Swiss prealpine Rietholzbach research catchment and lysimeter: 32 year time series and 2003 drought event

Sonia I. Seneviratne, Irene Lehner, Joachim Gurtz, Adriaan J. Teuling, Herbert Lang, Ulrich Moser, Dietmar Grebner, Lucas Menzel, Karl Schropp, Tomas Vitvar, and Massimiliano Zappa

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[1] The prealpine Rietholzbach research catchment provides long-term continuous hydroclimatological measurements in northeastern Switzerland, including lysimeter evapotranspiration measurements since 1976, and soil moisture measurements since 1994. We analyze here the monthly data record over 32 years (1976–2007), with a focus on the extreme 2003 European drought. In particular, we assess whether the well-established hypothesis that the 2003 event was due to spring precipitation deficits is valid at the site. The Rietholzbach measurements are found to be internally consistent and representative for a larger region in Switzerland. Despite the scale discrepancy (3.14 m² versus 3.31 km²), the lysimeter seepage and catchment-wide streamflow show similar monthly dynamics. High correlations are further found with other streamflow measurements within the Thur river basin (1750 km²) and—for interannual anomalies—also in most of northern Switzerland. Analyses for 2003 confirm the occurrence of extreme heat and drought conditions at Rietholzbach. However, unlike findings from regional-scale modeling studies, they reveal a late onset of the soil moisture deficit (from June onward), despite large precipitation deficits from mid-February to mid-April. These early spring deficits were mostly compensated for by decreased runoff during this period and excess precipitation in the preceding weeks to months (including in the 2002 fall). Our results show that evapotranspiration excess in June 2003 was the main driver initiating the 2003 summer drought conditions in Rietholzbach, contributing 60% of the June 2003 water storage deficit. Finally, long-lasting drought effects on the lysimeter water storage due to rewetting inhibition were recorded until spring 2004.


1. Introduction

[2] The land water cycle is a central component of the climate system, in particular in the context of climate change [e.g., Intergovernmental Panel on Climate Change (IPCC), 2007; Seneviratne et al., 2010]. Substantial decadal variations in hydroclimatological processes have been observed within the 20th century due to recent changes in greenhouse gas and aerosol concentrations [e.g., Shefield and Wood, 2008; Vautard et al., 2009; Teuling et al., 2009; Oliveira et al., 2011; Dai, 2011]. Trends and variability in land hydrological variables, in particular in soil moisture and evapotranspiration, are also relevant for the surface energy balance and temperature extremes [e.g., Seneviratne et al., 2006a; Fischer et al., 2007; Diffenbaugh et al., 2007; Teuling et al., 2010a; Hirschi et al., 2011], as well as for ecosystem productivity and carbon exchanges on land [e.g., Ciais et al., 2005; Reichstein et al., 2007; van der Molen et al., 2011]. Hence, reference measurements are essential to assess interannual to decadal variability in the relevant processes, together with associated impacts on climate and ecosystem functioning. These are also critical for validating corresponding processes in land, ecosystem, and climate models.

[3] While long-term observations of standard hydrometeorological variables (precipitation, streamflow, temperature, wind, pressure) are relatively widespread, only few measurement sites have long-term time series of all terrestrial water balance components. In particular measurements of evapotranspiration and soil moisture are very scarce (e.g., see Seneviratne et al. [2010] for an overview). Evapotranspiration measurement networks using the eddy-covariance flux measurement technique have been established as part of the FLUXNET project [Baldocchi et al., 2001; Baldocchi, 2008], but long-term measurements over several decades...
are generally not available. Lysimeter measurements are available at various sites around the world but long-term continuous reference measurement time series with these instruments are very scarce (section 2.2). Also existing long-term soil moisture measurement networks are spatially sparse [e.g., Robock et al., 2000; Seneviratne et al., 2010; Dorigo et al., 2011]. On the other hand, satellite-derived products for soil moisture and evapotranspiration, though promising [e.g., Wagner et al., 2007; De Jeu et al., 2008; Mueller et al., 2011], have several limitations and require ground validation themselves. Moreover, because the respective missions are generally only a few years long, their use for trend analyses is problematic.

[6] We present here an overview and analyses of hydroclimatological measurements at the Rietholzbach research catchment in northeastern Switzerland, with a focus on the 2003 drought and heat event. The Rietholzbach research catchment includes a unique set of measurements dating back to 1976 for evapotranspiration and most hydroclimatological measurements. In addition, it also includes measurements of soil moisture since 1994 and of global radiation since 1989. As highlighted in section 2, the lysimeter-based evapotranspiration measurements at this site constitute one of the longest continuous records of this type in the world. The Rietholzbach data is thus potentially invaluable to evaluate long-term changes in hydrology as well as hydrological extremes in the Swiss Plateau.

[5] The 2003 European drought and heat wave was one of the most extreme in recent decades and centuries in central Europe and the alpine region [e.g., Casty et al., 2005; Vidal et al., 2010]. It incurred significant impacts on ecosystems, agriculture, and human health [e.g., Schär and Jendritzky, 2004; Ciais et al., 2005; Fischer et al., 2007]. Several studies have investigated the development of the 2003 drought based on numerical experiments with regional climate models, land hydrological models, or ecosystem models [e.g., Ciais et al., 2005; Fischer et al., 2007; Vidal et al., 2010], or based on remote sensing data [e.g., Andersen et al., 2005; Loew et al., 2009]. However, a detailed investigation of this event based on ground observations of all main land hydrological components (precipitation, evapotranspiration, soil moisture, streamflow, groundwater) has to our knowledge not been performed previously, most likely due to the lack of such comprehensive sets of observations at a single location.

[6] As part of the present article, we aim to address the following main research questions:

[7] 1. How unique is the current lysimeter evapotranspiration record at Rietholzbach compared to available lysimeter records worldwide?

[8] 2. How representative is the lysimeter (3.14 m²) for the whole Rietholzbach catchment (3.31 km²), and how representative is the Rietholzbach catchment for other locations in the Thur basin and Switzerland?

[9] 3. Do the Rietholzbach data confirm commonly highlighted features of the 2003 drought event as interpreted from modeling experiments and remote sensing data? In particular, was an early vegetation onset and high spring precipitation deficit [e.g., Ferranti and Viterbo, 2006; Fischer et al., 2007; Loew et al., 2009] the main driver for the drought at that location?

[10] 4. What were the respective contributions of precipitation deficits and evapotranspiration excesses in driving the 2003 drought at the site?

[11] 5. How long did the 2003 drought persist and were there possible long-term effects of the drought?

[12] The article is structured as follows. Section 2 presents the Rietholzbach research catchment, the lysimeter instrument operated at this site including a perspective on other existing lysimeter stations, as well as the analyzed measurements and the methods applied in this study. Section 3 addresses the consistency of the lysimeter data with the measured catchment-wide streamflow, as well as the representativeness of the site for surrounding locations in Switzerland. Section 4 provides analyses of the 32 year (1976–2007) time series, focusing on the overall hydroclimatology of the catchment. Section 5 presents a corresponding analysis for the 1994–2007 period (including soil moisture and radiation measurements), with an in-depth analysis of the 2003 drought development at the site. Finally, section 6 provides a short summary and the main conclusions that can be drawn from these analyses in view of the site representativeness in Switzerland and the 2003 drought event.

2. Data and Methods

2.1. Rietholzbach Research Catchment

[13] The Rietholzbach research catchment is a small pre-alpine watershed located in northeastern Switzerland in the middle of the Thur river basin, a tributary to the Rhine (Figure 1). The catchment has an area of 3.31 km² and covers an altitude range of 682 to 950 m, with a mean slope of 14.5°, and a 2.23 km-long creek (for more details, see Table 1). A 3-D view of the catchment displaying the slopes and potential river flow paths is shown in Figure 2a. Figures 2b and 2c display maps of the land use and soil types within the catchment (see also Table 1). The catchment is sparsely populated and primarily used as pastureland (71.9%), while 25.6% of the area is forested; the rest of the area includes orchards (1.2%) and settlements (1.3%). As displayed in Figure 2c, the soil types include cambisol (cambisol, acidic cambisol, calcaric cambisol; in total 40.7%), gleyic cambisol (17.7%), while 25.6% of the area is forested; the rest of the area includes orchards (1.2%) and settlements (1.3%). As displayed in Figure 2c, the soil types include cambisol (cambisol, acidic cambisol, calcaric cambisol; in total 40.7%), gleyic cambisol (17.7%), gleysoi (23.9%), regosol (17.6%) and peaty soils (<0.1%, “Halbmoor”). Soil depth is highly variable and ranges from about 20–50 cm at steep slopes to over 2 m in the valley bottom. The Rietholzbach catchment is characterized by a pluvial hydrological regime [e.g., Lehner et al., 2010] and is mostly affected by precipitation events in the summer half year. The catchment is not torrential and not prone to flash floods. There is moderate accumulation of snow in winter.

[14] The geology controls the hydrological behavior of the basin (Figure 2d). It is characterized by Tertiary deposits of the Upper Freshwater Molasse consisting of consolidated clastic sediments such as conglomerates ( Nagelfluh), sandstones, layers of marls and banks of freshwater limestone. Gravel pockets of Würm glacial moraines form the riparian zone along the stream, where groundwater from hill slopes is mixed and discharged to the stream with a mean subsurface travel time of several years [Vitsar et al., 1999]. Quick lateral flow on hill slopes has typically shorter travel times of several months, contributing to an overall
mean groundwater travel time of about 1 year between the recharge and outflow in the stream [Vitvar and Balderer, 1997]. Gurtz et al. [2003b] analyzed the groundwater table depth during a snowmelt event and also demonstrated that interflow is the dominating component for runoff generation in the slope regions (Freshwater Molasse). It is hypothesized that some parts of the complex Tertiary-Quaternary aquifer also store substantially older water, which supplies the stream in dry periods. The heterogeneity of parent rock types and relief has produced a large variety of soil types with dominant macropore flow paths [Germann, 1981]. Dye tracer [Menzel and Demuth, 1993] and isotope [Vitvar et al., 1999] investigations on the Rietholzbach lysimeter demonstrated a rapid seepage, but also accompanied in periods of snowmelt or pronounced precipitation by a recharge into the soil matrix where water may remain over longer periods. This water is collected at the lysimeter outlet in dry periods when the macropore pathways are no longer active. The total seepage water was measured to have an average transit time through the lysimeter profile of about 7 months [Menzel and Demuth, 1993; Vitvar et al., 1999].

[15] The main measurement site Büel is located almost in the middle of the catchment (Figure 2a) at an elevation of 755 m (47°22’54”N, 8°59’42”E). Two discharge gauges (Oberer Rietholzbach and Huwilerbach) are located next to the Büel site. The main discharge gauge Mosnang is located at the outlet of the catchment at 682 m (Figure 2a). The Mosnang site is operated by the Federal Office for the Environment (FOEN), Hydrology Division, Bern, Switzerland (available at http://www.bafu.admin.ch/hydrologie).

[16] An overview of the available long-term measurements at Rietholzbach is provided in Table 2. Many time series start in 1976, following the installation of the weighing lysimeter (section 2.2). Other measurements were established more recently, such as the radiation measurements initiated in 1989, as well as the two soil moisture profiles and the regular retrieval of water samples for stable isotope analysis, all initiated in 1994 [e.g., Menzel, 1996; Vitvar and Balderer, 1997]. Also biweekly manual groundwater table measurements are conducted since 1996 at the Büel station and on the north- and south-facing slopes next to the Büel station. Automatic groundwater table measurements are also available at these three boreholes (since 1996 at Büel and since 1998 at the north- and south-facing slopes), however they display inhomogeneities and are thus not analyzed in the present publication. Details on the currently employed instruments are available on the Rietholzbach web page (available at http://www.iac.ethz.ch/url/research/rietholzbach/). Additional analyses over the 30 year 1976–2005 period and further information on the site are also provided in a German-language report [Gurtz et al., 2006].
Table 1. Overall Characteristics of Rietholzbach Catchment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morphometric Description</strong></td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>3.31 km²</td>
</tr>
<tr>
<td>Perimeter</td>
<td>7.93 km</td>
</tr>
<tr>
<td>Catchment length</td>
<td>2.50 km</td>
</tr>
<tr>
<td>Catchment average width</td>
<td>1.32 km</td>
</tr>
<tr>
<td>Length of river network</td>
<td>2.23 km</td>
</tr>
<tr>
<td>River network density</td>
<td>0.67</td>
</tr>
<tr>
<td>Average slope of main stream</td>
<td>57.5 m km⁻¹</td>
</tr>
<tr>
<td>Average slope of catchment</td>
<td>14.5°</td>
</tr>
<tr>
<td>Bifurcation ratio (n_1/n_2)</td>
<td>2.7</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>795 m</td>
</tr>
<tr>
<td>Max. altitude</td>
<td>950 m</td>
</tr>
<tr>
<td>Min. altitude</td>
<td>682 m</td>
</tr>
<tr>
<td><strong>Soil Type</strong></td>
<td></td>
</tr>
<tr>
<td>Cambisol (cambisol, acid cambisol, calcare cambisol)</td>
<td>40.7%</td>
</tr>
<tr>
<td>Gleyic cambisol</td>
<td>17.7%</td>
</tr>
<tr>
<td>Gleysol</td>
<td>23.9%</td>
</tr>
<tr>
<td>Regosol</td>
<td>17.6%</td>
</tr>
<tr>
<td>Peaty soil (&quot;Halbmoor&quot;)</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td><strong>Land Cover</strong></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>25.6%</td>
</tr>
<tr>
<td>Grassland</td>
<td>71.9%</td>
</tr>
<tr>
<td>Orchards</td>
<td>1.2%</td>
</tr>
<tr>
<td>Settlements</td>
<td>1.3%</td>
</tr>
</tbody>
</table>


Publications that have documented aspects of this data set for specific applications include those by Lang [1976], Brutsaert and Kustas [1986], Ohmura and Lang [1989], Menzel [1996], Gurtz et al. [1999], Wild et al. [2001], Gurtz et al. [2003a, 2003b], Calanca [2004], Teuling et al. [2009, 2010b], and Lehner et al. [2010]. Some short-term measurement campaigns were also conducted at the site (e.g., EVAPEX, Grebner and Brutsaert [1984]), and recently a variety of new soil moisture sensors were installed as part of the SwissSMEX project (e.g., Mittelbach et al. [2011]; see http://www.iac.ethz.ch/url/research/SwissSMEX). More information on past and present measurement campaigns is available in reports and publications on the Rietholzbach site web page.

[17] The Rietholzbach research catchment was established and equipped in 1975–1976 by the Laboratory of Hydrology, Hydrogeology and Glaciology (VWG) of ETH Zurich. In 1983, the Hydrology Division together with the research catchment was transferred to the Institute for Atmospheric and Climate Science at ETH Zurich (then Institute of Geography). Since 2007, the Land-Climate Interactions group at the same institute manages the research catchment. Further general information can be found on the following web page: http://www.iac.ethz.ch/url/research/rietholzbach.

### 2.2. Rietholzbach Lysimeter

[18] A specificity of the Rietholzbach catchment site is its large weighing lysimeter, which provides continuous evapotranspiration measurements since 1976 (Figure 2c). Weighing lysimeters are well-established instruments to measure evapotranspiration [e.g., Maidment, 1992; Rana and Katerji, 2000; Goss et al., 2010; Meissner et al., 2010], whereby the measurements consist of weight and seepage measurements, and the evapotranspiration is derived from water-balance computations. The term “lysimeter” itself is used for a wide range of devices and/or structures that allow the measurement of water flow through a given soil volume. Nonweighable lysimeters are common (e.g., for the measurement of solute fluxes or other applications; Goss et al. [2010]), but only weighing lysimeters allow quantitative measurements of evapotranspiration and changes in soil water storage. A 2004 survey of lysimeters in Europe [Lanthaler and Fank, 2005] identified that out of 2440 considered instruments, only 11% (269) were weighing and as many as 84% (2054) were nonweighable (5% with unknown status). Another critical issue for lysimeter-based evapotranspiration measurements is the size of the lysimeters, both in terms of diameter and depth [Young et al., 1996; Rana and Katerji, 2000], larger instruments (>1–2 m² area and >2 m depth) being of advantage but expensive. Weighing lysimeters deeper than 2 m have been reported as rare [Young et al., 1996].

[19] The Rietholzbach lysimeter container has a surface of 3.14 m² (2 m diameter) and depth of 2.5 m, and thus belongs to the “large lysimeters” category (see above). The surface is grass-covered and reflects the conditions of the surroundings (structure, composition, cutting, fertilization). The container is synthetic and back-filled with gleyic cambisol, except for a filter layer (gravel and sand) between 2 and 2.5 m depth to avoid issues with drainage. The electronic scale has a resolution of 100 grams, which corresponds to a water column of approximately 0.032 mm, and thus allows high measurement accuracy (Gurtz et al. [2003a]; see also section 2.3). The drainage occurs by gravitation only and the water volume is measured with a tipping bucket (50 mL). The water is collected in a barrel at the bottom of the container and, since 1994, is sampled biweekly for stable isotope analyses. The lysimeter includes a soil moisture measurement profile with time domain reflectometry (TDR) instruments in seven depths (Figure 2e).

[20] Despite the relatively high number of publications citing lysimeters for hydrological applications [e.g., Meissner et al., 2010], it is difficult to assess how many long-term and continuous measurements of evapotranspiration with large weighing (undisturbed) lysimeters are actually available. Possibly the longest available evapotranspiration records fulfilling these criteria are from the Coshocton site in Ohio, which pioneered the use of high-quality weighing lysimeters in the mid-1930s, and is still active nowadays [e.g., Harmel et al., 2007]. Owens et al. [2010] report on three long-term multidecadal evapotranspiration records at this site (one from 1945 to present and two over the time period 1945–2003). We are not aware of analyses of these complete time series, although publications have considered part of the record (analysis for 1987–1997 by Chapman and Malone [2002], and analysis for 1986–1995 by Schlosser and Gao [2010]). Muller and Bolte [2009] also report on a small-scale (1 m² area, 1.5 m deep) weighable lysimeter at the forest hydrology research site in Eberswalde in north-east Germany, which was installed in 1929. This is possibly the oldest lysimeter station used for forest hydrological purposes in the world [Muller and Bolte, 2009], although the relatively small size of the lysimeter...
Figure 2. The Rietholzbach catchment and lysimeter. (a) 3-D-view of the catchment displaying the slope and potential river flow paths, as well as the location of the Büel and Mosnang measurement sites; Maps of land use types (b), soil types (c) and geology (d) within the catchment (see also Table 1); (e) Cross-section of lysimeter with description of measurements: (1) Container; (2) Concrete wall; (3) Cellar; (4) Soil; (5) Filter (sand and gravel); (6) Electronic scales; (7) Drainage outlet; (8) Soil moisture sensors; (9) Temperature sensors; (10) Grass.
### Table 2. List of Measured Variables, Including Site, Measurement Height, and Start of Continuous Measurements

<table>
<thead>
<tr>
<th>Variable</th>
<th>Site</th>
<th>Measurement Height(s) [m]</th>
<th>Typical Output Interval (Highest Frequency)</th>
<th>Start</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>Büel</td>
<td>2</td>
<td>Hourly (5')</td>
<td>1976</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Büel</td>
<td>2</td>
<td>Hourly (5')</td>
<td>1976</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Büel</td>
<td>0</td>
<td>Hourly (5')</td>
<td>1977</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Büel, Büel</td>
<td>1.5</td>
<td>Hourly (5')</td>
<td>1976</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>Büel</td>
<td>10</td>
<td>Subhourly (5’)</td>
<td>2000</td>
</tr>
<tr>
<td>Snow depth</td>
<td>Büel</td>
<td>–</td>
<td>Subhourly (5’)</td>
<td>2000</td>
</tr>
<tr>
<td>Net radiation</td>
<td>Büel</td>
<td>2</td>
<td>Hourly (5’)</td>
<td>2000</td>
</tr>
<tr>
<td>Incoming short-wave radiation (global radiation)</td>
<td>Büel</td>
<td>2</td>
<td>Hourly (5’)</td>
<td>1989</td>
</tr>
<tr>
<td>Outgoing short-wave radiation</td>
<td>Büel</td>
<td>–</td>
<td>Hourly (5’)</td>
<td>1997</td>
</tr>
<tr>
<td>Incoming long-wave radiation</td>
<td>Büel</td>
<td>2</td>
<td>Subhourly (5’)</td>
<td>2006</td>
</tr>
<tr>
<td>Outgoing long-wave radiation</td>
<td>Büel</td>
<td>2</td>
<td>Subhourly (5’)</td>
<td>2006</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>Büel</td>
<td>–0.05, −0.1, −0.2, −0.4</td>
<td>Hourly (60’)</td>
<td>2000</td>
</tr>
<tr>
<td>Soil temperature (field)</td>
<td>Büel</td>
<td>−0.05, −0.2</td>
<td>Hourly (60’)</td>
<td>1993</td>
</tr>
<tr>
<td>Soil temperature (lysimeter)</td>
<td>Büel</td>
<td>−0.1</td>
<td>Hourly (60’)</td>
<td>2000</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>Büel</td>
<td>−0.05, −0.15, −0.25, −0.35, −0.55, −0.8, 1.1 (horizontally orientated)</td>
<td>Hourly (60’)</td>
<td>1994</td>
</tr>
<tr>
<td>Soil moisture profile (field)</td>
<td>Büel</td>
<td>−0.05, −0.15, −0.25, −0.35, −0.55, −0.8 (horizontally orientated); −0.95 (vertically orientated sensor positioned between 0.8 and 1.1 m depth)</td>
<td>Hourly (60’)</td>
<td>1994</td>
</tr>
<tr>
<td>Soil moisture profile (lysimeter)</td>
<td>Büel</td>
<td>−2.5 m</td>
<td>Hourly (5’)</td>
<td>1976</td>
</tr>
<tr>
<td>Evapotranspiration (lysimeter)</td>
<td>Büel</td>
<td>–</td>
<td>Hourly (5’)</td>
<td>1976</td>
</tr>
<tr>
<td>Seepage (lysimeter)</td>
<td>Büel</td>
<td>−2.5 m</td>
<td>Hourly (5’)</td>
<td>1976</td>
</tr>
<tr>
<td>Lysimeter weight</td>
<td>Büel</td>
<td>–</td>
<td>Hourly (5’)</td>
<td>1976</td>
</tr>
<tr>
<td>Groundwater table depth (manual measurements)</td>
<td>Büel, Büel, Büel (B2)</td>
<td>–</td>
<td>Biweekly</td>
<td>1996</td>
</tr>
<tr>
<td>Groundwater table depth (automatic measurements)</td>
<td>Büel, Büel (B2), Büel (B3)</td>
<td>–</td>
<td>Biweekly</td>
<td>1996</td>
</tr>
<tr>
<td>Groundwater temperature</td>
<td>Büel, Büel (B2), Büel (B3)</td>
<td>–</td>
<td>Biweekly</td>
<td>1996</td>
</tr>
<tr>
<td>Discharge</td>
<td>Mosnang, Huwilerbach, Oberer Rietholzbach</td>
<td>–</td>
<td>Subhourly (5’)</td>
<td>1976</td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>Mosnang, Huwilerbach, Oberer Rietholzbach</td>
<td>–</td>
<td>Subhourly (5’)</td>
<td>1995</td>
</tr>
<tr>
<td>Water samples</td>
<td>Büel, Mosnang, Oberer RHB, Huwilerbach</td>
<td>Precipitation, seepage, groundwater streamflow</td>
<td>Biweekly</td>
<td>1994</td>
</tr>
</tbody>
</table>

### Notes:

- Measurements analyzed in present study are indicated in bold face.
- Homogenized time series (see Gurtz et al. [2006] and Moesch [2001] for details).
- Some of these measurements present positive trends over the whole measurement record, likely due to instrumental drifts; these drifts are corrected in the analyses (linear detrending; trends over 1994–2007 time period for measurements analyzed in Figures 7 and 8: −0.15 m, no trend; −0.55 m, 0.30 m m−1 yr−1; −0.95 m, 0.21 m m−1 yr−1); in addition outlier values at 0.55 and 0.95 depth for Mar 2001 were removed (replaced with NA values) for the present analysis.
- Processed data for absolute weight since 2000 only; weight changes available since 1976.
- North-facing slope.
- South-facing slope; deepest measurements at 6.8 m (manual) and 5.3 m depth (automatic) do not allow full range of measurements during drought events.
- Measurements entail significant inhomogeneities.
- Station from the Federal Office for the Environment (FOEN).
- Measurement interval of data provided by FOEN.
could imply limitations in the accuracy of the measurements (see above). Further studies mentioning long-term analyses of weighing lysimeter data include those by Seyfried et al. [2001] (1978–1991 and 1980–1991 records for two lysimeters at Reynolds Creek, Idaho), Scanlon et al. [2005] (1994–2002 measurements from vegetated and nonvegetated lysimeters in the Mojave Desert), and Teuling et al. [2009] (1982–2000 discontinuous record at Mönchengladbach-Rheindahlen, Germany; see also Xu and Chen [2005] for a shorter analysis of this record from 1983–1994). Another available study on long-term lysimeter measurements [Harsch et al., 2009] is based on a non weighable lysimeter, and hence only provides leachate rather than actual evapotranspiration measurements. Overall, many published studies based on weighing lysimeters only report measurements over short time periods (several months to 2–3 years; e.g., Young et al. [1996], Choudhury [1997], Lopez-Urrea et al. [2006], Drexler et al. [2008]). Based on the existing literature, it is thus likely that the weighing lysimeter data set at Rietholzbach constitutes one of the few long-term (>30 years) high-quality evapotranspiration records in the world, given the size of the lysimeter and the continuity of the measurements.

2.3 Analyzed Measurements and Uncertainties

[21] We analyze here monthly time series from the Rietholzbach catchment site. The analyzed measurements are indicated in bold in Table 2. The 32 year time series for temperature, precipitation, relative humidity, wind and evapotranspiration were previously homogenized as described in the work of Gurtz et al. [2006] and Moesch [2001]. Further data handling applied in this publication includes the detrending of the analyzed soil moisture measurements within the lysimeter (see also Table 2). Indeed, closer investigation revealed discrepancies in the long-term trends across measurements depths, which were thus attributed to instrumental drift. Some available measurements (e.g., soil moisture profiles in the field, automatic measurements of groundwater level) display some inhomogeneities and/or substantial data gaps (see Table 2 for details) and have thus not been analyzed here.

[22] Since much of this article is dedicated to the analysis of the water-balance components, we provide here a brief evaluation of the measurement uncertainties for precipitation, evapotranspiration, and runoff. Several publications have documented the systematic biases in precipitation records, in particular due to undercatch caused by wind field deformation above the rain gauge, wetting of gauge walls, evaporation of accumulated water, and blowing of snow into or out of the gauge [e.g., Sevruk, 1982; Adam and Lettenmaier, 2003]. Measurement biases are of the order of 3 to 15% for liquid precipitation, and up to more than 50% for solid precipitation [e.g., Sevruk, 1982; Groisman and Legates, 1994; Sevruk, 1996; Adam and Lettenmaier, 2003]. Gurtz et al. [2003] provided estimates of uncertainties in the precipitation measurements at Rietholzbach from a comparison between the rain gauge measurements and the lysimeter water balance. Large discrepancies were identified in the winter half year (15–25% for liquid precipitation, and 55–65% for snow), some of which may also be due to errors in the lysimeter measurements (see hereafter). On the other hand, that study identified good agreement between the two estimates from late spring to fall, with estimated errors in liquid precipitation of only 3–5% in May, June, October and November, and close to zero in July, August and September [Gurtz et al., 2003a]. We thus expect the largest precipitation undercatch during the winter season in Rietholzbach. For the lysimeter-based evapotranspiration measurements, the estimated error is of 100 g (precision of electronic scale, see section 2.2). Given the total area of 3.14 m², this implies an error of ca. 0.032 mm. Other errors are induced by the lysimeter design, i.e., the lack of connection to the groundwater storage and the lack of interfloow, which can be particularly critical during dry periods. Moreover, existing literature suggests that soil cracks may also build up along the sides of the lysimeter in dry conditions [Rana and Katerji, 2000]. The building of snow bridges in winter, and some ridge effects at the surface, may additionally affect the measurements in case of snow cover. The total effect of these errors for the lysimeter-based evapotranspiration record is difficult to quantify exactly, as they depend very much on specificities of the given instrument and the surrounding environment (e.g., importance of groundwater-soil moisture interactions). However, the relatively good agreement reported by Gurtz et al. [2003a] between the precipitation measurement at Büel and the lysimeter water balance in late spring and summer (less than 5% in late spring and summer, see above) suggest that these errors may actually be limited in Rietholzbach. Finally, the FOEN streamflow measurements at Mosnang, which use a calibrated stage-discharge relationship, are assumed to be of relatively good accuracy. The measurements are performed at a concrete weir located short before a high waterfall, so as to ensure that no major amount of water flows past the gauge. Errors of the order of 5–10% have been reported in the literature for long-term statistics and daily values [e.g., Gutowski et al., 1997; Herschy, 1999]. We assume overall errors of similar magnitude at Rietholzbach at the monthly time scale.

2.4 Analysis of Drivers for 2003 Conditions

[24] In section 5, we investigate the hydrological drivers for the 2003 drought conditions, as well as for the conditions directly preceding and following this event. We introduce here the methodology followed in this analysis. Note that we use the term “soil moisture,” annotated as \( S(t) \), to refer to soil moisture either in a single layer or in the overall unsaturated water storage (e.g., as estimated with the lysimeter storage).

[24] For a monthly time lag \( \Delta t \), we distinguish the respective contributions of preexisting soil moisture deficits at the beginning of the considered time period \( S'(t - \Delta t) \) and of anomalous soil moisture changes over the considered time period \( (\Delta S)' \) to the resulting soil moisture anomaly \( S'(t) \) at the end of the time period \( t \), \( S'(t), S'(t - \Delta t), \) and \( (\Delta S)' \) being expressed as anomalies with respect to the mean seasonal cycle:

\[
S'(t) = S'(t - \Delta t) + (\Delta S)' .
\]

[25] This framework is illustrated in Figure 3. For a detailed discussion of the role of initial soil moisture anomalies for soil moisture memory, see also Seneviratne and Kohler [2012]. Note that in the analyses we use
monthly mean soil moisture values as estimates for the midmonth soil moisture conditions.

This analysis is extended further by attributing the \((\Delta S)'\) value to either anomalous values of precipitation minus discharge \((\Delta S_{\text{P-R}})'\) or anomalous evapotranspiration \((\Delta S_{\text{E}})'\), and assuming that the respective effects of the forcing are largely independent of the considered soil depths:

\[
(\Delta S)' = (\Delta S_{\text{P-R}})' + (\Delta S_{\text{E}})' = \gamma [(P' - R') + (-E')],
\]

where \(P'\), \(R'\), and \(E'\) stand for the anomalies of precipitation, discharge, and evapotranspiration with respect to their respective mean seasonal cycle over the considered time period, and \(\gamma\) refers to the respective fraction of the overall land water storage considered with \(S(t)\). Note that strictly speaking, the considered storage for \(\gamma = 1\) also encompasses the groundwater and snow storage in addition to the unsaturated water storage. The contributions of precipitation \((\Delta S_{\text{P}})'\) and discharge \((\Delta S_{\text{R}})'\) to \((\Delta S_{\text{P-R}})'\) are further disentangled as follows:

\[
(\Delta S_{\text{P-R}})' = (\Delta S_{\text{P}})' + (\Delta S_{\text{R}})' = \gamma [(P' + (-R')].
\]

3. Spatial Representativeness of Measurements

3.1. Representativeness of Lysimeter for Whole Catchment

As any sets of water cycle measurements for entire catchments, the Rietholzbach data have inherent spatial discrepancies: Indeed, the streamflow measured at Mosnang (Figure 2a), which captures the whole-catchment runoff, is representative of the whole Rietholzbach catchment (3.31 km²), while the other measurements are provided at a point location (Büel station, Figure 2a). The Büel site is grass-covered, while about one fourth of the catchment is forested (section 2.1, Table 1). The lysimeter itself has an area of 3.14 m² (section 2.2). Hence, it is important to evaluate to which extent the lysimeter measurements are representative of the whole catchment behavior, in particular when inferring possible regional-scale features from these point-scale measurements (see hereafter).

With this aim, we provide in Figure 4 comparisons of the lysimeter seepage with the streamflow measurements at the Mosnang station (referred to as “catchment-wide discharge”): Figure 4a displays a scatterplot of the two measurement time series, while Figure 4b displays monthly box plots of their differences over the 1976–2007 time period. Note that in addition to the scale discrepancy, streamflow does not only result from soil percolation but also from groundwater discharge to the stream, a process not captured in the lysimeter seepage. Beside the missing link to the groundwater storage, lysimeter measurements have further known limitations, in particular caused by the lack of lateral flow (see section 2.3).

Despite the mentioned limitations, Figure 4a shows that the lysimeter seepage and catchment-wide discharge are highly correlated (slope of 0.98 and \(R^2\) of 0.91). The agreement is also high at the yearly time scale (\(R^2 = 0.87\),

Figure 4. Lysimeter seepage versus catchment-wide discharge (1976–2007). (a) Scatterplot of monthly lysimeter seepage versus catchment-wide discharge (streamflow measured at Mosnang site), including regression line (solid black line; statistics: lower right); (b) Box plot of difference between monthly lysimeter seepage and runoff measurement at Mosnang station (for mean and median values, see Table 3). The horizontal line stands for the long-term mean of the difference (−1.3 mm/mth).
not shown) and thus not merely the result of correspondences in the seasonal cycle. The lower values of the lysimeter seepage compared to the Mosnang discharge are mostly induced by a negative bias of the lysimeter seepage in March (−14.9 mm/mth on average, Figure 4b), with an outlier value of −115.2 mm/mth in March 2006 (not shown). The March bias could be linked to snowmelt or vegetation dynamics (spring onset), which are likely to strongly vary across the catchment during that month due to the topography and the presence of forest patches. March is also the month with highest total discharge, which may play a role for this imbalance. Furthermore, camera records for the phyt and the presence of forest patches. March is also the dynamics (spring onset), which are likely to strongly vary.

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3.2. Representativeness of Rietholzbach Research Catchment for Surrounding Swiss Locations

Another important question is the extent to which the Rietholzbach catchment can be considered as representative for surrounding locations in Switzerland. We assess this aspect by analyzing monthly correlations of the catchment streamflow at Mosnang with streamflow measurements at other FOEN stations (Table 4). Correlations are computed both for absolute values and for monthly anomalies with respect to the mean seasonal cycle (Figure 5). The correlation values are also listed in Table 4, together with the respective correlations between the streamflow at Mosnang and the lysimeter seepage.

The considered FOEN stations span a broad range of hydrological regimes [FOEN, 2010], whereby the Rietholzbach catchment is characterized by a pluvial hydrological regime (see section 1). It should be noted that the hydrological regime is likely to play an important role in the correlation of the absolute values, which are necessarily affected by the seasonal cycle of streamflow at each location. However, it is expected to be of less relevance for the correlations of the monthly anomalies from the seasonal cycle, which are likely rather affected by interannual climate anomalies. For instance, the summer 2003 was characterized by low-flow in a large part of Switzerland, with the exception of glacerized catchments [Zappa and Kan, 2007].

The analysis in Table 4 and Figure 5 reveals that the measured streamflow at Rietholzbach-Mosnang is highly correlated with streamflow measured at surrounding stations in the Thur river basin and the neighboring Toess river (correlations of 0.74 to 0.94 for absolute values and 0.86–0.94 for anomalies with respect to mean seasonal cycle). The correlations decrease for further locations (Figure 5), but still remain high in northern Switzerland (up to a distance of about 100–120 km), in particular for the anomalies (0.56–0.80). Note that correlations between the lysimeter seepage and the streamflow at Mosnang (0.95 for both the absolute values and the anomalies) are larger than the correlations with any surrounding stations. The lysimeter seepage also displays significant correlations with runoff within most catchments in the Thur basin and in northern Switzerland in general (not shown). The overall region for which the catchment is found to be representative agrees well with the eastern Swiss Plateau hydroclimatic region commonly defined in Swiss climatologic studies [e.g., Schmocker-Fackel and Naef, 2010; see also Kirchhofer, 2000; Schiepp, 1979]. Hence the Rietholzbach research catchment is found to be representative for this wider hydroclimatic region in Switzerland, and in particular for the Thur river basin.

The fact that the seasonal anomalies at the stations tend to be more highly correlated with the Rietholzbach catchment streamflow than the absolute runoff values (see in particular Limmat–Baden, Reuss–Meilingen, and Rhine–Rheinfelden) reflects the impact of the climate forcing which is expected to be homogeneous over larger regions, an effect that is partly masked by the seasonal cycle of streamflow in the analysis of the absolute values. This can be easily illustrated at the case of the 2003 drought (see discussion above), but is also expected to be a more general feature of atmospheric forcing [e.g., Robock et al., 1998]. For the anomalies, low or negative correlations are only found for the stations located south of the Alps. This is not surprising, given that all of these stations are characterized by a large fraction of glacerization (Table 4) and thus a markedly different hydrological regime, and that they are also significantly affected by human water management (Table 4) unlike the Rietholzbach catchment and the surrounding Thur river basin [FOEN, 2010].


Figure 6 displays box plots of selected key hydroclimatological variables over the 32 year 1976–2007 time period, including highlights on three extreme years: 1976 (drought year; violet points), 2001 (highest total precipitation; blue points), and 2003 (drought year, highest mean
temperature, and lowest total precipitation; red points). A summary of main climatological characteristics is provided in Table 5. The observations confirm that the 2003 summer was a clear outlier with respect to the overall long-term climatology in Switzerland (and central Europe; see also Schär et al. [2004], Beniston et al. [2004], Andersen et al. [2005], Fischer et al. [2007], Zappa and Kan [2007]). This event is investigated in more detail in section 5 in combination with the soil moisture measurements available over the 1994–2007 time period.

The Rietholzbach site has a temperate humid climate, with ample precipitation (1459 mm yr⁻¹) and a clear seasonal cycle. Wind generally blows along the catchment axis and presents a marked diurnal cycle, with highest values during daytime (not shown). The storage dynamics (precipitation minus evapotranspiration minus discharge, hereafter P – E – R) shows a net input of water into the subsurface in the late summer and autumn (August–December) and net output from winter to midsummer (January–July). The average water balance residual is negative (–13.7 mm/nth, Figure 6j), which may be caused by precipitation undercatch, especially during snowfall (section 2.3).

Most variables present a clear and often marked seasonal cycle, with the exception of the wet-day frequency. While the seasonal cycle of precipitation appears mostly impacted by the wet-day intensity, the wet-day frequency is the main explaining factor for several extreme (low or high) precipitation values both in 2003 and 2001. Months with extreme (low or high) precipitation values often result in extreme discharge values, as is illustrated for the highlighted 2003 and 2001 years.

Figures 6k and 6l display the long-term trends of the (yearly) temperature, wind, precipitation, evapotranspiration and discharge. A significant upward trend in yearly temperature can be identified from the measurements over the 1976–2007 time period (+0.10°C yr⁻¹, Figure 6k). This trend is consistent with other reports of temperature trends in Switzerland [Organe Consultatif sur les Changements Climatiques, 2007]. The temperature trends are stronger in spring and summer than in the fall (not shown). Unlike other locations in Switzerland and other midlatitude regions [McVicar et al., 2010], the Rietholzbach site does not present evidence of a trend in yearly mean wind speed (Figure 6k). There are also no significant linear trends in the precipitation, evapotranspiration and discharge time series at the yearly timescale (Figure 6l). However, evapotranspiration presents a tendency for a decreasing trend in the first half, and increasing trend in the second half of the record [Teuling et al., 2009], consistent with reported trends in global radiation (“dimming” and “brightening”, e.g., Wild [2009]). Yearly evapotranspiration is weakly correlated with radiation over the 1994–2007 time period (R² = 0.24, not shown), while yearly precipitation and discharge present a strong correlation (R² = 0.86) as can be seen on Figure 6l. This is expected given the humid characteristics of the catchment. Nonetheless, the monthly discharge also presents dynamical features independent of the precipitation forcing (e.g., more clearly related to storage during the 2003 summer, see Figures 6d and 6g).


This section provides an in-depth analysis of the 2003 drought based on the measurement record at Rietholzbach.
over the 1994–2007 time period. Several measurements are only available over this more recent time period, in particular the soil moisture measurements, which is the reason for the analysis over this shorter time frame. In addition, the radiation measurements are only available since 1989.

5.1. Overall Behavior

Figure 7 provides an analysis of measured variables over the 1994–2007 time period based on box plots of selected variables, similar to those provided in Figure 6. The conditions for 2003, as well as the conditions prevailing in the preceding and following years (2002 and 2004) are highlighted in color in the plots. Figures 7a, 7b, 7d, and 7e, which provide analyses for temperature, evapotranspiration, precipitation and discharge, allow us to compare the average climatology over the 1994–2007 time period to the 32 year (1976–2007, Figure 6) record. Precipitation and runoff present a similar behavior over the two time periods.

Temperature also presents similar features, except for an increase of 1°C over the later period. For its part, evapotranspiration presents a marked increase in June over the last 14 years of the record. This leads to a shift of the seasonal evapotranspiration peak from July to June in some years (concomitant with the global radiation peak, Figure 7c, rather than the temperature peak).

5.2. The 2003 Summer and Long-Term Anomalies of Soil Moisture

The global radiation and evaporative fraction (defined here as the ratio of the latent heat flux $\lambda E$ and global radiation) both show a clear seasonal cycle and a marked behavior in the 2003 summer (Figures 7c and 7f). The global radiation measurements reveal strong anomalies in both June and August 2003 (concomitant with temperature anomalies in these two months). On the other hand, while the evaporative fraction was at the upper end of the

Figure 5. Representativeness of Rietholzbach station for surrounding conditions. Correlation of monthly streamflow at Mosnang (white-filled circle) with measurements at other FOEN stations (Table 4) based on (a) absolute values and (b) monthly anomalies. All computations are for 1976–2007, except for Kleine Emme–Littau (1978–2007).
interquartile range in June, it was anomalously low in August, suggesting a possible effect of soil moisture limitation on evapotranspiration, and hence on temperature in that later month [e.g., Seneviratne et al., 2006a, 2010]. This is consistent with modeling results [e.g., Fischer et al., 2007], and is likely to have contributed to the extremely high temperatures recorded in that month.

Figure 6. The 1976–2007 monthly time series and yearly trends. (a–j) Box plots of monthly measurements over the 1976–2007 time period, including values for 2003 (red), 2001 (blue), 1976 (violet), and mean over whole time period (μ): (a) 2 m temperature; (b) Evapotranspiration measured with lysimeter (E); (c) 2.5 m wind speed; (d) Precipitation measured with a standard rain gauge at a height of 1.5 m (P); (e) Wet-day frequency; (f) Wet-day intensity; (g) Catchment runoff measured at Mosnang site (R); (h) Lysimeter seepage; (i) P–R; (j) P–E–R. Trends over 1976–2007 period: (k) Trends of yearly mean 2-m temperature (T, circles) and wind speed (U, squares); (l) Trends of yearly summed precipitation (circles), evapotranspiration (squares) and discharge (triangles). Nonsignificant trends are indicated with “n.s.”

[41] The soil moisture measurements in 15, 55, and 95 cm depth (Figures 7g–7i) also confirm the presence of large anomalies during and after the 2003 summer. While they indicate that the root uptake of water is confined to a relatively shallow layer in normal years (down to 15–25 cm), the extensive soil moisture depletion that took place in summer 2003 suggests that root water uptake shifted toward
deeper depths (Figures 7h and 7i). This is consistent with findings at a Belgian site for the summer of 2003 [Teuling et al., 2006]. It is interesting to note that with the exception of the 2003 summer, the lower-lying instruments do never present a depletion of soil moisture in summer, and have their lowest peak in fall and winter, due to soil moisture redistribution within the soil layers. The measurements clearly highlight the extent of the soil moisture depletion in the 2003 summer, in particular in August 2003: the recorded anomaly in 15 cm depth compared to the 1994–2007

Table 5. Climatology of Rietholzbach Catchment Site Over Time Period 1976–2007

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Linear Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m air temperature</td>
<td>7.1°C</td>
<td>4.7°C (1978)</td>
<td>8.8°C (2000)</td>
<td>0.10 °C yr⁻¹</td>
</tr>
<tr>
<td>Precipitation</td>
<td>1459 mm</td>
<td>1114 mm (2003)</td>
<td>1816 mm (2001)</td>
<td>n.s.</td>
</tr>
<tr>
<td>Discharge</td>
<td>1063 mm</td>
<td>674 mm (2003)</td>
<td>1474 mm (1999)</td>
<td>n.s.</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>560 mm</td>
<td>480 mm (1996)</td>
<td>629 mm (1979)</td>
<td>n.s.</td>
</tr>
<tr>
<td>Wind speed</td>
<td>1.36 m s⁻¹</td>
<td>1.15 m s⁻¹ (1991, 1996, 2005)</td>
<td>1.73 m s⁻¹ (1982)</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

*Mean for temperature and wind speed at 2 m, and annual sums for precipitation, discharge, evapotranspiration: Long-term mean, minimum, maximum, and (linear) trend. Non statistically significant trends are indicated with “n.s.”

Convex tendency over time period [Teuling et al., 2009].

Figure 7. The 1994–2007 time series. Box plots of monthly measurements over the 1994–2007 time period, including values for 2004 (orange), 2003 (red) and 2002 (green), and mean over whole time period (μ): (a) 2 m temperature. (b) Evapotranspiration measured with lysimeter (E). (c) Global radiation (Rg). (d) Precipitation measured with a standard rain gauge at a height of 1.5 m. (e) Catchment discharge (measurement at the Mosnang site). (f) Evaporative fraction (latent heat flux over global radiation, λE/Rg; λ stands for the latent heat of vaporization). (g–i) Volumetric soil water content (lysimeter profile) at depths of 0.15, 0.55, and 0.95 (0.80–1.10) m, measured with TDR sensors (see also Table 2 for more details). For the soil moisture at 15 cm depth (Figure 7g), the ratio of the August 2003 anomaly (S') with the standard deviation (σ) and interquartile range (iqr) over all years except 2003 is provided on the plot.
climatology (excluding the 2003 values) was equivalent to 4.1 standard deviations and 7.1 times the interquartile range (values indicated on Figure 7g).

The measurements also reveal substantial persistence effects in the soil moisture levels before and after the 2003 event. While previous publications often highlighted the anomalously low-precipitation levels in the 2003 spring as a possible driver for the drought [e.g., Ferranti and Viterbo, 2006; Fischer et al., 2007; Loew et al., 2009], our analysis reveals a positive near-surface (15 cm) soil moisture anomaly in the early 2003 spring (Figure 7g), following the extensive 2002 fall precipitation (Figure 7d) that was concomitant with severe flooding in central Europe [e.g., Christensen and Christensen, 2003; Trenberth et al., 2007]. This anomaly acted as a buffer for the low spring precipitation, so that soil moisture remained above or within the climatological range until June 2003. A pronounced drought was only seen in July 2003, following the large evapotranspiration and precipitation anomalies that occurred in June 2003 (Figure 7b and 7d). Hence, the positive soil moisture anomaly in the 2003 spring did further exacerbate the often highlighted dichotomy in the two phases of the 2003 heat wave in June versus August, with much higher soil moisture deficits in the latter period [e.g., Teuling et al., 2010a].

Furthermore, the measurements also reveal that the soil moisture levels at 15 cm depth did not recover from the 2003 drought until August 2004 (Figure 7g). Similar effects are also seen at 55 cm depth (Figure 7h). This hence suggests possible long-term effects of soil moisture anomalies over time periods of up to 6-10 months at least in certain years, which is much more extended than the ca. 1-3 month autocorrelation time scales highlighted in several publications [e.g., Vinnikov et al., 1996; Entin et al., 2000; Koster and Suarez, 2001; Seneviratne et al., 2006b]. While this may reflect conditions that were also found in the field, it is important to note that these measurements were conducted within the lysimeter and may be affected by the design of the instrument (see section 2.3 and hereafter).

To investigate these findings further, we display in Figure 8 time series of the soil moisture anomalies (compared to the seasonal cycle and expressed in percents) over the January 2002 to December 2004 time period, together with corresponding analyses of the lysimeter weight. The lysimeter weight can be seen as an integrative measure of soil moisture content over the whole soil column. Note that records of the absolute lysimeter weight are only available since 2000 (Table 2; weight changes are available since 1976). This comparison confirms the presence of long-term anomalies in the lysimeter soil moisture content following

Figure 8. The 2002–2004 storage anomalies. Storage anomalies (compared to climatological mean of given month) from January 2002 to December 2004 estimated from: (a) Soil moisture measurement in 15 cm depth (anomaly in % compared to 1994–2007 mean); (b) Soil moisture measurement in 55 cm depth (anomaly in % compared to 1994–2007 mean); (c) Lysimeter weight (anomaly in % compared to 2000–2007 mean).
the 2003 summer, which persisted until the 2004 spring to summer period (until April 2004 for the lysimeter as a whole, and until June–July 2004 for the soil moisture measurements). On the other hand, the effect of the 2002 fall precipitation events seems mostly limited to the upper soil layers.

Because of the lack of reference measurements of the soil moisture conditions in the field, we cannot exclude that the measured extended soil moisture anomaly following the 2003 drought may have been partly caused by the lysimeter conditions. As highlighted in section 2.3, cracks can possibly form along the lysimeter border in contact with soil in dry conditions, which may lead to an overestimation of evapotranspiration and more extensive drying compared to the surrounding environment [Rana and Katerji, 2000]. In addition, lysimeters are decoupled from the groundwater storage, which can be critical for soil moisture content during dry periods. On the other hand, the observed conditions could have been induced by soil water repellency following the drought conditions, a phenomenon that is also commonly observed across soil and land cover types in the field [Doerr et al., 2000], and may thus have not been limited to the lysimeter storage.

Figure 9 additionally displays the groundwater level anomalies over the time period January 2002 to December 2004 based on manual measurements at two boreholes in Büel (one at the site and another one on the north-facing slope; see also Table 2 for details). These clearly show a sharp decrease in groundwater level from June 2003 onward, consistent with the lysimeter measurements in Figure 8. On the other hand, they also indicate a recovery to normal conditions after October 2003, following the intensive rainfall that occurred in that month (Figure 7d). This is not necessarily inconsistent with enhanced water repellency and the presence of cracks in the upper soil, which would allow drainage through the soil but without a rewetting of the respective soil layers [e.g., Doerr et al., 2000].

Overall, this analysis reveals significant year-to-year carry-over effects of soil moisture anomalies from the measurements in the lysimeter. This is an important result in the view that year-to-year changes in surface water storage are often assumed to be equal to zero in hydrological studies, e.g., when estimating evapotranspiration from the surface water balance or estimating terrestrial water storage from the combined surface and atmospheric water balances [e.g., Seneviratne et al., 2004; Ramirez et al., 2005; Teuling et al., 2009]. Thereby, it should be emphasized that the long-term persistence effects in the lysimeter storage after October 2003 are not related to the amount of water required to refill the soil but to changes in physical properties, as can be inferred from the precipitation, runoff, and groundwater measurements. This further highlights the need for long-term field measurements of soil moisture to assess such effects, and in particular to distinguish water-balance versus soil physical impacts of droughts.

5.3. Drivers of 2003 Drought Conditions

Based on the approach introduced in section 2.4, we display in Figures 10a and 10b the respective monthly contribution of $S(t - \Delta t)$ and $(\Delta S)'$ to the overall water storage anomalies over the whole 2003 year, based on the soil moisture measurements in 15 cm depth and the lysimeter weight data. This analysis confirms that the main drivers of the 2003 event at the Rietholzbach site were anomalous fluxes from June 2003 onward, and that preceding late winter to spring fluxes only played a minor role for the 2003 event, although they helped depleting a positive soil moisture anomaly in the upper soil (see also section 5.2).
Figure 10. Drivers of 2003 storage anomalies. Analysis of drivers of storage anomalies from January to December 2003 estimated following the conceptual framework of equations (1)–(3). (a) Impact of pre-existing soil moisture anomalies and monthly storage variation anomalies for resulting soil moisture anomalies in 15 cm depth [anomalies in %]; (b) same analysis as Figure 10a for the lysimeter weight anomalies [in %]; (c) analysis of impact of flux anomalies for anomalies in storage change: role of $P/C_0$, evapotranspiration, and $P/R$ [mm] (flux averaged from 15th of preceding month to 14th of considered month); (d) same analysis as Figure 10c for the $P/R$, precipitation, and discharge contributions to the storage variation anomalies [mm].
[49] The analysis of Figures 10a and 10b can be extended further by attributing the overall storage change anomalies \((\Delta S)^{t}\) to either anomalous values of precipitation minus discharge \((\Delta S_{p-e})^{t}\) or anomalous evapotranspiration \((\Delta S_{e})^{t}\) (whereby \((\Delta S)^{t}\) refers to changes in the total storage, i.e., for \(\gamma = 1\); see section 2.4 for details). Figure 10c displays the corresponding values of \((\Delta S_{p-e})^{t}\), \((\Delta S_{e})^{t}\), and \((\Delta S_{e}+\Delta S_{p-e})^{t}\) over the same time period as Figures 10a and 10b, whereby the monthly fluxes are computed for periods with midmonth end points (15th to 14th) to allow a better comparison with the monthly soil moisture estimates in Figures 10a and 10b. This analysis illustrates a close correspondence between the single contribution of precipitation and discharge anomalies inferred from Figure 6j given the dominant role of the initiation of the 2003 drought event (which can also be inferred from Figure 6j given the dominant role of the P_E–R anomalies in June). Figure 10d displays further the single contribution of precipitation and discharge anomalies to the combined \((\Delta S_{p-e})^{t}\) anomalies displayed in Figure 10c. Interestingly, this analysis shows that discharge anomalies often counteract precipitation anomalies, and played an important role in the months preceding the 2003 event. In certain months, discharge anomalies almost totally cancel out the precipitation anomalies, such as from mid-March to mid-April 2003 (compare as well with Figure 6i). Hence precipitation anomalies alone are not informative enough to infer changes in storage, a fact that is often overlooked in the evaluation of droughts using precipitation-based drought indicators (see also discussion at the end of this section).

[50] These results are further confirmed from the analysis of the flux anomalies over different time frames during June to August 2003 in Table 6. The surface storage changes induced by anomalous evapotranspiration amount to 40% of the water balance deficit over this whole time period, and to over 60% of the June water balance deficit (76% over the first half of June). The fact that the overall contribution of evapotranspiration anomalies to storage change anomalies decreases over the course of the drought (compare values in June to those in August) is likely due to an increasing limitation of the evapotranspiration fluxes through the soil moisture levels (which is also consistent with the observed decreased of evaporative fraction in August 2003, see section 5.2). Furthermore, it is important to note that negative discharge anomalies associated with low-precipitation values (and low storage during the drought) also partly compensate negative precipitation anomalies by leading to a net storage increase, as previously highlighted.

[51] The results discussed in this section reveal thus some intriguing findings regarding the drivers of the 2003 drought conditions in the Rietholzbach catchment. Drought indicators based on precipitation only, such as the Standardized Precipitation Index (SPI) [e.g., Lloyds-Hughes and Saunders, 2002] or the Consecutive Dry Days index (CDD) [Frich et al., 2002] are commonly used in hydrological or climate research. They rarely consider memory effects of soil moisture beyond 3 or 6 months and only provide indirect information on evapotranspiration forcing (to the extent that it is correlated with the precipitation deficit). They also do not consider possible compensation of the precipitation anomalies through discharge anomalies (this compensation being itself dependent on the storage conditions). Although precipitation-based indices such as the SPI have been shown to correctly capture drought conditions for several applications [e.g., Hirschi et al., 2011], this analysis highlights the importance of also considering soil moisture, evapotranspiration and runoff dynamics to investigate drought development in regions such as Switzerland or central Europe. This is also relevant for studies using other drought indices, such as the Palmer Drought Severity Index (PDSI) [e.g., Dai et al., 2004; Burke et al., 2006; Dai, 2011]. Indeed, the PDSI index partly takes into account the effect of evapotranspiration, but this variable is generally computed using a simple two-layer bucket-type model in these applications (which implies significant shortcomings for the computation of evapotranspiration; e.g., Henderson-Sellers et al. [1996], Seneviratne et al. [2002]), as well as an oversimplified representation of potential evapotranspiration [Thorntwaite, 1948].

[52] Finally, one should mention that this analysis is only focusing on the 2003 drought event and is not analyzing drought development in other years in Rietholzbach (such as e.g., 1976). Further analyses assessing drought development for different types of events would be useful to assess whether the features identified for the 2003 event are unique or also relevant in other years.

6. Conclusions and Outlook

[53] In this article, we provide a comprehensive analysis of long-term hydroclimatological measurements conducted at the Rietholzbach research catchment in northeastern Switzerland, with a focus on the spatial representativeness of the site and the 2003 drought event. Based on a literature review, we assess that this site is one of the few worldwide including long-term (>30 years) continuous large-lysimeter (>1–2 m² area and >2 m in depth) evapotranspiration measurements. In addition, based on a comparison of the lysimeter seepage with the streamflow measurements at the outlet of the catchment, the lysimeter measurements are found to be well representative of the whole catchment, and analyses further reveal that the catchment streamflow is highly correlated with streamflow measurements at other sites within the Thur river basin (1750 km²) and—for interannual anomalies—also in most of northern Switzerland.

[54] Our results for the 2003 drought and heat wave partly confirm those from previous (regional-scale) studies.

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**Table 6. Impact of Flux Anomalies on Changes in Overall Storage During 2003 Event**

<table>
<thead>
<tr>
<th>Date Range (Monthly and Bweekly)</th>
<th>2003 Anomalies [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((\Delta S_{p-e})^{t})</td>
</tr>
<tr>
<td>Jun 1–30</td>
<td>–7.12</td>
</tr>
<tr>
<td>Jul 1–31</td>
<td>–42.6</td>
</tr>
<tr>
<td>Aug 1–31</td>
<td>–93.3</td>
</tr>
<tr>
<td>Jun 1–4</td>
<td>–37.9</td>
</tr>
<tr>
<td>Jun 15–30</td>
<td>–33.3</td>
</tr>
<tr>
<td>Jul 1–15</td>
<td>–53.6</td>
</tr>
<tr>
<td>Jul 16–31</td>
<td>+10.9</td>
</tr>
<tr>
<td>Aug 1–15</td>
<td>–7.8</td>
</tr>
<tr>
<td>Aug 16–31</td>
<td>–16.5</td>
</tr>
<tr>
<td>Total (JA)</td>
<td>–207.1</td>
</tr>
</tbody>
</table>

*Shown are average anomalies over different time frames within June–July–August 2003 with respect to 1994–2007 mean.*
suggesting that this event was particularly extreme in comparison with the climatological conditions prevailing in the preceding decades in Central-Western Europe [e.g., Schär et al., 2004; Beniston et al., 2004; Ciais et al., 2005; Fischer et al., 2007]. But we also find previously unidentified aspects, most importantly the strong role of evapotranspiration anomalies in driving the early stage of the drought (60% of the anomalies in soil moisture storage change in June 2003), as well as a partial buffering of the event in the upper soil layers in spring 2003 due to the high precipitation levels in the 2002 fall. These two findings partly contradict previous hypotheses suggesting that spring conditions (early vegetation onset and spring precipitation deficits before June) were the main drivers for the 2003 drought [Ferranti and Viterbo, 2006; Fischer et al., 2007; Loew et al., 2009]. These results reflect the conditions at the Rietholzbach site, and may have been less salient at other locations. Further larger-scale analyses would be necessary to assess to which extent these conclusions apply more widely in Switzerland and central Europe.

[55] The lysimeter storage, including soil moisture measurements within the lysimeter, reveals long-term carry-over effects of the drought after the summer 2003, which reach up to spring-summer 2004. Water-balance analyses and the groundwater measurements reveal that after October 2003 these long-term effects were due to changes in soil physical properties within the lysimeter. While these conditions may have also prevailed in the field due to enhanced soil water repellency following the drought event [e.g., Doerr et al., 2000], it is possible that these have been particularly exacerbated within the lysimeter due to modifications of the soil properties along the sides of the lysimeter and the lack of connection to the groundwater storage [e.g., Rana and Katerji, 2000]. Keeping this caveat in mind, this result points at possible drought persistence effects through impacts on soil physical properties, rather than water-balance impacts alone (i.e., linked to the rewetting of the soil), an aspect that is generally not considered in the literature [e.g., Koster and Suarez, 2001; Seneviratne et al., 2006b].

[56] In conclusion, more than three decades of high-quality hydroclimatological measurements (1976 to present) are available from the Rietholzbach catchment site. These include long-term continuous measurements of evapotranspiration with a large lysimeter. Our results suggest that the site is representative for hydroclimatological conditions in a broader region within the Thur basin and in northern Switzerland. The collected data set is thus invaluable for hydroclimatological applications, as well as for comparison with newly available denser but short-term networks of flux measurements established e.g., within the FLUXNET initiative [Baldocchi et al., 2001; Baldocchi, 2008]. The measurements reveal in particular the leading role that evapotranspiration can play in the occurrence of extreme events such as the 2003 drought, even in humid temperate prealpine conditions such as those prevailing in the Rietholzbach catchment.

[57] Acknowledgments. Several persons have worked to successfully develop the Rietholzbach research site over the years. We would like to acknowledge Daniel Vischer, Atsumu Ohmura, and Christoph Schär, the respective chairs of the research groups under which the site was operated from 1976-1983, 1983-1999, and 1999-2007, respectively, as well as the researchers, students, and technicians who contributed to the site in its more than 30 years of existence, especially, P. Achleitner, S. Badertscher, A. Baltensweiler, S. Bernasconi, M. Bohrer, S. Bourgeois, L.N. Braun, W. Brutsaert, B. Burghalter, J. C. Demiere, E. M. Fischer, H. J. Frei, O. Fuhrer, B. Fürholz, A. Gallus, P. Germann, L. Hutter, M. Hutterli, S. Jaun, F. Kuhn, P. Koenig, R. Meier, H. Mössch, G. Müller, M. Perli, F. Pos, B. Schädler, J. Schulla, B. Sevruck, R. Stöckli, R. Voelksch, C. Walther, and M. Zingg. We also thank B. Orlowsky for help with R. H. Mittelbach and J. von Freyberg for useful discussions on soil properties at the site, and the Federal Office for the Environment (FOEN/BAFU) for providing the runoff data analyzed in Figure 5 and Table 4. We acknowledge partial financial support from the Swiss National Foundation through the NFP61 DROUGHT-CH project and NCCR-Climate program.

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