/88		87/88	89/90	
Rh	87/88	87/88	87/88	87/88	
Em	87/88		88/89	87/88	
Aa	87/88		87/88	87/88	
RhSe	87/88		88/89	87/88	87/88
RhNe	87/88	87/88	85/86	87/88	87/88
EmSi	87/88	86/87	87/88	88/89	
	94/95	94/95	94/95		90/91
AaKi	87/88	87/88	87/88	87/88	87/88
	96/97	97/98	94/95	96/97	96/97
ToLi	87/88		88/89	87/88	
	93/94	93/94			93/94
			Pettitt		
AT	87/88**		87/88***	87/88**	
Rh	87/88***	87/88**	87/88**	87/88***	
Em	87/88***		88/89***	88/89***	
Aa	87/88***		87/88***	87/88*	
RhSe	87/88***		88/89*	87/88***	87/88***
RhNe	87/88***	88/89***	87/88***	87/88***	87/88*
EmSi	88/89***	88/89***	87/88***	87/88***	89/90***
AaKi	88/89***	88/89***	88/89***	88/89***	88/89***
ToLi	87/88***	92/93*	88/89***	87/88***	93/94**
			Barry-Hartigan		
AT	87/88°	87/88°	87/88°	87/88°	
Rh	87/88°°°		87/88°°°	87/88°	
Em	87/88°°		88/89°°°		
Aa	87/88°°°		87/88°°°		
RhSe	87/88°°°			87/88°°°	87/88°
RhNe	87/88°°°	89/90°°	85/86°°	87/88°°°	
EmSi	88/89°°	86/87°°	87/88°°°	89/90°°	
	93/94°°°	94/95°°	94/95°°	92/93°°	93/94°°°
AaKi	87/88°°°	89/90°°	88/89°°	87/88°°°	87/88°°
	96/97°°°	97/98°°	94/95°°	96/97°°°	96/97°°°
ToLi	87/88°°		87/88°°	87/88°°°	87/88°
	93/94°°°	93/94°°°	92/93°°	93/94°	93/94°

[a]Results of the STARS regime shift test: listed are the temporal locations of significant ($p < 0.01$) regime shifts. Results of the Pettitt change-point test: listed are the temporal locations of change-points detected at significance levels $p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.01$ (***). Results of the Barry-Hartigan change-point test: listed are the temporal locations of the highest posterior probability P of a change-point for $0.01 < P < 0.20$ (°), $0.20 < P < 0.70$ (°°), and $P > 0.70$ (°°°). All tests were applied to the time-series (1978–2000) of annual and seasonal means of regional air temperature (AT), river water temperatures (Rh, Em, Aa) and groundwater temperatures (RhSe, RhNe, EmSi, AaKi, ToLi) in Switzerland.

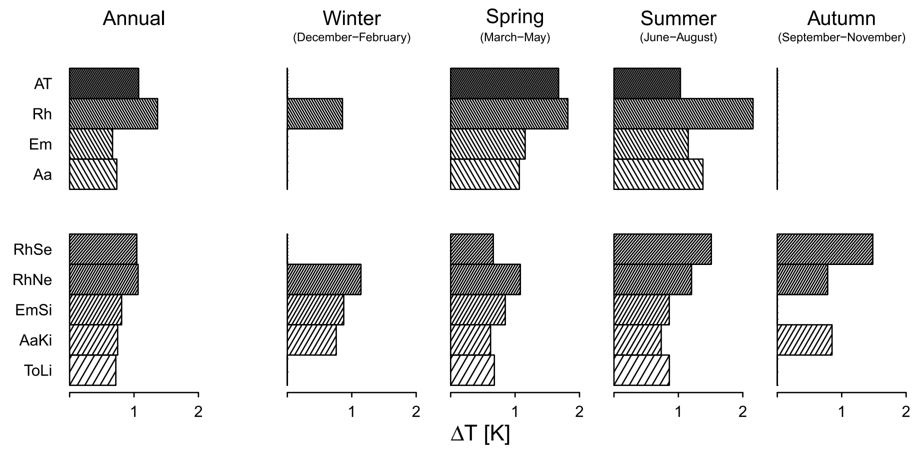

Figure 2. Magnitude of the late 1980s regime shift. Magnitude of the late 1980s regime shift in annual and seasonal mean values of regional air temperature (AT), river water temperatures (Rh, Em, Aa), and groundwater temperatures (RhSe, RhNe, EmSi, AaKi, ToLi) in Switzerland. Shown is the increase ΔT in the mean of each time series from Regime I (1978–1987) to Regime II (1988–2000) for all cases when a regime shift was detected by the STARS test [*Rodionov*, 2004] between 1985 and 1990 (Table 1); when no regime shift was detected, ΔT was assumed to be zero.

change-points in a time-series, the Pettitt test can detect only one change-point (see the auxiliary material for a more detailed description of the tests). The period covered by the analysis is 1978–2000, for which the density of available data was optimal. All three tests are commonly used to detect abrupt shifts in climatic and environmental time-series [*Rodionov and Overland*, 2005; *Hari et al.*, 2006; *Metsaranta and Lieffers*, 2010].

[8] Cross-correlation functions between time-series of monthly mean air, river, and groundwater temperatures were computed to estimate temperature travel time during the river-bank infiltration process. Trend and seasonality were removed from all time-series prior to computation using the seasonal-trend decomposition procedure of *Cleveland et al.* [1990].

3. Results

3.1. The Late 1980s Regime Shift in the Time-Series of Annual Means

[9] In the late 1980s, regional air temperature, river water temperatures, and groundwater temperatures all exhibited an abrupt regime shift (Figure 1). Application of STARS to the time-series of the respective annual means provided objective confirmation of this (Table 1). In regional air temperature and river water temperatures an abrupt regime shift ($p < 0.01$) occurred from 1987 to 1988, with the means for the period 1988–2000 (henceforth Regime II) exceeding those for the period 1978–1987 (henceforth Regime I) by 0.7 to 1.4 K (the To river temperature time-series was excluded from this part of the analysis because of its shortness). The groundwater temperature time-series behaved similarly: in all five aquifers, a statistically significant regime shift ($p < 0.01$) was detected from 1987 to 1988, with the Regime II mean exceeding the Regime I mean by 0.7 to 1.1 K. In all cases analyzed, the difference between the two regimes in the groundwater temperature time-series was comparable to that in the relevant river water temperature time-series (Figure 2, left). Note that in three of the aquifers (EmSi, AaKi, ToLi), an additional regime shift was detected in the mid-1990s (Table 1).

[10] The Pettitt [*Pettitt*, 1979] and Barry-Hartigan [*Barry and Hartigan*, 1993] change-point tests provided additional confirmation of the existence of a regime shift in the annual mean temperature time-series in the late 1980s. The change-points detected by the Pettitt test are in all cases located between 1987 and 1989 (Table 1). The locations of the most likely change-points detected by the Barry-Hartigan test (Table 1) generally agree with the locations of the regime shifts detected by STARS: i.e., 1987–1989 (and, for aquifers EmSi, AaKi and ToLi, additionally the mid-1990s).

3.2. The Late 1980s Regime Shift in the Time-Series of Seasonal Means

[11] To determine whether seasonal differences existed in the occurrence of the late 1980s regime shift, STARS was also applied to time-series consisting of either winter (December–February), spring (March–May), summer (June–August) or autumn (September–November) data only, focusing on the detection of shifts within the period 1985–1990 (Table 1). For regional air temperature, the occurrence of the late 1980s regime shift was confined to spring and summer. This was also true for two of the rivers (Em and Aa); for the third river (Rh), the temperature regime shift was additionally detected in winter. In all five aquifers, the late 1980s groundwater temperature regime shift showed a seasonal pattern that was different and less consistent than that shown by the air and river water temperature regime shifts (Figure 2). In the groundwater temperatures, the late 1980s regime shift could occur in any or all seasons. The Pettitt and Barry-Hartigan tests provided confirmation of the STARS results for the seasonal data (Table 1).

3.3. Time-Lags Between River Water and Groundwater Temperatures

[12] Computation of cross-correlation functions between the time-series of the monthly mean temperature data allowed the relevant time-lags between the time-series to be determined (Table 2). The locations of the maxima of the

Table 2. Cross-Correlation Functions of Monthly Mean Time-Series[a]

	Rh		Em	Aa	To
Regional air temperature and river water temperature	0.58 (0)		0.75 (0)	0.61 (0)	0.70 (0)
	RhSe	RhNe	EmSi	AaKi	ToLi
Regional air temperature and groundwater temperature	0.27 (4 ± 1)[b]	0.23 (4 ± 1)[b]	0.28 (2 ± 1)	0.24 (3 ± 1)	0.17 (2 ± 1)
River water temperature and groundwater temperature	0.40 (3 ± 1)[b]	0.28 (2 ± 1)[b]	0.34 (2 ± 1)	0.31 (3 ± 1)	0.15 (2 ± 1)

[a]Value and lag of the maximum of each cross-correlation function computed between monthly mean time-series of Swiss regional air temperature and river water temperatures (Rh, Em, Aa, To), regional air temperature and groundwater temperatures (RhSe, RhNe, EmSi, AaKi, ToLi), and river water temperatures and groundwater temperatures. The lag in months is given in parentheses, along with the estimated uncertainty associated with the sampling interval and the damping of the temperature signal. A positive lag implies groundwater temperature lags air temperature or river water temperature. All computations are based on the period 1978–2000 except for those involving the River Toess, which are based on the period 1984–2000. Trend and seasonality were removed prior to all computations using the seasonal-trend decomposition procedure of *Cleveland et al.* [1990]. All cross-correlation coefficients listed differ significantly from zero at the $p < 0.05$ level.

[b]Note that the discrepancies between the lags for RhSe and RhNe lie within the estimated range of uncertainty.

cross-correlation functions indicate that the water temperature in all rivers responds rapidly to fluctuations in regional air temperature. By contrast, the groundwater temperature in the pumping wells lags the water temperature of the river feeding the aquifer, and hence also the regional air temperature, by 2–4 months. The maxima of the cross-correlation functions between the regional air temperature and the river water temperatures were 2–3 times greater than the maxima of the cross-correlation functions between the regional air temperature and the respective groundwater temperatures (Table 2), implying that, as would be expected, the signal of the regional air temperature transmitted to the groundwater is weaker than that transmitted to the river water.

3.4. Non-stationarity in Regime II

[13] All the time-series illustrated in Figure 1 are statistically stationary during Regime I, but not all are statistically stationary during Regime II. For regional air temperature and river water temperature, linear regression revealed no statistically significant ($p < 0.05$) linear trend during either Regime I or Regime II, implying that the late 1980s regime shift is able to explain the entire temperature increase that occurred during the period 1978–2000. The same was true for two groundwater temperature time-series (RhSe, RhNe). However, the other three groundwater temperature time-series (EmSi, AaKi, ToLi) behaved differently: although no significant linear trend was detected during Regime I, a significant linear trend (of ~0.065 K yr^{-1}) was detected during Regime II. As noted above, in these three aquifers both STARS and the Barry-Hartigan test detect not only the late 1980s regime shift, but also an additional regime shift, involving increasing temperatures, in the mid-1990s (Table 1). Regardless of the statistical description employed (linear increase or abrupt shift), it follows that groundwater temperatures in three of the five aquifers increased during Regime II.

4. Discussion and Conclusions

[14] The late 1980s CRS was a large-scale atmospheric phenomenon that had substantial impacts on various environmental systems in the Northern Hemisphere. In Switzerland, most of the warming that rivers throughout the country have undergone since the 1970s is attributable to an abrupt water temperature increase of 0.1–1.1 K that occurred from 1987 to 1988 [*Hari et al.*, 2006]. Here we have shown that a regime shift in the late 1980s is also clearly detectable in the groundwater temperatures of Swiss aquifers that are recharged by river-bank infiltration, providing evidence that large-scale climatic forcing can strongly affect groundwater temperatures. Although the response of river water temperature to climatic forcing is strong and almost immediate, this is not necessarily the case for groundwater temperatures, in which the climatic signal is damped and delayed. Because lag times differ from aquifer to aquifer, the effect of seasonally specific climatic forcing can manifest itself at the pumping station at different times of the year depending on the hydraulic conductivity of the aquifer, the groundwater hydraulic gradient, the pumping rate, and the distance of the pumping station from the river.

[15] The statistical stationarity of the annual mean time-series of regional air temperature and of all river water temperatures during each of Regimes I and II implies that the only significant temperature increase that occurred during 1978–2000 was the abrupt increase associated with the late 1980s CRS. This was also the case for the two aquifers fed by the River Rhine (RhSe and RhNe). However, groundwater temperatures in the other three aquifers (EmSi, AaKi and ToLi) all exhibited a substantial, statistically significant increase during Regime II. Thus, as emphasized by *Holman et al.* [2011] for the related case of groundwater levels, the response of groundwater temperature to climatic forcing is likely to be complex and heterogeneous, varying from aquifer to aquifer (perhaps as a result of differences in pumping rates or land use, or because of differences in the intrinsic properties of the aquifers).

[16] Nevertheless, this study strongly suggests that an abrupt change in large-scale climatic forcing, represented here by the well-documented late 1980s CRS, had a clear and substantial impact on groundwater temperature in all five aquifers analyzed. Because biogeochemical processes in groundwater are strongly temperature-dependent [*Von Gunten et al.*, 1991; *Sprenger et al.*, 2011; *Green et al.*, 2011], this suggests that the quality of water extracted from aquifers recharged by river-bank infiltration for drinking-water production is likely to be affected by large-scale

climatic forcing, and hence by climate change. In some countries this may necessitate modifications to the current drinking-water supply infrastructure, which may not be able to cope with the adverse effects of altered redox conditions that may be encountered in the future as a result of higher groundwater temperatures.

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