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The heatwaves in Switzerland in summer 1947

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Abstract

In 1947, Switzerland was affected by a heat period of large spatial and temporal extent and rare occurrence. The heatwaves of 1947 can be compared with the events of 2003 in terms of intensity and duration. The summer of 1947 is studied based on the analysis of MeteoSwiss station data as well as the "Twentieth Century Reanalysis" (20CR) data set. Heatwaves were defined as six consecutive exceedances of the local 90th percentile of temperature. Five different heatwaves were identified which struck Switzerland during the summer of 1947. The most intense heatwave event is analysed in more detail. The meteorological situation was characterized by a high-pressure bridge over Central Europe. Based on a comparison with literature and with observations, the applicability of the 20CR dataset for the meteorological analysis of heatwave events could be demonstrated. The representation of the heat period in summer 1947 in 20CR is satisfactory when compared with station data, albeit with a temperature bias due to differences in topography. Hence, heatwaves cannot be defined using an absolute threshold. We conclude that 20CR is applicable for an overview of the meteorological patterns characterizing a heat wave but may not reproduce local details.

1. Introduction

Heatwaves and accompanying drought and air pollution episodes have a major effect on plants, animals and human well-being. In particular, elderly people afflicted by cardiovascular or respiratory problems suffer and mortality increases. It is therefore important to analyse the development of heatwaves and their relation to the large-scale flow, all the more as heatwaves are expected to increase in intensity and frequency in a changing climate. Health relevant heat stress indices are projected to increase strongly in Europe (Fischer and Schär, 2010). For the

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past, observations show that the length of heatwaves has doubled in Switzerland over the past 150 years (Della-Marta et al., 2007). However, persistent heatwaves are rare events, and therefore it is important to also revisit past heatwaves.

This report focuses on the heat period of 1947 in Switzerland. The summer of 1947 marked the culmination of a prolonged drought period that affected central Europe from around 1945 to the early 1950s (see Hirschi et al., this volume). This extraordinary drought period is known for its large impact on agriculture and forestry. In Germany, forests suffered during the summer of 1947 from pests and fires (Baumgartner, 1950). In Switzerland, a complete crop loss was recorded for the summer of 1947 (Calanca, 2007). In this study we focus on Switzerland. Anomalies of the April-to-October mean temperature with respect to the 1901 to 1960 reference period amounted to 2-4 °C at most Swiss stations (Pfister, 1999). This extreme event sets itself apart from other events by the length of the warm period more than by its absolute heat record (Schweizerische Meteorologische Anstalt, 1948).

A heatwave is commonly defined as a "prolonged period of unusually high temperatures observed in a given region" (Silverstovs et al., 2009). A heatwave usually has a duration of a few days up to weeks. Within a heatwave, one single day with extraordinary high temperatures is defined as a heat day. A prolonged period with above-average temperatures and comprising several heatwaves is referred to as a heat period (usually occurring on a continental scale).

The variability of air temperature in general and of extreme temperature events in particular is governed by atmospheric circulation. In particular, persistent high-pressure systems and associated circulation patterns may lead to positive anomalies of surface air temperature affecting a large area over prolonged time periods (Kysely and Huth, 2008). Heatwaves are often caused by quasi-stationary anticyclonic circulation anomalies or atmospheric blocking, which may be sustained or amplified by land-atmosphere feedbacks (IPCC, 2012). This is also the case for the region under study (Rüttimann et al., 2009).

Compared to the heatwaves in 2003, which are well studied and documented (*e.g.*, Z'Graggen, 2006; Schär et al., 2004; Beniston, 2004), the heatwave events of 1947 in Switzerland have not been analysed in detail previously. More often, the year 1947 is referred to and analysed as a drought period (*e.g.*, Calanca, 2006; Pfister, 2000; Schorer, 1992; Griesser, 2008). A focus on this year as a heat period and a comparison with studies on the heat period of 2003, therefore, is the aim of this report. The event in summer 1947 is used to address the ability and limitations of the Twentieth Century Reanalysis dataset to represent a heatwave.

The paper is organised as follows. Section 2 introduces the data sets and indices used. Sections 3 and 4 present the results and discussion. Conclusions are drawn in Section 5.

2. Data and Methods

The analysis of the heatwaves of 1947 in Switzerland in our study is based on the Twentieth Century Reanalysis data set (20CR) version 2 (Compo et al., 2011). 20CR is a global three-dimensional atmospheric data set. It is based on an assimilation of surface and sea-level pressure observations using first-guess fields from the NCEP Global Forecast System (GFS).

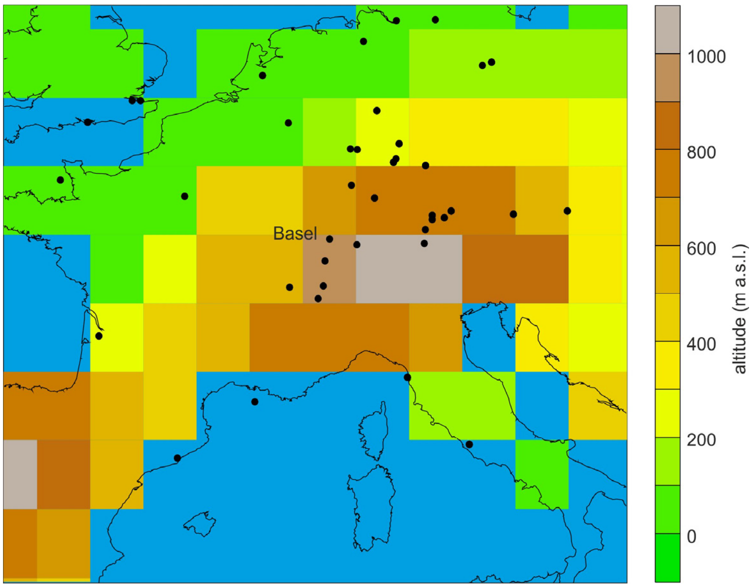

Figure 1. Map showing the surface and sea-level pressure measurements assimilated into 20CR on 29 July 1947, 12 UTC. Colours indicate the orography in 20CR and the land-sea mask as depicted in the Gaussian grid (192x94 cells).

An Ensemble Kalman filter assimilation approach is used with 56 members. Thus, 20CR provides 56 equally likely estimates of the atmospheric state every six hours on a 2°x2° spatial resolution (Compo et al., 2011). All analyses in this paper were done based on the ensemble mean of the 56 members. A map of the assimilated station data for the event under consideration as well as the model orography are shown in Figure 1. Note that the central Swiss Plateau, including the site of Basel, is at an elevation of 959 m a.s.l. (rather than 316 m a.s.l. as in reality); the eastern Swiss Plateau is even above 1000 m a.s.l.

To obtain an overview of the circulation anomalies that caused the heat period, the variables 500 hPa geopotential height (GPH), sea-level pressure (SLP) and surface air temperature from April to June and from July to September 1947 were analysed. Anomalies are calculated based on the 1981-2010 period except where noted otherwise (for comparison with the literature, 1961-1990 is used in some cases).

Heatwaves may be locally amplified, and therefore we also analysed station data from MeteoSwiss to obtain an overview of the small-scale temperature features in Switzerland during the year 1947. In total, data from fourteen stations were analysed (cf. Table 1).

For further assessing 20CR, we used independent or quasi-independent, observation-based data sources. Surface temperature anomalies and precipitation from 20CR were compared with those from the CRU TS3.1 data set (Harris et al., 2013), which provides monthly data on a 0.5° x 0.5° grid. Note that no temperature information was assimilated and hence these data sets are independent. Daily SLP fields from 20CR were compared with those from the EMULATE data set (Ansell et al., 2006). For assessing daily 500 hPa GPH we used observations from the Comprehensive Historical Upper-Air data set (CHUAN, Stickler et al., 2010). Finally, monthly mean fields of 500 hPa GPH were compared with statistical reconstructions, which are based on historical upper-air data (Brönnimann et al., 2012). As these reconstructions end in 1957, they are expressed as anomalies with respect to the ERA-Interim data set (Dee et al., 2011), 1981-2010.

Table 1. Meteorological stations used in this study and maximum temperature observed in 1947.

Station	Longitude / Latitude	Altitude (m a.s.l.)	Max. T_{Max} (°C)
Altdorf	8°37' / 46°53'	438 m	38.0
Arosa	9°40' / 46°47'	1840 m	26.9
Basel/Binningen	7°35' / 47°32'	316 m	38.7
Bern/Zollikofen	7°28' / 46°59'	552 m	35.4
Davos	9°51' / 46°49'	1594 m	26.2
Genève	6°08' / 46°15'	420 m	36.4
Locarno/Monti	8°47' / 46°10'	366 m	33.0
Lugano	8°58' / 46°00'	273 m	36.2
Luzern	8°18' / 47°02'	454 m	37.2
Montana	7°28' / 46°18'	1427 m	31.5
Montreux-Clarens	6°54' / 46°27'	405 m	37.2
Neuchâtel	6°57' / 47°00'	485 m	36.4
Säntis	9°21' / 47°15'	2502 m	26.4
Zürich/Fluntern	8°34' / 47°23'	555 m	37.7

A heatwave is commonly defined as a series of at least three successive (heat) days exceeding a defined temperature threshold value (Neu and Thalmann, 2005), whereas in Switzerland a heat day is often referred to as a day with maximum temperature exceeding 30 °C (termed HW30, Z'Graggen, 2006). In the literature, several definitions and different reference data are used to determine heatwaves. In this report we followed Beniston et al. (2007) and used the heatwave index of six consecutive exceedances of the local 90th percentile of temperature (termed HW6-90). This definition ensures that an event of a fixed rarity is measured. In contrast to absolute thresholds, the relative heatwave definition can also be applied to mountain stations. The 90th percentile was calculated for each station based on maximum temperature (T_{max}) from all summer days (Jun.-Aug.) of the reference period 1981-2010. The 30 °C threshold definition (HW30) was applied to Basel, to show the number of heat days in Switzerland and to ensure the comparison for a heatwave event with a fixed intensity. Daily maximum temperatures at 2 m from Basel are compared to daily maximum 2 m temperatures at the closest grid point to Basel in the 20CR dataset (see Figure 1). The meteorological analysis focuses on the most intense heatwave event in 1947 (22 Jul. to 2 Aug. 1947) and specifically 29 July 1947, the day on which record temperatures were measured.

3. Results

3.1. Anomalies from April to September 1947

Based on the analysis of 20CR monthly mean temperature anomalies, the time period analysed in this study was limited to months with above-average temperatures, *i.e.,* April to September 1947. This period was subdivided into two 3-month periods, April to June and July to September. Clear anomalies of temperature and atmospheric circulation appear in 20CR (Fig. 2), but the two subperiods also differ. In 20CR, 500 hPa GPH over Switzerland was 50 gpm above climatology from April to June, but only 10 gpm from July to September (Fig. 2 top). The anomalies are in very good agreement with those found in the statistical

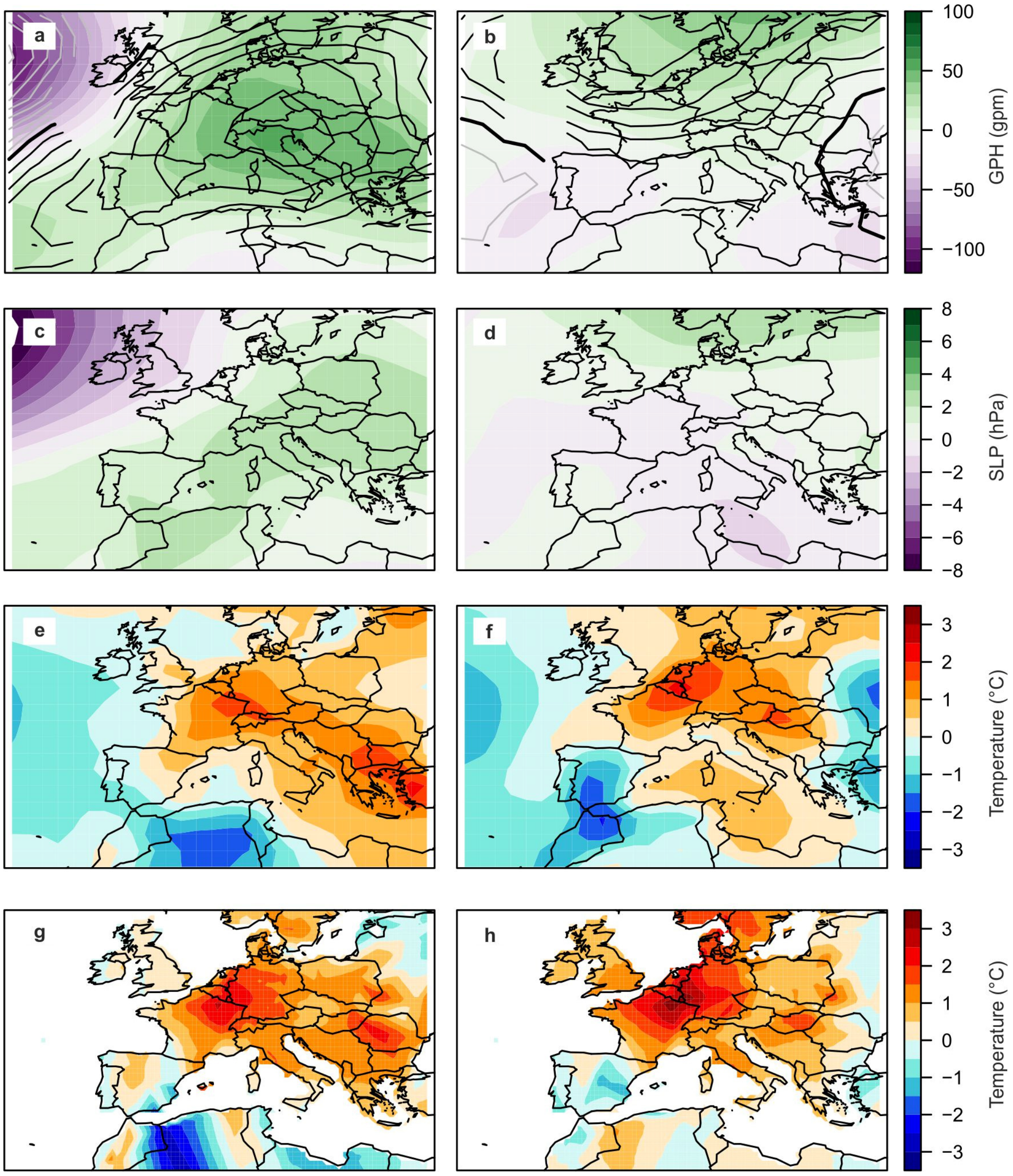

Figure 2. Anomalies (with respect to 1981-2010) of 500 hPa GPH (a,b), SLP (c,d), and 2 m temperature (e-h) in April to June (left) and July to September (right) 1947. Colours in a-f indicate 20CR data, contours in a and b indicate 500 hPa GPH from REC2 (10 gpm, zero contour in bold, note that this field has missing values). Panels g an h indicate temperature anomalies from CRU TS3.1.

reconstructions from April to June, both in terms of amplitude and position, but less so from July to September, when reconstructions imply rather pronounced positive anomalies over the North Sea. A comparison of the two climatologies used to define anomalies (20CR and ERA-Interim, both 1981 to 2010) shows rather large differences, pointing to a positive bias of 500 hPa GPH in 20CR of around 40 gpm over Switzerland in summer.

Sea-level pressure over Switzerland in 20CR shows a positive anomaly of 2.4 hPa from April to June and a slight negative anomaly of 0.5 hPa from July to September. The temperature anomaly in 20CR amounted to 1.5-2 °C from April to June and to 0.5-1.5 °C from July to September 1947, respectively. Almost the entire European continent was warmer than average. Over land, the 20CR results can be compared with CRU TS3.1 temperature data

(Fig. 2, bottom). The spatial anomaly patterns in the two data sets agree well, but the magnitude of the maximum is slightly underestimated in 20CR. There are differences between the data sets over North Africa and the Iberian Peninsula.

3.2. Overview of heatwaves in 1947

In this Section we give an overview of all heatwaves in the summer of 1947. Figure 3 shows the time series of daily maximum temperatures at 2 m measured at the station in Basel (7°35' E, 47°32' N, blue line) and the 20CR grid point at 7°50' E and 47°46' N (black line) from April to September 1947. In the observations, the 30 °C threshold (HW30) was exceeded on 49 days during summer 1947 and it was exceeded five times for at least five consecutive days. This 30 °C threshold corresponds to the climatological 90% quantile of summer T_{max} at Basel, which according to Zhang et al. (2011) is a useful index for warm days.

The temperature evolution in 20CR is similar as in the observations, however, due to the difference in altitude and orography, 20CR temperatures are generally lower and exceed the 30 °C threshold only twice. The difference between 20CR and the station temperature in Basel ranges between 0 °C and 13 °C (16 Sep. 1947). Based on the considerable altitude difference (643 m) a mean temperature difference of ca. 4 °C is expected. A further difference is expected due to the specific topographic situation of Basel in a small basin.

Temperature in Basel is highly correlated with local 500 hPa GPH in 20CR (Fig. 3, bottom). Values exceeding 5900 gpm are found. Observed values from radiosoundings from Payerne, Switzerland, are shown in green. Soundings were performed only sporadically, and

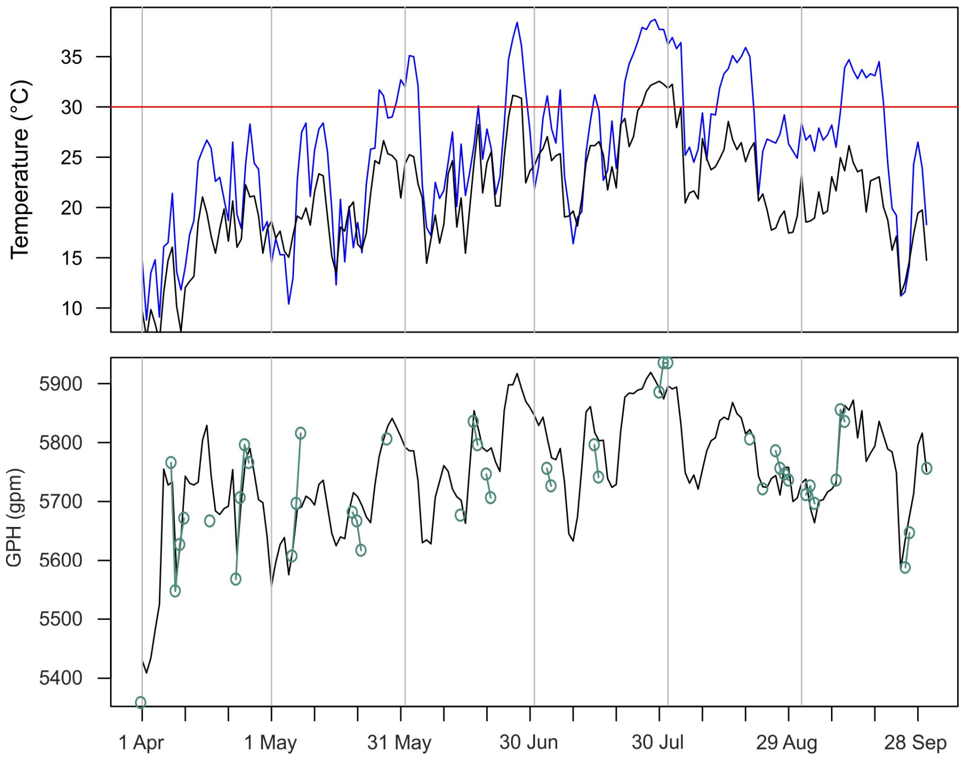

Figure 3. Time Series of (top) maximum temperature at 2 m from station data from Basel (blue line) and 20CR (gridpoint: 7°50' E, 47°46' N, black line) and (bottom) 500 hPa GPH from the station of Payerne (green line, increased by 100 gpm) and 20CR (gridpoint: 8° E, 48° N, black line) from April to September 1947. The 30 °C threshold (red) visualizes the days referred to as heat days.

Table 2. Heatwaves according to HW6-90 (reference period 1981-1990) at 14 stations in 1947. The first and last column indicate the thresholds obtained for HW6-90 for the reference periods 1981-1990 and 1961-1990, respectively.

Station	90p	Event I	Event II	Event III	Event IV	Event V	90p JJA 1961-90 [1]
Altdorf	28.6 °C	30 May-4 Jun.	-	21 Jul.-4 Aug.	15-20 Aug.	-	27.5 °C
Arosa	21.3 °C	-	-	23 Jul.-4 Aug.	-	11-20 Sep.	19.7 °C
Basel-Binningen	30.3 °C	30 May-4 Jun.	-	22 Jul.-4 Aug.	13-20 Aug.	11-20 Sep.	29.5 °C
Bern/Zollikofen	29.3 °C	-	-	24 Jul.-4 Aug.	15-20 Aug.	-	28.3 °C
Davos	23.1 °C	-	-	25 Jul.-4 Aug.	-	-	22.6 °C
Genève	30.9 °C	-	-	26 Jul.-2 Aug.	-	-	29.2 °C
Locarno	29.9 °C	-	-	27 Jul.-3 Aug.	-	-	28.8 °C
Lugano	29.5 °C	-	25 Jun.-6 Jul.	23 Jul.-4 Aug.	16-21 Aug.	12-21 Sep.	29.0 °C
Luzern	29.3 °C	-	-	22 Jul.-4 Aug.	15-20 Aug.	-	28.5 °C
Montana	24.8 °C	-	-	22 Jul.-5 Aug.	16-21 Aug.	12-19 Sep.	23.3 °C
Montreux-Clarens	29.4 °C	-	-	24 Jul.-4 Aug.	-	-	28.4 °C
Neuchâtel	29.5 °C	-	-	23 Jul.-4 Aug.	13-20 Aug.	-	28.7 °C
Säntis	13.7 °C	-	-	25 Jul.-4 Aug.	-	-	13.0 °C
Zürich-Fluntern	28.9 °C	-	-	22 Jul.-4 Aug.	12.-21 Aug.	11-20 Sep.	28.4 °C

the random error σ_{err} of an individual measurement amounts to about 20-30 gpm (Wartenburger et al., 2013). While the correlation is high (r = 0.92), there is a large offset of 110 gpm, which is much larger than the likely bias of 20CR in the 1981-2010 climatology and which might be related to an error in the radiosonde observations. After removing the offset, differences are consistent with the 20CR ensemble spread assuming a random observation error of 30 gpm (*i.e.* 6% of the measurements are outside ±2 $(\sigma_{sprd}^2 + \sigma_{err}^2)^{0.5}$; for Gaussian distributed errors we expect 5%).

The analysis of 14 meteorological stations of Switzerland in 1947 reveals that in summer 1947, five heatwave events according to HW6-90 occurred (Table 2). Of these, the heatwave in July and August (22 Jul.-2 Aug. 1947) was the longest and most intense, with a duration of up to 15 days in Montana and Altdorf (Basel: 14 days, Fig. 3). Additionally, the criterion for a heatwave was met by all 14 stations (Table 2).

In the analysis of the maximum temperature from the 14 meteorological stations, 29 July was the hottest day during summer 1947. The mean maximum temperature from all lowland (<560 m a.s.l.) stations on this date was 36.1 °C; 26.4 °C were reached at 2502 m a.s.l. In Basel 38.7 °C were measured - the highest recorded temperature during the heat period of 1947 and the highest temperature ever observed in Switzerland until 2003 (note, however, that the Wild screen used at that time in Basel was sensitive to radiation errors, see Auchmann and Brönnimann, 2012).

[1] The reference period from 1961-1990 is used in the discussion for the comparison with literature on the 2003 heat period.

3.3. Heatwave in July-August 1947

Meteorological situation

Based on the analysis of the 20CR dataset the meteorological development can be characterized as follows: On 21 July 1947 a low pressure system was located over the Atlantic Ocean near the British Isles and a high pressure over Central and Northern Europe (Fig. 4). The depression led to warm air advection in the direction of the Norwegian Sea. A belt of high pressure stretched from Portugal to the north of Scandinavia. By 23 July the high pressure belt extended from North Africa, across the Mediterranean, France and Central Europe to Norway. Associated subsidence may have stabilized the atmosphere and the weather was fair all over Europe. The circulation changed on 25 July, which had an important influence on Northern Europe. The occlusion of the North Atlantic depression reached Scandinavia. However, the meteorological situation in Central Europe did not change and was stable for several days. Another depression originating from the Azores reached Great Britain and moved even further to the North Sea and to the Baltic. Switzerland, by 29 July 1947, was still influenced by the Central European high. The hot temperatures and the fair weather from 21 July to 4 August were due to the continuous presence of a stable Central European high pressure system and southwesterly flow.

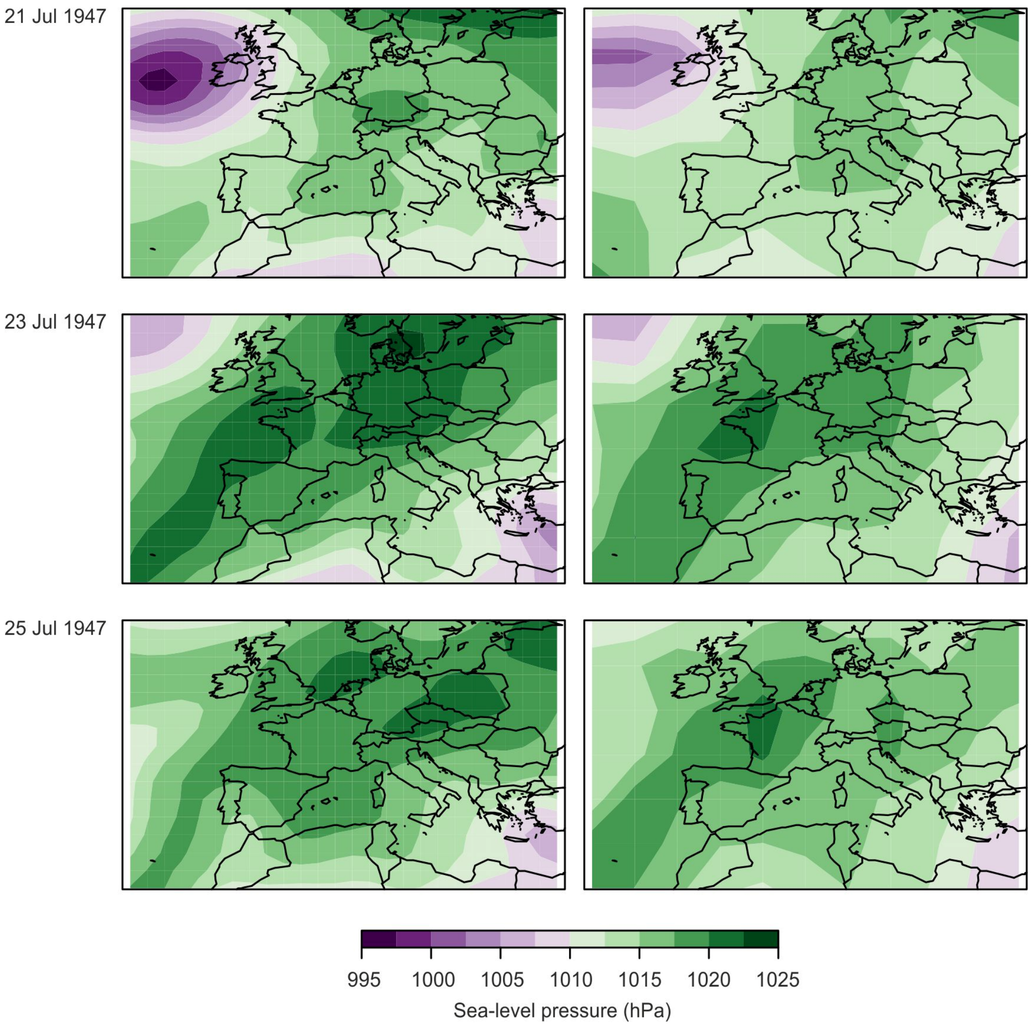

Figure 4. Mean sea-level pressure (in hPa) on (top) 21, (middle) 23 and (bottom) 25 July 1947 in 20CR (left) and EMULATE (right).

The comparison between 20CR and EMULATE data reveals very good agreement, though EMULATE tends to exhibit slightly smaller amplitudes. For other comparisons of 20CR and EMULATE see contributions by Schneider et al. and Feuchter et al. in this volume.

Heat day on 29 July 1947

The 29th of July was chosen to compare the measured temperatures with the 20CR dataset and to analyse the meteorological situation characteristic for the heatwave from 22 July to 4 August 1947. The temperature anomaly on 29 July is also strongly positive in the 20CR dataset. Over Switzerland the temperature anomaly amounted to 5-7 °C in the 20CR data compared to the mean of the period of 1981-2010 (Fig. 5). The MeteoSwiss station data of 14 stations (Table 1) shown in Figure 5 recorded temperature anomalies between 1.1 °C (Locarno) and 8.9 °C (Altdorf) above the stations' 90th percentile summer months' threshold (reference period 1981-2010).

Geopotential height at 500 hPa on 29 July shows a high pressure area over Central Europe (Fig. 5). It was accompanied by a low pressure area above Northern Europe. This situation is characteristic for the Grosswetterlage "Central-European high". Upper-air observations were sparse in Europe in the post-war period. Only six measurements were available in the 40-hour time window 28 July, 16 UTC to 30 July, 8 UTC (even fewer if the time window is more restricted). They confirm the general pattern (including also the likely positive bias in 20CR), but more and better observations would be needed to assess the details of the 500 hPa GPH field in 20CR.

The SLP field shows a low pressure area over the North Sea and a high pressure system over Central Europe and the Atlantic Ocean. The SLP distribution over Europe on 29 July corresponds to the Grosswetterlage "high pressure bridge over Central Europe" (Werner et al., 2010), which had established between the Azores high and an Eastern-European high.

4. Discussion

The analysis of the summer 1947 using a percentile based definition of a heatwave demonstrates that this year can be defined as a heat period in Switzerland. Five heatwaves of different intensity, duration and spatial extent affected Switzerland during this heat summer.

The heat period of 1947 can be compared with the year 2003 in terms of maximum temperatures and duration of the heatwaves. For instance, the maximum temperature anomaly, computed as departures from the 1961-1990 average, of the year 1947 amounted to 5 °C. This is only 1 °C less than for the year 2003. Another aspect is that in Basel, the threshold of 30 °C was exceeded 49 times in 1947, more often than in 2003 (41 times). During the 1961-1990 period, the 30 °C threshold was exceeded for the first time on average on 19 June. In 2003, the first day with maximum temperatures exceeding 30 °C was 2 June (Beniston, 2004) and in 1947 30 °C were exceeded already on 26 May (Basel). The period of consecutive days during which the maximum temperature exceeded the 90% quantile of the summer temperature was also longer in 1947 than in 2003. During the year 1947 the longest heatwave lasted 14 days from 22 July to 4 August, whereas in 2003 only twelve consecutive heat days were recorded at the beginning of August (Z'Graggen, 2006; Beniston, 2004).

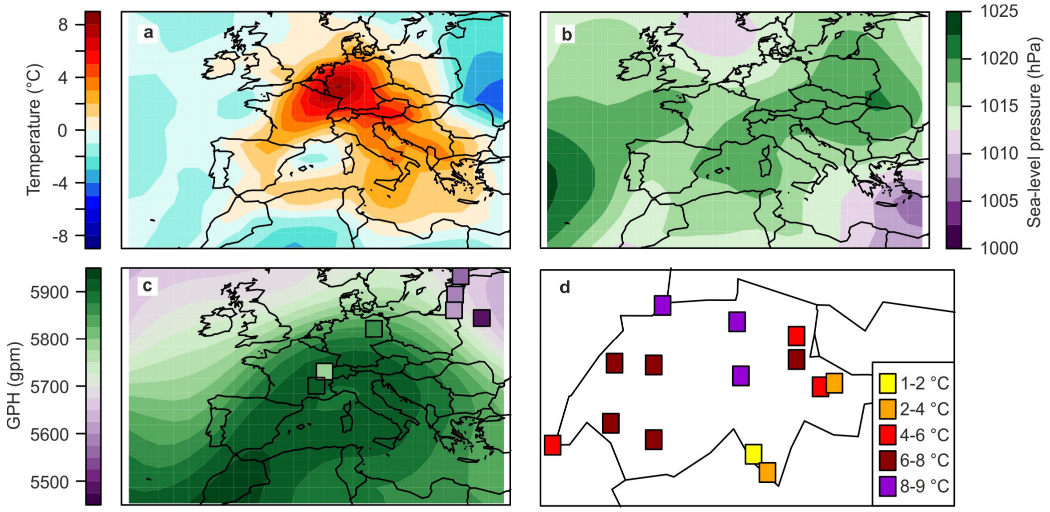

Figure 5. Fields of (a) temperature anomalies (with respect to 1961-1990), (b) sea-level pressure, and (c) 500 hPa geopotential height in 20CR on 29 July 1947. Station temperature anomalies for that day are shown in (d). Dots in (c) are upper-air observations from CHUAN data.

The SLP anomalies in 20CR over Europe during the period 22 July to 4 August 1947 were similar to those during the heatwave from 1 to 13 August 2003 (Z'Graggen, 2006). In both years a high pressure system moved from the Atlantic Ocean to Central Europe and a low pressure system was situated near the British Isles. Thus, warm air was transported from the South to Europe and fair weather led to the heating of the continent (Z'Graggen, 2006; Schweizerische Meteorologische Anstalt, 1948).

The second aim of our study was to assess the applicability of 20CR for the purpose of studying this heatwave event (see also Hirschi et al., this issue, for the drought summers 1945, 1947, and 1949). The SLP field in 20CR compares well with daily charts from the National Center of Atmospheric Research (see www.wetterzentrale.de/topkarten/tkslpar2.htm) and MeteoSwiss reports from 1948. Comparison with EMULATE SLP data for individual days also shows good agreement.

The comparison of the maximum air temperature at 2 m of a selected 20CR grid point with the MeteoSwiss station data of Basel shows that the maximum temperature in the 20CR dataset was always lower than observations due to differences in elevation and perhaps the rather coarse resolution of the 20CR dataset. However, the temporal evolution of temperature in 20CR is very similar to observations. 20CR also shows a north-south gradient of maximum temperatures, but the spatial resolution is coarse and hence it is important to consider station data for capturing small-scale temperature features that may occur during heatwaves.

Seasonally averaged fields of 500 hPa GPH fit very well with statistical reconstructions. A likely positive bias is found in 20CR over Central Europe in summer. Correlations with observations are high, but the analysis also shows that errors in radiosonde data are still large.

5. Conclusions

The meteorological situation during the heatwave event in 1947 analysed with the 20CR dataset shows typical features of a heatwave. The stationary high pressure system over the study region - the Central-European High - during the episode from the 22 July to 4 August 1947 is conductive for a heatwave according to Kysely and Huth (2008).

The analysis of the heatwaves in 1947 indicates that the event is comparable to 21st century heat periods such as the summer 2003 and that 1947 was extraordinary. Five heatwave events were recorded by MeteoSwiss in Switzerland, embedded in a long period of seven months with anomalous warmth. Even if the heatwave 2003 exceeded the maximum temperatures measured in 1947, in terms of the length of a heatwave and the exceedance of the 30 °C temperature threshold, the heat period 1947 was more intense.

Analysing the hottest day during the heat period 1947, 29 July, demonstrated the usefulness of the Twentieth Century Reanalysis dataset for the analysis of the synoptic scale circulation during heatwaves. The meteorological situation as depicted in 20CR was compared with other data sources and could be verified through a literature review. The sea level pressure field for 29 July 1947 exhibits a depression originating near the Azores, which passed the British Isles. Furthermore, the high pressure area over Central Europe is clearly visible in 500 hPa GPH. Overall, the analysis of the MeteoSwiss station data as well as the 20CR dataset shows that the summer 1947 can be defined as a heat period in Switzerland, characterized by five longer lasting heatwaves.

For temperature, 20CR shows a good agreement of day-to-day variability in terms of anomalies. The positive temperature anomaly (compared to the reference period 1981-2010) shown in the 20CR dataset on the 29 July was supported by MeteoSwiss station data. However, complex topographic situations may be important for temperature extremes during heatwaves, and these situations are not resolved in 20CR. therefore station-based information is necessary for a full assessment of the heatwave.

Acknowledgments

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References

Ansell, T. J., P. D. Jones, R. J. Allan, D. Lister, D.E. Parker, M. Brunet, A. Moberg, J. Jacobeit, P. Brohan, N. A. Rayner, E. Aguilar, M. Barriendos, T. Brandsma, N. J. Cox, P. M. Della-Marta, A. Drebs, D. Founda, F. Gerstengarbe, K. Hickey, T. Jónsson, J. Luterbacher, Ø. Nordli, H. Oesterle, M. Petrakis, A. Philipp, M. J. Rodwell, O. Saladie, J. Sigro, V. Slonosky, L. Srnec, V. Swail, A. M. García-Suárez, H. Tuomenvirta, X. Wang, H. Wanner, P. Werner, D. Wheeler, and E. Xoplaki (2006) Daily mean sea level pressure reconstructions for the European-North Atlantic region for the period 1850–2003. *J. Climate,* **19,** 2717–2742.

Auchmann, R. and S. Brönnimann (2012) A physics-based correction model for homogenizing sub-daily temperature series. *J. Geophys. Res.,* **117,** D17119, doi:10.1029/2012JD018067

Beniston, M. (2004) The 2003 heat wave in Europe: A shape of things to come? An anal-ysis based on Swiss climatological data and model simulations. Fribourg (University of Fribourg).

Beniston, M., D. Stephenson, O. Christensen, C. Ferro, C. Frei, S. Goyette, K. Halsnaes, T. Holt, K. Jylhä, B. Koffi, J. Palutikof, R. Schöll, T. Semmler, and K. Woth (2007) Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change,* **81,** 71–95

Baumgartner, A. (1950) Niederschlagsschwankungen und Dürregefährdung mit Bezug auf den Waldbau. *Forstwissenschaftliches Centralblatt,* **69,** 636-662.

Brönnimann, S., T. Griesser, and A. Stickler (2012) A gridded monthly upper-air data set from 1918 to 1957. *Climate Dynamics,* **38,** 475-493.

Calanca, P. (2007) Climate change and drought occurrence in the Alpine region: How severe are becoming the extremes? *Global and Planetary Change,* **57,** 151-160.

Compo, G. P., J. S. Whitaker, P. D. Sardeshmukh, N. Matsui, R. J. Allan, X. Yin, B. E. Gleason, R. S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R. I. Crouthamel, A. N. Grant, P. Y. Groisman, P. D. Jones, M. C. Kruk, A. C. Kruger, G. J. Marshall, M. Maugeri, H. Y. Mok, Ø. Nordli, T. F. Ross, R. M. Trigo, X. L. Wang, S. D. Woodruff, and S. J. Worley (2011) The Twentieth Century Reanalysis project. *Q. J. Roy. Meteorol. Soc.,* **137**, 1-28.

Dee, D. P., S. M. Uppala, A. J Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thépaut, and F. Vitart (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. Roy. Meteorol. Soc.,* **137,** 553–597.

Della-Marta, P. M., M. R. Haylock, J. Luterbacher, and H. Wanner (2007) Doubled length of western European summer heatwaves since 1880. *J. Geophys. Res.,* **112,** D15103.

Feuchter, D., C. Jörg, G. Rosenhagen, R. Auchmann, O. Martius, and S. Brönnimann (2013) The 1872 Baltic Sea storm surge. In: Brönnimann, S. and O. Martius (Eds.) *Weather extremes during the past 140 years*. Geographica Bernensia G89, p. 91-98, DOI: 104480/GB2013.G89.10.

Fischer, E. M., and C. Schär (2010) Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geosci.,* **3,** 398–403.

Griesser, T. (2008) *Reconstruction of global upper-level circulation 1880-1957 for analyzing decadal climate variability.* Dissertation ETH Zürich.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister (2013) Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 dataset. *Int. J. Climatol.,* doi: 10.1002/joc.3711.

Hirschi, E., R. Auchmann, O. Martius, and S. Brönnimann (2013) The 1945-1949 droughts in Switzerland. In: Brönnimann, S. and O. Martius (Eds.) *Weather extremes during the past 140 years*. Geographica Bernensia G89, p. 81-90, DOI: 104480/GB2013.G89.09.

IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge (Cambrige University Press).

Kysely, J. and R. Huth (2008) Relationships of surface air temperature anomalies over Europe to persistence of atmospheric circulation patterns conducive to heat waves. *Adv. Geosci.,* **14,** 243–249.

Neu, U. and E. Thalmann (2005) *Hitzesommer 2003 – Synthesebericht*. ProClim Bern.

Pfister, C. (1999) *Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen 1496-1995.* Paul Haupt, Bern.

Schär, C., P. L. Vidale, D. Lüthi, C. Frei, C. Häberli, M. A. Liniger, and C. Appenzeller (2004) The role of increasing temperature variability in European summer heatwaves. *Nature,* **427,** 332–336.

Schorer, M. (1992) *Extreme Trockensommer in der Schweiz im 20. Jh. und ihre Folgen für Natur und Wirtschaft.* Geographica Bernensia, Bern.

Schneider, T., H. Weber, J. Franke, and S. Brönnimann (2013) The Storm Surge Event of the Netherlands in 1953. In: Brönnimann, S. and O. Martius (Eds.) *Weather extremes during the past 140 years*. Geographica Bernensia G89, p. 35-43, DOI: 104480/GB2013.G89.04.

Schweizerische Meteorologische Anstalt (1948) *Annalen der Schweizerischen Meteorologischen Zentralanstalt.* Vol. 84. Zürich.

Silverstovs, B., R. Ötsch, C. Kemfert, C. Jaeger, A. Haas, and H. Kremers (2009) Climate change and modelling of extreme temperatures in Switzerland. *Stoch Env. Res Risk Asses,* **24,** 311-326.

Stickler, A., A. N. Grant, T. Ewen, T. F. Ross, R. S. Vose, J. Comeaux, P. Bessemoulin, K. Jylhä, W. K. Adam, P. Jeannet, A. Nagurny, A. M. Sterin, R. Allan, G. P. Compo, T. Griesser, and S. Brönnimann (2010) The comprehensive historical upper-air network. *Bull. Amer. Meteorol. Soc.,* **91,** 741-751.

Wartenburger, R., S. Brönnimann, and A. Stickler (2013) Observation errors in early historical upper-air observations. *J. Geophys. Res.,* **118,** doi:10.1002/2013JD020156.

Werner, P. and F.-W. Gerstengarbe (2010) *Katalog der Grosswetterlagen Europas (1881-2009) nach Paul Hess und Helmut Brezowsky 7., verbesserte und ergänzte Auflage.* Potsdam Institute for Climate Impact Research.

Z'Graggen, L. (2006) *Die Maximaltemperaturen im Hitzesommer 2003 und Vergleich zu früheren Extremtemperaturen.* Meteo Schweiz Arbeitsberichte. Nr. 212, Zürich.

Zhang, X., L. Alexander, G. Hegerl, P. Jones, A. Klein Tank, T. Peterson, B. Trewin, and F. Zwiers (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Clim. Change,* **2,** 851-870.