Article

The physical impact of the late 1980s climate regime shift on Swiss rivers and lakes

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Abstract

In the late 1980s, a sudden climate regime shift (CRS) occurred throughout the Northern Hemisphere that affected both marine and inland waters. In Switzerland, rivers and lakes underwent an abrupt warming. A month-by-month comparison of water temperatures before and after the late 1980s CRS shows seasonal differences in the magnitude of the warming, which was stronger in winter, spring, and summer than in autumn. In lakes, the magnitude of the increase and the abruptness of the change diminished with increasing depth. Surface temperatures showed the most consistent abrupt warming. Hypolimnetic temperatures also increased, but the change was gradual in 3 of the 4 lakes studied. The abrupt warming in the late 1980s contributed substantially to the overall increase in temperature that has occurred in water bodies in Switzerland over the last few decades.

Key words: climate, regime shift, rivers, lakes, Switzerland, temperature, thermal stability

Introduction

At the end of the 1980s, a large-scale, abrupt climate regime shift (CRS) occurred over large parts of the Northern Hemisphere, associated with a shift in the Arctic Oscillation and in related climate modes such as the North Atlantic Oscillation and the Pacific Decadal Oscillation (Yasunaka and Hanawa 2002, Alheit et al. 2005, Rodionov and Overland 2005, Lo and Hsu 2010). It affected not only Northern Hemisphere temperatures, but also other climatic variables such as the frequency and intensity of cyclones (McCabe et al. 2001). Its impact on the marine environment is especially well documented. Sea surface temperatures throughout the Northern Hemisphere were affected (Yasunaka and Hanawa 2002), as were the physics and biology of marine areas as diverse as the North Pacific (Hare and Mantua 2000, Benson and Trites 2002), Bering Sea (Hare and Mantua 2000, Benson and Trites 2002, Rodionov and Overland 2005), North Sea (Reid et al. 2001, Beaugrand 2004, Alheit et al. 2005), Baltic Sea (Alheit et al. 2005), Mediterranean Sea (Conversi et al. 2009, 2010), and Sea of Japan (Zhang et al. 2007, Tian et al. 2004, 2008, Kidokoro et al. 2010). The influence of the late 1980s CRS was not confined to marine systems, however; it has also been detected in lake ecosystems in Germany (Gerten and Adrian 2000, Jochimsen et al. 2013) and Sweden (Temnerud and Weyhenmeyer 2008). In Switzerland, the influence of the

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late 1980s CRS has been detected in lakes (Anneville et al. 2004, 2005), rivers (Hari et al. 2006), and even groundwater (Figura et al. 2011). Here we investigate in more detail the physical impact of the late 1980s CRS on Swiss river and lake temperatures.

Study sites and data

Time-series of water temperature from 18 river and stream measuring stations and 4 perialpine lakes in Switzerland were analysed. The main analysis was limited to data measured from 1972 onward because data quality before 1972 was considered inadequate at one or more locations.

For several decades, water temperatures have been measured at subdaily intervals in many Swiss rivers and streams, allowing the computation of reliable daily means (Hari et al. 2006). Reliable daily mean water temperature data were available for each day of the period 1972–2001 from 15 measuring stations and for more than 99.9% of the same period from an additional 3 stations. Based on these daily data, a monthly mean water temperature time-series was computed for each measuring station. Because river temperature time-series are broadly coherent within Switzerland (Hari et al. 2006), the 18 time-series were aggregated to yield one monthly mean time-series representative of the general behaviour of river water temperatures (RWTs) in Switzerland.

The 4 study lakes—Lower Lake Zurich, Upper Lake Zurich, Greifensee, and the Lake of Walenstadt—are all located in northeastern Switzerland (Table 1). Upper Lake Zurich and Greifensee are considerably shallower than the other 2 lakes. The Lake of Walenstadt mixes twice a year but has never been known to freeze over (Zimmermann et al. 1991); in the other 3 lakes, the presence or absence of ice cover and the frequency and intensity of mixing vary depending on the severity of the winter (Zimmermann et al. 1991, Livingstone 1993, Hendricks Franssen and Scherrer 2008, Rempfer et al. 2010). For further details on the limnological characteristics of the 4 lakes see Zimmermann et al. (1991) and Rempfer et al. (2010). For Lower Lake Zurich, Upper Lake Zurich, and Greifensee, reliable water temperature data measured at approximately monthly intervals at the deepest point of each lake were available from 1972 to 2005; for the Lake of Walenstadt, the monthly time-series extended only from 1972 to 2000.

Lake temperature profiles were interpolated spatially at intervals of 1 m using linear interpolation (North and Livingstone 2013). From the resulting interpolated profiles, volume-weighted mean temperatures were derived for the full water column, the epi-metalimnion (epilimnion plus metalimnion) and the hypolimnion. The depth of the upper boundary of the hypolimnion (z_h) varies among the lakes (Table 1). For each lake, values of the Schmidt stability, a measure of overall thermal stability, were calculated from the interpolated temperature profiles (Schmidt 1928, Idso 1973). Time-series of surface water temperature, the 3 volume-weighted mean temperatures, and Schmidt stability were interpolated temporally at daily intervals using cubic spline interpolation. These daily values were then aggregated to yield monthly and annual means. From Lower Lake Zurich, reliable water temperature data covering a much longer period are available. This extended Lower Lake Zurich dataset, covering the period 1944–2010, was also analysed.

Because air temperatures fluctuate with a high degree of coherence over the entire Swiss Plateau, the behaviour of the regional air temperature on the Swiss Plateau is characterized well by an averaged time-series of the air temperatures measured at the 4 Swiss Meteorological Office stations of Zurich, Berne, Basle, and Neuchâtel (Livingstone and Lotter 1998). Daily maximum and minimum temperatures were used to calculate daily means for each station, from which the regional mean was determined. The resulting time-series of daily means was aggregated to yield monthly and annual means.

Table 1. Characteristics of the 4 study lakes (z_h = depth of the upper boundary of the hypolimnion in summer). Morphometric data from Zimmermann et al. (1991).

	Lake of Walenstadt	Greifensee	Lower Lake Zurich	Upper Lake Zurich
Altitude a.s.l. (m)	419	435	406	406
Surface area (km^2)	24	8	65	20
Volume (km^3)	2.42	0.15	3.3	0.47
Mean depth (m)	103	18	51	23
Maximum depth (m)	145	33	136	48
z_h (m)	20	17	20	30
Mean retention time (yr)	1.4	1.5	1.2	1.4
Trophic status	Oligotrophic	Hypertrophic	Mesotrophic	Mesotrophic

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Methods

Change-points between regimes were detected using the sequential t-test STARS (Rodionov and Overland 2005). Mean annual temperatures were tested using a threshold significance level $p = 0.15$, a Huber weight parameter $h = 1$ (Rodionov 2006), and a cut-off length $L = 15$ yr. The threshold significance level and the cut-off length determine the magnitude of the shifts detected by STARS (Rodionov and Overland 2005). The cut-off length determines the detection scale of interest (Rodionov and Overland 2005), which in this case was approximately 15 yr (1972–1987 and 1988–2005). The Huber weight parameter accounts for outliers when calculating the mean value of a regime (Rodionov 2006). The cut-off length was reduced to 10 yr for the RWT time-series and the Lake of Walenstadt time-series because of their shorter lengths. When STARS detected a shift, an additional (and more stringent) t-test was applied to the 2 regimes. While the STARS threshold significance level was set to $p = 0.15$, any shift that did not satisfy a significance criterion of $p < 0.05$ was rejected. Because the focus of this study was the impact of the late 1980s CRS, the discussion focuses on shifts detected between 1984 and 1991. The nonparametric Mann-Kendall test was used to test for significant monotonic trends within individual regimes.

Results

Air temperature

Annual mean regional air temperatures on the Swiss Plateau underwent an abrupt increase of 0.9 °C from 1987 to 1988 ($p < 0.001$), dividing the period 1972–2005 into 2 regimes: Regime I from 1972 to 1987 and Regime II from 1988 to 2005 (Fig. 1a). Comparing the 2 regimes month by month, the regional air temperature increased from Regime I to Regime II by more than 0.7 °C from January to August and in October (Fig. 1b; Table 2). No statistically significant monotonic trend was found in either Regime I or Regime II ($p < 0.05$), suggesting that the entire increase in air temperature during the period 1972–2005 resulted from the late 1980s CRS.

River and stream temperatures

River and stream temperatures in Switzerland closely follow regional air temperature (Livingstone and Hari 2008). The abrupt increase in air temperature in Switzerland associated with the late 1980s CRS was therefore reflected in a corresponding abrupt increase in river and stream temperatures (Hari et al. 2006). Analysis of the annual mean 18-station RWT time-series confirmed the existence of an abrupt increase from Regime I to Regime II ($p < 0.001$) with a magnitude of $\Delta T = 0.7$ °C (Fig. 1c). As in the case of air temperature, this increase was more pronounced from January to August and in October than during the rest of the year (Fig. 1d; Table 2). No statistically significant monotonic trend was found in either Regime I or Regime II ($p < 0.05$), suggesting, in agreement with Hari et al. (2006), that the entire temperature increase in Swiss rivers and streams from 1972 to 2001 can be explained by the late 1980s CRS.

Lake temperatures

Lake surface temperature: In all 4 of the study lakes, an abrupt increase in annual mean lake surface water temperature was detected during the late 1980s ($p < 0.01$) (Fig. 2a–d; Table 3). The regime shift occurred from 1987 to 1988 in the Lake of Walenstadt and Greifensee, from 1988 to 1989 in Lower Lake Zurich, and from 1989 to 1990 in Upper Lake Zurich. The magnitude of the regime shift ranged from 0.6 to 0.8 °C (Table 3). In general, the regime shift tended to be more coherently pronounced in all 4 lakes from April to August (Table 2). In Regime I, no statistically significant trends were found for any of the lakes ($p < 0.05$). In Regime II, a significant (upward) trend was found only for Lower Lake Zurich ($p < 0.05$).

Mean lake temperature: For the annual, volume-weighted mean lake temperature, a regime shift of 0.3–0.4 °C was detected in all 4 lakes in the late 1980s (Fig. 2e–h; Table 3). The regime shift occurred from 1988 to 1989 in the Lake of Walenstadt, from 1987 to 1988 in Greifensee and Lower Lake Zurich, and from 1984 to 1985 in Upper Lake Zurich. The largest temperature increases between Regimes I and II occurred from January to August (Table 2), except for Greifensee (Apr–Aug). A statistically significant upward trend was found in Regime II for the Lake of Walenstadt ($p < 0.05$); otherwise, no monotonic trends were found in either of the 2 regimes.

An exceptionally long temperature time-series, encompassing more than 60 years of data, is available from Lower Lake Zurich (Fig. 3). When the time window was increased to span the period 1944–2010, the STARS test identified 2 regime shifts in mean lake temperature: a main regime shift of 0.4°C from 1987 to 1988 ($p < 0.001$) and a smaller regime shift of 0.2 °C from 1964 to 1965 ($p < 0.05$). The main regime shift involved a year-round increase in mean lake temperature and a significant shift ($p < 0.05$) in each individual month from December to May, as well as August. Despite the smaller regime shift from 1964 to 1965, the extended Lake Zurich temperature data show no significant trend ($p < 0.05$) before or after the regime shift in 1987–1988. The abrupt temperature

Table 2. Change in monthly mean temperature (°C) and thermal stability (J m^{-2}) from Regime I (up to and including 1987) to Regime II (1988 and after). Statistical significance: $p < 0.05$ (*).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature	1.2	1.2	1.4*	1.0*	1.7*	1.2*	0.7	1.5*	−0.3	0.9	0.0	0.2
River water temperature	0.6*	0.4*	0.7*	0.7*	1.4*	1.0*	0.8*	1.4*	0.2	0.6*	0.3	0.3
Lake surface water temperature												
Lake of Walenstadt	0.4*	0.4*	0.1	0.4	2.0*	1.8*	1.6*	1.3*	0.2	0.3	0.5*	0.3
Greifensee	0.5	0.2	−0.1	1.2*	2.1*	0.8	1.0*	0.8	0.3	0.5	0.5	0.2
Lower Lake Zurich	0.4*	0.6*	0.6	0.9	1.9*	0.6	1.1	1.2*	0.3	0.4	0.5	0.4
Upper Lake Zurich	0.2	0.4	0.3	1.5*	1.6*	−0.1	1.4	0.9	−0.1	−0.1	0.2	0.2
Volume-weighted mean lake temperature												
Lake of Walenstadt	0.4*	0.4*	0.5*	0.5*	0.5*	0.4*	0.3	0.3*	0.3*	0.2	0.3*	0.3*
Greifensee	0.3*	−0.1	0.2	0.6*	0.6*	0.5*	0.5*	0.5*	0.3	0.2	0.3	0.3
Lower Lake Zurich	0.4*	0.5*	0.5*	0.5*	0.5*	0.5*	0.4*	0.3*	0.2	0.2	0.3*	0.3*
Upper Lake Zurich	0.5*	0.5*	0.5*	0.7*	0.7*	0.5	0.5*	0.3	−0.1	0.0	0.2	0.3
Volume-weighted mean epi-metalimnetic temperature												
Lake of Walenstadt	0.4*	0.4*	0.5*	0.6*	1.3*	1.2*	0.7	0.8*	0.5*	0.4	0.4*	0.3
Greifensee	0.4*	−0.1	0.2	0.7*	0.8*	0.7*	0.7*	0.8*	0.4	0.3	0.4	0.4
Lower Lake Zurich	0.4*	0.5*	0.6*	0.9*	1.1*	0.9*	0.6	0.6*	0.4	0.4	0.4	0.5
Upper Lake Zurich	0.5*	0.5*	0.5	0.7*	0.8*	0.5	0.6*	0.3	−0.1	0.0	0.2	0.3
Volume-weighted mean hypolimnetic temperature												
Lake of Walenstadt	0.4*	0.4*	0.6*	0.5*	0.4*	0.3*	0.2	0.3*	0.3*	0.1	0.2*	0.3*
Greifensee	0.3*	−0.1	0.2	0.2	0.1	0.0	−0.1	−0.2	−0.2	−0.2	−0.1	0.3
Lower Lake Zurich	0.3*	0.4*	0.4*	0.4*	0.3*	0.3*	0.3*	0.2	0.2	0.2	0.2	0.2*
Upper Lake Zurich	0.5*	0.6*	0.4*	0.2	0.1	0.0	0.1	−0.1	−0.1	−0.1	0.0	0.4*
Schmidt stability												
Lake of Walenstadt	17	−1	24	187*	1071*	1385*	775	1131*	512	282	295	104
Greifensee	−3	0	−3	40*	102*	112*	120*	148*	61	40	20	2
Lower Lake Zurich	48*	16	11	228*	741*	725*	805*	984*	409	252	268	124
Upper Lake Zurich	−2	2	1	55*	83*	87	191*	169*	49	19	2	−14

increase of 0.4 °C in the late 1980s therefore contributed substantially to the overall increase in mean lake temperature that has occurred over the last few decades.

Epi-metalimnetic temperature: Coarse estimates of the dependence of the temperature regime shift on depth were obtained by analysing the mean volume-weighted epi-metalimnetic and hypolimnetic temperatures separately. Significant shifts in annual mean epi-metalimnetic temperature occurred in the Lake of Walenstadt and Lower Lake Zurich from 1987 to 1988 ($p < 0.001$), and in Upper Lake Zurich from 1984 to 1985 ($p < 0.01$; Fig. 2i–l), although in Greifensee, a shift was detected in the early 1980s (Table 3). Comparing Regimes I and II month by month, epi-metalimnetic temperatures in all 4 lakes increased in nearly every month of the year, with the largest increases occurring from April to August (Table 2). As in the case of lake surface water temperature, a significant (upward) trend in epi-metalimnetic temperature was found for Lower Lake Zurich in Regime II ($p < 0.05$).

Hypolimnetic temperature: Lower Lake Zurich was the only lake with a statistically significant regime shift in annual mean hypolimnetic temperature ($p < 0.01$; ΔT = 0.3 °C; Fig. 2m–p; Table 3), although an increase in hypolimnetic temperature from Regime I to Regime II occurred in every month of the year not only in Lower Lake Zurich, but also in the Lake of Walenstadt (Table 2). The largest increases in temperature in the hypolimnion of the Lake Walenstadt, Lower Lake Zurich, and Upper Lake

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Table 3. Temporal location, statistical significance, and magnitude (ΔT) of abrupt shifts in annual mean Swiss lake temperatures and thermal stability as detected by the STARS test (Rodionov 2005). The lake temperatures listed are: surface temperature (T_0); mean lake temperature (T_l); mean epi-metalimnetic temperature (T_{em}); and mean hypolimnetic temperature (T_h). Thermal stability calculated as Schmidt stability (S). Statistical significance: $p < 0.05$ (*); $p < 0.01$ (**); $p < 0.001$ (***). ΔT is given only for regime shifts detected in the 1980s.

		Lake of Walenstadt	Greifensee	Lower Lake Zurich	Upper Lake Zurich
T_0	STARS	1987–1988 (***)	1987–1988 (***)	1988–1989 (***)	1989–1990 (**)
	ΔT_0 (°C)	0.8	0.6	0.8	0.6
T_l	STARS	1988–1989 (***)	1987–1988 (*)	1987–1988 (***)	1984–1985 (**)
	ΔT_l (°C)	0.4	0.3	0.4	0.4
T_{em}	STARS	1987–1988 (***)	1981–1982 (***)	1987–1988 (***)	1984–1985 (**)
	ΔT_{em} (°C)	0.6	—	0.6	0.4
T_h	STARS	—	—	1987–1988 (**)	—
	ΔT_h (°C)	—	—	0.3	—
S	STARS	1982–1983 (**)	1980–1981 (***)	1989–1990 (***)	1988–1989 (***)
	ΔS (J m^{-2})	—	—	422	55

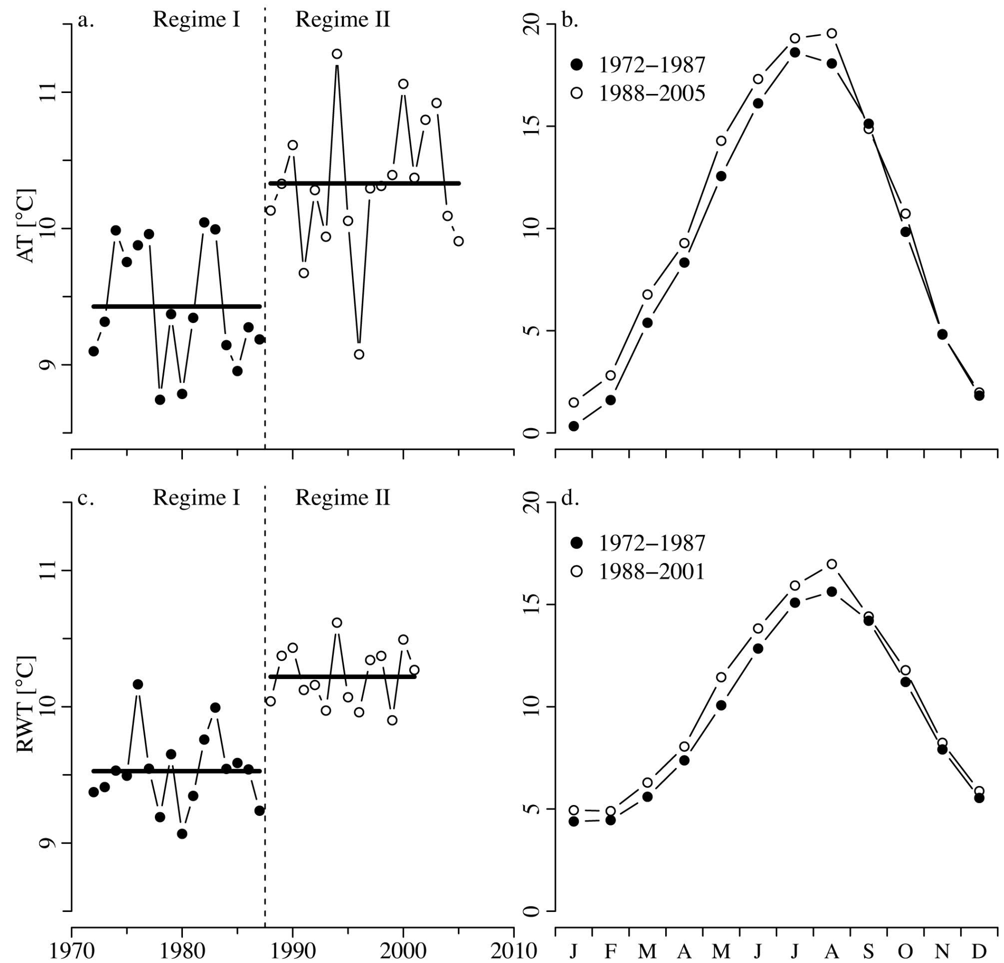

Fig. 1. (a) Annual mean regional air temperature (AT) in northern Switzerland in Regimes I (1972–1987) and II (1988–2005) based on data from the meteorological stations of Zurich, Berne, Basle, and Neuchâtel. (b) Comparison of monthly mean AT in Regimes I and II. (c) Combined mean annual river water temperatures (RWT) from 18 rivers and streams across Switzerland in Regimes I (1972–1987) and II (1988–2001). (d) Comparison of monthly mean RWT in Regimes I and II. The thick horizontal lines illustrate the mean temperatures in Regimes I and II.

Zurich occurred from January to April, while in Greifensee changes were small (≤0.3 °C) throughout the year (Table 2). A test for monotonic trends in hypolimnetic temperature ($p < 0.05$) revealed no trend for any of the 4 lakes in Regime I, and no trend for 3 of the lakes in Regime II (the exception was the Lake of Walenstadt, for which the Regime II time-series extends only up to 2000).

Lake thermal stability

A late 1980s regime shift in the annual mean Schmidt stability (S) was detected in Lower Lake Zurich and Upper Lake Zurich ($p < 0.001$) but not in the other 2 lakes (Fig. 4a–d; Table 3). In all 4 lakes, the Schmidt stability increased from Regime I to Regime II during the stratified period (from late spring to early autumn), when thermal stability is high (Table 2). During winter and early spring, when thermal stability is low and the lakes undergo mixing, the Schmidt stability changed very little from Regime I to Regime II (Table 2). The largest increases tended to occur between April and August, and in all 4 lakes a significant regime shift ($p < 0.05$) was detected for this 5-month period (Fig. 4e–h). A significant upward trend in Regime II was found in Greifensee ($p < 0.05$) and Lower Lake Zurich ($p < 0.01$). Otherwise, the Schmidt stability was statistically stationary in both Regimes I and II.

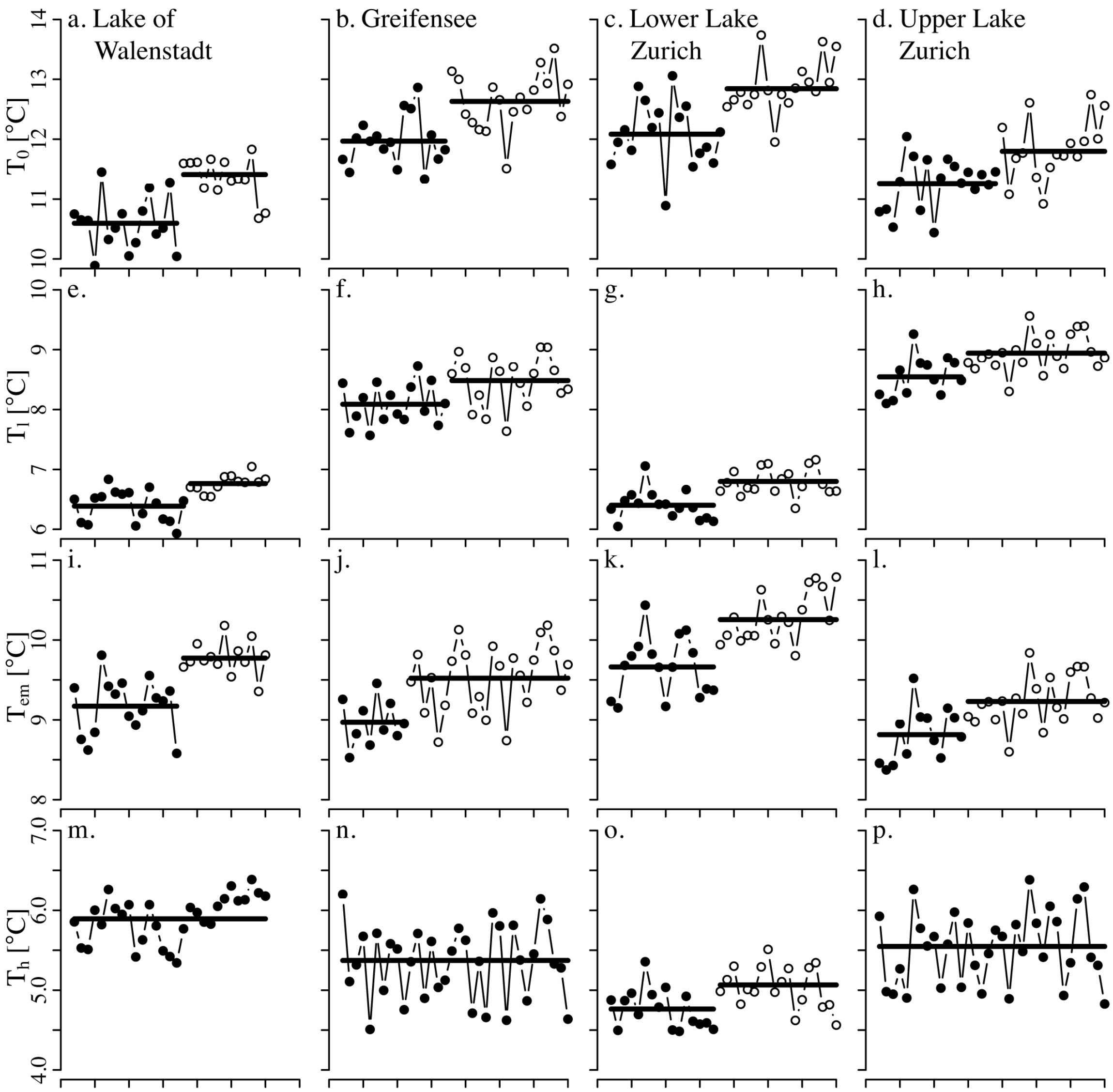

Fig. 2. Annual mean lake surface water temperatures (T_0) for the Lake of Walenstadt, Greifensee, Lower Lake Zurich, and Upper Lake Zurich (a, b, c, d), and the corresponding mean lake temperatures (T_l) (e, f, g, h), mean epi-metalimnetic temperatures (T_{em}) (i, j, k, l), and mean hypolimnetic temperatures (T_h) (m, n, o, p). All means are volume-weighted. The thick horizontal lines illustrate the mean temperatures in Regimes I and II.

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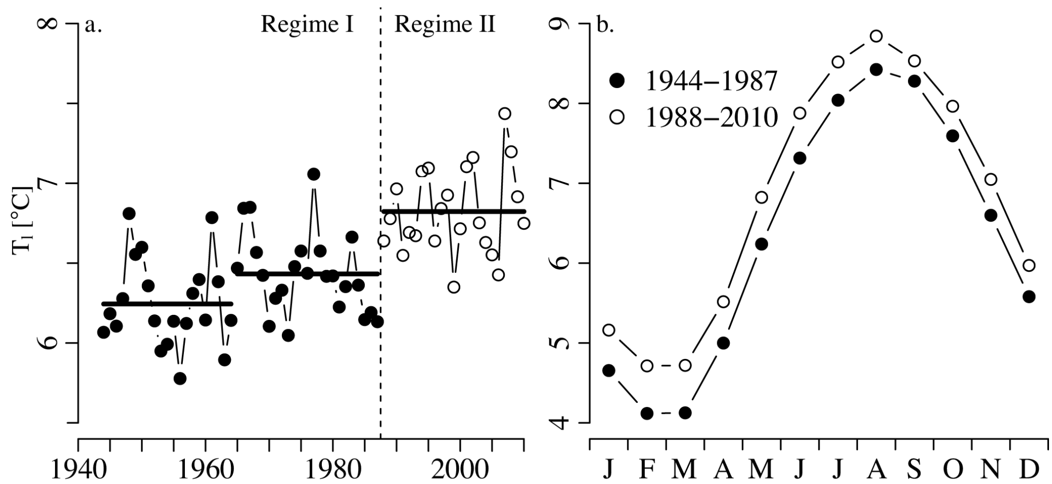

Fig. 3. (a) Annual volume-weighted mean lake temperature (T_l) of Lower Lake Zurich (extended data series, 1944–2010). The thick horizontal lines illustrate the mean temperatures in Regimes I and II. (b) Comparison of monthly mean lake temperatures in Regimes I and II.

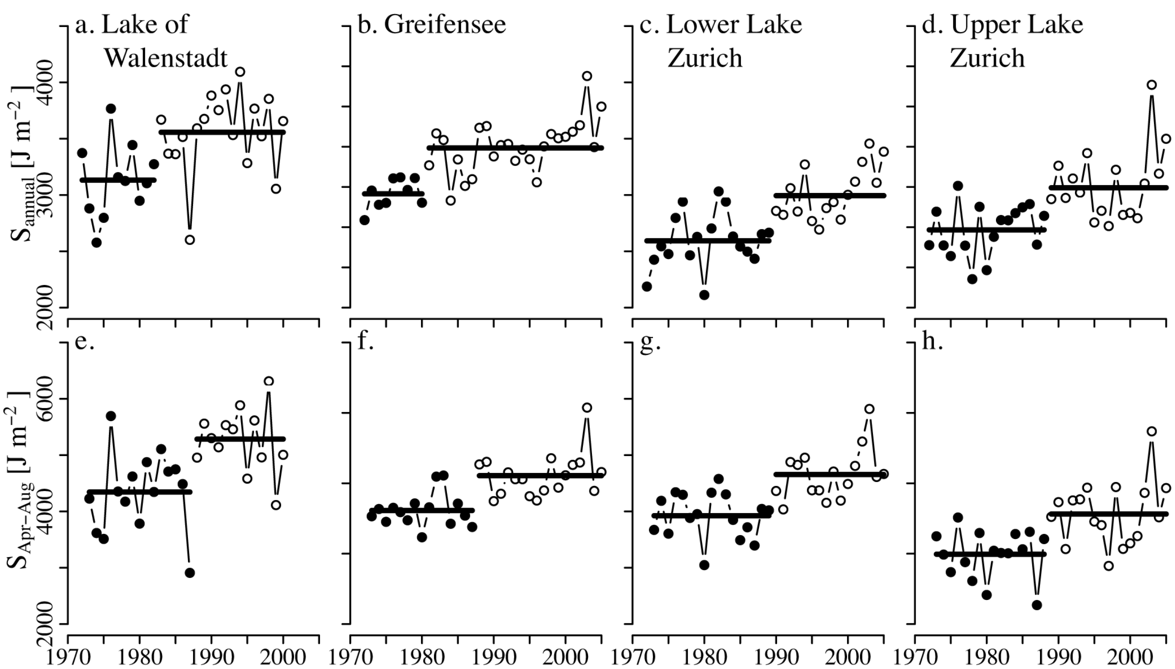

Fig. 4. Schmidt stability of the Lake of Walenstadt, Greifensee, Lower Lake Zurich, and Upper Lake Zurich, averaged over the full year (S_{annual}) (a, b, c, d) and over April to August ($S_{Apr-Aug}$) (e, f, g, h). The thick horizontal lines illustrate the mean Schmidt stabilities in Regimes I and II.

Discussion

In the late 1980s, water temperatures in rivers and lakes in Switzerland (along with some groundwaters: see Figura et al. 2011) clearly underwent a regime shift corresponding to, and presumably caused by, the late 1980s CRS. The late 1980s CRS was associated with, and may ultimately have been triggered by, a shift in the Arctic Oscillation and other large-scale climate modes (Rodionov and Overland 2005, Lo and Hsu 2010). The shift in water temperature occurred in conjunction with an abrupt increase of 0.9 °C in annual mean air temperatures on the Swiss Plateau, centred around 1987–1988. The shift was reflected most strongly in river water temperatures (ΔT = 0.7 °C) and lake surface water temperatures (ΔT = 0.6 − 0.8 °C), which are tightly related both to each other and to regional air temperature (Livingstone and Hari 2008).

In all 4 study lakes the magnitude of the shift decreased with depth, from the lake surface through the epi-metalimnion to the hypolimnion. No temperature regime shift in the late 1980s was detected in the epi-metalimnion of Greifensee, and only Lower Lake Zurich showed an abrupt temperature shift in the hypolimnion. Nonetheless, all 4 lakes showed an abrupt regime shift in mean lake temperature ($\Delta T = 0.3 - 0.4$ °C; $p < 0.05$). This indicates that, although the late 1980s CRS had a detectable effect on the heat budgets of all 4 lakes, its effect on the internal distribution of heat varied from lake to lake, presumably depending on individual lake characteristics, which differ substantially (Table 1).

Applying the STARS test to the extended Lower Lake Zurich time-series of mean lake temperature (1944–2010), the regime shift from 1987 to 1988 was still easily detectable, statistically highly significant, and strong. Despite a small additional regime shift detected from 1964 to 1965 (Fig. 3a), the extended time-series showed no significant monotonic trend ($p < 0.05$) during Regime I, even when this regime was extended back to 1944. The lack of trend across the small regime shift, and its relatively low significance ($p < 0.05$), suggest that it might not be a true regime shift, but rather the realisation of an autoregressive stationary red-noise process (Rudnick and Davis 2003). To distinguish between the 2 possibilities, prewhitening can be applied to the time-series to remove its red-noise component prior to testing for a regime shift (Rodionov 2006). When this was done, the shift from 1964 to 1965 became nonsignificant ($p > 0.05$), and the magnitude of the shift from 1987 to 1988 increased to 0.5 °C ($p < 0.001$). Thus, most of the increase in the mean lake temperature of Lower Lake Zurich over the past 65 years seems to be associated with the late 1980s CRS.

No significant trends ($p < 0.05$) in the air temperature or river water temperature time-series were detected during either Regime I or Regime II, suggesting, in agreement with Hari et al. (2006), that the entire recent increase in river water temperatures in Switzerland can be interpreted as a result of the late 1980s CRS. This is not necessarily true, however, for all of the lake surface water temperature records. Although no significant trends ($p < 0.05$) in lake surface water temperature were found in Regime I for any of the lakes, one of the 4 lakes showed a significant warming trend during Regime II. This one exception was Lower Lake Zurich, in which the surface water temperature showed a significant upward trend ($p < 0.05$) of approximately 0.04 °C yr^{-1} during Regime II, which is similar to the global lake surface water warming rate of 0.045 ± 0.011 °C yr^{-1} determined for 1985–2009 from satellite data (Schneider and Hook 2010). Thus, although the late 1980s CRS can statistically explain the entire observed increase in the surface water temperature of some Swiss lakes over the past few decades, this is not true of all. The surface water temperature of Lower Lake Zurich, in common with the temperatures of some Swiss groundwaters (Figura et al. 2011), has continued to increase even after the late 1980s CRS.

Comparing the 2 regimes month by month, the regional air temperature, mean river water temperature, and lake water temperatures (excluding the hypolimnion) increased from Regime I to Regime II throughout most of the year, with the exception of part of autumn and early winter. The largest increases tended to occur from January to August for air temperature, from March to August for river water temperature, and from approximately April to August for lake surface water temperatures. The lack of any strong increase in the temperatures of rivers or the uppermost layers of lakes from Regime I to Regime II in the first 2 months of the year, despite comparatively large increases in air temperature, is not surprising. In January and February, snow in river catchment areas (and often ice in the rivers themselves) buffers the effect of changes in air temperature on river water temperatures, so the increase in the mean air temperature from Regime I to Regime II is unlikely to have been fully reflected in river temperatures in these winter months. In lakes, partial ice cover (e.g., in Greifensee and Upper Lake Zurich; see Hendricks Franssen and Scherrer 2008) also has a buffering effect. Even in lakes not subject to ice cover, however, vertical mixing during winter and spring, when thermal stability is low and wind-induced mixing is common, also buffers the effect of changing air temperatures, diminishing the impact of a rise in mean air temperature from Regime I to Regime II. After the establishment of a stratified water column in April, the relatively thin epilimnion responds much more sensitively to changes in air temperature (Livingstone and Lotter 1998), explaining the greater differences in lake temperatures between the 2 regimes that are apparent from April to August.

The asymmetric warming between the surface and bottom waters of the lakes, with the epi-metalimnion warming more than the hypolimnion, resulted in a general increase in thermal stability. The increase was strongest from April to August in all 4 lakes, and thermal stabilities averaged over these months showed an abrupt increase in the late 1980s. Despite the general increase in thermal stability from Regime I to Regime II, the frequency of occurrence of complete mixing (defined here as occurring when the Schmidt stability < 15 J m^{-2}) did not change noticeably in 3 of the 4 lakes. The exception was Lower Lake Zurich, which underwent complete mixing in 13 out of the 16 years of Regime I, but in only 9 out of the 18 years of Regime II, suggesting a shift from monomixis in Regime I to oligomixis in Regime II. Because Lower Lake Zurich did not undergo complete mixing every year during Regime II, on several occasions hypolimnetic temperatures were able to increase over a period of several

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consecutive years as a result of the gradual downward transport of heat from the lower metalimnion by turbulent diffusion (Livingstone 1993, 1997). Although mixing episodes always eventually returned the hypolimnetic temperature approximately to its long-term mean value, the existence of this multiannual "sawtooth" mixing pattern in Regime II automatically resulted in hypolimnetic temperatures that were on average higher in Regime II than in Regime I.

The existence of a regionally coherent response of lake water temperatures to climatic forcing in general has been well documented in previous studies (e.g., Magnuson et al. 1990, Blenckner et al. 2007, Livingstone et al. 2010). In the specific case of the abrupt CRS in the late 1980s, the present study has confirmed that rivers and lakes in Switzerland responded coherently to the step-change in external forcing, but has also demonstrated a certain degree of heterogeneity in the response, especially in lake hypolimnia. Regional coherence among lakes is known to be strongest for physical variables that have a direct causal link to climatic forcing (Magnuson et al. 1990). Thus, inter-lake coherence in lake temperature is strongest at the surface, but weakens with depth as the influence of climatic forcing becomes more indirect and individual lake processes become more dominant. Differences in the mixing characteristics of the individual lakes, related to, for instance, differences in lake morphometry (Table 1), are likely to be primarily responsible for this. Rempfer et al. (2010) have already shown, for example, that morphometric differences among the same 4 Swiss lakes (Table 1) result in different hypolimnetic responses to wind forcing in winter.

Research on the physical impact of climate change on aquatic systems has tended to focus on gradual long-term trends (e.g., Schneider and Hook 2010), but the present study shows clearly that abrupt changes in large-scale climatic forcing can result in similarly abrupt regime shifts in the physical environments of rivers and lakes. In addition to the late 1980s CRS, at least 2 other abrupt, large-scale CRSs seem to have occurred in the past few decades; i.e., in the mid 1970s and the late 1990s (Hare and Mantua 2000, Rodionov and Overland 2005, Overland et al. 2008). The impact on aquatic ecosystems of such unannounced and, perhaps, ultimately unpredictable abrupt shifts in physical boundary conditions will likely differ from the impact of more gradual change. Thus, if drastic changes in their functionality are to be avoided, aquatic ecosystems may have to adapt not only to gradual changes in water temperature as climate change progresses, but also to abrupt changes. This emphasizes the importance of maintaining the resilience of aquatic ecosystems (Scheffer et al. 2001, Folke et al. 2004) in the face of climate change.

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