**Climate
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Extreme climate, not extreme weather: the summer of 1816 in Geneva, Switzerland

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Abstract

We analyze weather and climate during the "Year without Summer" 1816 using sub-daily data from Geneva, Switzerland, representing one of the climatically most severely affected regions. The record includes twice daily measurements and observations of
5 air temperature, pressure, cloud cover, wind speed, and wind direction as well as daily measurements of precipitation. Comparing 1816 to a contemporary reference period (1799–1821) reveals that the coldness of the summer of 1816 was most prominent in the afternoon, with a shift of the entire distribution function of temperature anomalies by 3–4 °C. Early morning temperature anomalies show a smaller change for the
10 mean, a significant decrease in the variability, and no changes in negative extremes. Analyzing cloudy and cloud-free conditions separately suggests that an increase in the number of cloudy days was to a significant extent responsible for these features. A daily weather type classification based on pressure, pressure tendency, and wind direction shows extremely anomalous frequencies in summer 1816, with only one day (com-
15 pared to 20 in an average summer) classified as high-pressure situation but a tripling of low-pressure situations. The afternoon temperature anomalies expected from only a change in weather types was much stronger negative in summer 1816 than in any other year. For precipitation, our analysis shows that the 80 % increase in summer precipitation compared to the reference period can be explained by 80 % increase in
20 the frequency of precipitation, while no change could be found neither in the average intensity of precipitation nor in the frequency distribution of extreme precipitation. In all, the analysis shows that the regional circulation and local cloud cover played a dominant role. It also shows that the summer of 1816 was an example of extreme climate, not extreme weather.

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1 Introduction

One of the most severe climatic deviations of the past few hundred years, in Central Europe, was the "Year Without Summer" (YWS) 1816 (Stothers, 1984; Briffa and Jones, 1992; Harington, 1992; Robock, 1994, 2000). This event has been studied extensively
5 both by historians (Skeen, 1981; Pfister 1992, 1999) and climate scientists (Briffa and Jones, 1992; Kington, 1992; Shindell et al., 2004) with respect to causes and consequences. The event is mostly related to the 1815 eruption of Tambora in Indonesia, which injected a huge amount of sulfur into the stratosphere that was capable of altering global climate (Stommel and Stommel, 1983; Stothers, 1984, 1999; Piervitali et al.,
10 1997; Briffa et al., 1998; Chenoweth, 2001; Stendel et al., 2005). In addition, reduced solar activity related to the so-called Dalton minimum might have played a role (Lean et al., 1995; Mann et al., 1998).

The global scale cooling due to the Tambora eruption is estimated to approximately 0.5°C. However, in Central Europe, where consequences were devastating both economically and socially (Hoyt, 1958; Stothers, 1999; Oppenheimer, 2003), the cold
15 anomalies were much larger (Trigo et al. 2009; Luterbacher et al., 2004), calling for additional or amplifying mechanisms.

Most previous studies on the YWS in Europe addressed the monthly or seasonal scale (e.g. Self et al., 1980; Trigo et al., 2009), for which abundant information is avail-
20 able from direct measurements as well as climate proxies and documentary data. Daily or even sub-daily data have much more rarely been studied (Baron, 1992; Chenoweth 2009). This would be important, however, as sub-daily information might potentially give further insights into the underlying processes. One main restriction so far was data availability as many data series were simply not available in their original form.
25 In this paper we analyze the YWS 1816 in a recently digitized record of twice daily measurements performed in Geneva, Switzerland, including air temperature, pressure, cloud cover, wind speed and direction, and daily precipitation. Geneva is in the region with the largest negative temperature anomaly (e.g. Pfister, 1992; Trigo et al., 2009)

in summer 1816. The aim of the paper is to analyze to what extent the year without summer was characterized by extreme climate or by extreme weather (i.e. whether changes are largest in the central part of the frequency distribution or near the extremes). Furthermore, by analyzing sub-daily data we hope to get more insights into the mechanisms responsible for the YWS. Finally, the paper aims at identifying new characteristics of the YWS that are testable in or comparable to a modeling framework.

The paper is organized as follows. In Sect. 2, data (including all aspects of homogeneity) and methods are explained. In Sect. 3 we present and discuss the results. Conclusions are drawn in Sect. 4.

2 Data and methods

2.1 Meteorological measurements and observations from Geneva

The data from Geneva were digitized from printed sources (Journal de Genève, Bibliothèque britannique/universelle) reaching back to the 1780s. We digitized all elements (temperature, precipitation, pressure, clouds, wind) at the full temporal resolution and converted the data to current units. No further pressure reduction was necessary as it was already reduced to constant 10°R. This is different to nowadays standard (0°C), but irrelevant for our study. We focus on the sub-period 1799–1821, which can be considered internally homogeneous at least with respect to temperature (the homogenization of the full record is ongoing). There were no reported changes in station operation during that time. Measurements were made in the old botanical garden, situated on the Bastion St-Léger in the southwest of Geneva (Fig. 1). The old botanical garden had an effective area of 1800 m^2 (Sigrist and Bungener, 2008) and hence the influence of surrounding buildings can be assumed small (Pictet, 1822). Before 1799 observations were made in Genthod, after 1822 (until 1825) the observation site was situated at the southeastern edge of the town. In 1826 it was relocated to the new botanical garden, on the northern shore of Lake Geneva (Schuepp, 1961).

During the period 1799–1821 Marc-Auguste Pictet was responsible for collecting and publishing the observational data. There are twice daily measurements of air temperature and pressure and twice daily observations of cloud cover, wind direction and (sometimes) speed. One observation was performed at sunrise (most likely local astronomical sunrise) with the aim of capturing the minimum temperature and one at 02:00 LT which is close to the maximum. Because anomalies from the seasonal cycle are computed later on, the effects of systematic errors related to the time of observation are small. In addition to the twice daily reports, daily precipitation measurements are also reported. According to our information, there were no changes in instruments, reporting, and location during the period 1799–1821. However, notes in the station history revealed a trend inhomogeneity in this period which was corrected. Available calibration information indicated a drift in temperature, which is a known error that is caused by the chemical composition of the glass and has been studied in detail for the case of Hohenpeißenberg in Germany (see Winkler, 2009, and references therein). As the instrument in Geneva was of the same type as that used at Hohenpeißenberg and because the reported shift in the calibration ($0.6\,°C$) also was very similar, we corrected it in the same way as Winkler (2009) by decreasing temperature by $0.1\,°C$ per year (from 1796–1801). From 1802 onwards we subtracted $0.6\,°C$. The instrument type used was a mercury thermometer with an isolated bulb, divided in 80 parts in unit degree Réaumur (Pictet, 1822).

Cloud cover observations were recorded qualitatively and noted verbally in a semi-standardized terminology. In a step-wise procedure, we categorized the cloud observations into six cloudiness groups, from clear sky to fully covered. For our analysis, we isolated days on which both, the morning and noon observations, could clearly be identified as either cloud free or fully covered, respectively. By analyzing the distribution of the cloudiness classes over time we clearly found the cloud cover series to be inhomogeneous. Unreasonable cloud cover distributions and year-to-year variations appeared in the entire period 1799–1811 (which is partly also reflected in the terminology used). However, the period 1812–1821 was found to be more homogeneous and

relatively reliable. Therefore, any further analysis involving cloud cover used only this (shorter) period.

2.2 Analysis methods

The period 1799–1821 was chosen as a base period. From this period we removed the volcanically perturbed years, namely the years 1815 to 1817 (which are perturbed by the eruption of Tambora in April 1815, Bradley and Jones, 1995) and the years 1809 to 1811 (unknown eruption in 1809, Cole-Dai et al., 2009). The remaining 16 yr were used as a reference against which we could compare the YWS 1816. The focus in this paper is on the summer of 1816, although we also analyzed the summer of 1815 and the winters of 1815/1816 and 1816/1817 (Breda, L., unpublished master thesis).

First, temperature values were analyzed and compared to the reference because analyzing the occurrences of frost or other environmentally relevant indicators requires an absolute scale rather than anomalies. In a second step, a mean annual cycle for temperature was formed from the reference period by fitting a seasonal cycle consisting of the first two harmonics. We then subtracted this annual cycle from both the reference period and the YWS period in order to study anomalies. Precipitation was analyzed in the form of absolute values (not anomalies) because of its skewed and bounded distribution function and because the seasonal cycle is not well defined. In addition, statistics of precipitation frequency (number of days with > 0.1 mm) and 24-h precipitation intensity (i.e. the amount of precipitation on days with precipitation > 0.1 mm) were analyzed. For temperature anomalies and 24-h precipitation intensity we estimated probability density functions in order to address the frequencies of weather extremes. Also, we assessed the dependence of temperature anomalies upon cloud cover. Note that due to homogeneity reasons (see Sect. 2) all analyses involving cloud cover used a reduced base period 1812–1821 (without the volcanically perturbed years 1815–1817).

Finally, in order to further analyze the mechanisms, we performed a simple weather type classification for summer based on wind direction, pressure, and pressure

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tendency in order to address the effects of changing frequencies of weather types and changes within weather types. The weather types were defined based on all summers in the reference period. Then the same criteria were applied to the summer of 1816. By retaining only the weather type information for 1816, randomly sampling from the corresponding weather types during the reference period, and then comparing back with the observed anomaly, we can estimate the contribution of changes in weather types to the anomalies in temperature, precipitation, or cloud cover. A Monte Carlo approach ($n = 10\,000$) was applied to obtain a measure of variability associated with the sampling, assuming temporal independence of the weather types from one day to the next. Although this assumption is certainly not valid, the effect on the result is considered small as other sampling strategies (e.g. distinguishing 1st and 2nd days in a sequence or sampling 2-day periods) gave similar results.

3 Results and discussion

3.1 Morning and afternoon temperature and frequency distributions

Daily temperatures of the years 1816 are shown in Fig. 2 together with the mean annual cycle from the reference period as well as the corresponding annual cycle of minima and maxima. The last negative spring temperature in 1816 was observed at sunrise on the 16 April. This corresponds almost exactly to the mean date of the last negative spring temperature in the reference period. The annual maximum temperature in 1816 was 26.9 °C (observed on the afternoon of the 14 August). Although this is a low value for an annual maximum, one even lower value was observed in the reference period.

Both the early morning temperatures and afternoon temperatures were clearly and consistently below the reference mean in summer 1816. However, the afternoon temperatures were more anomalous than the early morning temperatures. This appears more clearly in Fig. 3, which shows histograms of the anomalies with respect to the reference period for the reference period (red) and the YWS (black) for the sunrise

observation (left) and the 2 p.m. observation (right) for the summer period (June–August). The sunrise temperature was, on average, about 1.8 °C cooler than the reference. Interestingly, the distribution is quite different. Contrary to what one might expect, negative extremes were not more frequent in 1816 than in the reference, but

5 positive extremes were much less frequent in 1816. The distribution is significantly narrower for 1816 than for the reference period. In the early afternoon, the difference in the mean was much larger and amounts to about 3.8 °C cooling for 1816 relative to the reference period. In this case, the entire distribution is shifted: cold extremes were more frequent, warm extremes less frequent. From this analysis we conclude that the

10 YWS was mainly an afternoon phenomenon.

3.2 Frequency of cloud-free days and temperature anomalies

Clouds might explain the different effect found in the sunrise and the 2 p.m. temperature. Cloud cover is expected to lead to an increase of the downwelling longwave radiation during the nights and to a decrease of the incoming shortwave radiation dur-

15 ing the day. If nothing else changes, cloud cover would thus lead to warmer conditions at sunrise and colder conditions at 2 p.m. This is observed in the (short) reference period (Table 1), where overcast nights were about 2 °C warmer than clear nights, and 2 p.m. temperature were about 6 °C cooler, leading to a 8 °C change in the difference between 2 p.m. and sunrise (which for simplicity we address as diurnal temperature

20 range or DTR).

In fact, the summer of 1816 was anomalously cloudy. Not a single cloud-free day was observed in June 1816 and only 15 in the whole summer. This is much less than in the (short) reference period 1812–1821 (22 days). Conversely, the number of fully covered days was much larger in summer 1816 (21 days) than in the reference period

25 (11 days).

Similar as in the reference period, overcast days in summer 1816 were ca. 5.5 °C colder during the day and 2.5 °C warmer during the night compared to clear days (Table 1), again resulting in an 8 °C effect on DTR. However, in summer 1816 all

temperature anomalies were much more negative compared to the short reference period. Fully covered summer days in 1816 were 1.1 °C and 1.9 °C colder than the reference for sunrise and 2 p.m., respectively. Clear summer days were even 1.6 °C and 2.5 °C colder than in the reference period, for sunrise and 2 p.m., respectively.

Can the temperature anomalies be explained by cloud cover alone? Table 1 (row 5) shows estimated average temperature anomalies for summer 1816 for sunrise and 2 p.m. (for cloudy plus clear days) assuming mean values for the corresponding categories in the short reference period. These numbers can then be compared to observed anomalies (for cloudy plus clear days) in 1816. For the 2 p.m. value, the estimated anomaly is −2.16 °C compared to an observed −4.67 °C. Hence, about 50 % of the afternoon summer temperature anomalies in 1816 can be explained by a simple cloud metric. Note, however, that this only addresses cloud-free and overcast conditions and that the reference period is shorter.

3.3 Precipitation sum, frequency and intensity

The total amount of rainfall was as much as 80 % higher in summer 1816 compared to the reference period. Partitioning the precipitation sum into frequency and intensity (Fig. 4) reveals that this can be fully explained by an increase in the frequency of days with > 0.1 mm of precipitation of 80 %.

The mean rainfall intensity (8 mm per day with > 0.1 mm precipitation) was the same in summer 1816 than for the average summer of the reference period (note that within the reference period, average summer precipitation intensities vary between 4 and 12 mm d^{-1}, hence there is a considerable variation). Not only did the mean intensity not change, but we also find no evidence for changes in the distribution of precipitation intensities (Fig. 4 right). A χ^2-test (4 classes with theoretical frequencies > 5) yields a p-value of 0.96. The highest daily precipitation amount in summer 1816 was 47.5 mm, which is slightly higher than the maximum in the reference period (43 mm), but even higher values occurred in the two excluded years 1810 and 1811. The second highest amount (among 43 rainy days) was 27.2 mm. This rainfall amount corresponds

to the 96-percentile of the reference period, i.e. an excellent match. The fact that extreme precipitation events were not more frequent in 1816 than in "normal" summers contradicts to some extent the contemporary Swiss newspaper reports, which often speak about torrential rain falls and thunderstorms (see Bodenmann et al. 2011, although the reports cited therein do not specifically refer to the region of Geneva).

3.4 Frequency of weather types

For the 2 p.m. observation, we addressed the role of the mesoscale circulation by defining weather types and analyzing whether those types that typically are cold and rainy were more frequent in 1816 than in other years. Ideally, the classification should be chosen such that the classes that can be interpreted synoptically and distinguished from each other (i.e. large distance between classes in terms of mean temperature anomalies and precipitation) and at the same time have a small variability of these variables within each class. For forming classes, we confined ourselves to air pressure and wind direction because they define the atmospheric circulation most directly. Cloud cover is seen as a dependent variable and hence was not used to define weather types, especially since the time series is not homogeneous.

The wind rose already provides a classification of the wind direction into nine classes (calm, N, NE, W, SE, S, SW, W, NW). For pressure we used both the actual values as well as the tendency over the past 24 h to separate days into high, low, rising, falling, and stationary pressure (see below). The large annual variation in pressure variations made it necessary to base the classification on standardized anomalies, where annual cycles of both the mean and the standard deviation (s.d.) were computed as the first two harmonics of the corresponding data for each day-of-year from the reference period. Plotting the standardized data revealed an asymmetric distribution for pressure, but not for the pressure tendency. Hence, we considered non-symmetric thresholds in the case of pressure.

Cases with very low pressure or with very fast rising or falling pressure are often associated with the passage of a cold front. These cases show distinct temperature

and precipitation anomalies. We used thresholds of ±2.5 s.d. for the pressure tendency and a threshold of −2.5 s.d. for pressure. All days that crossed one of the three thresholds were considered as frontal passages. The other days were separated into categories low, medium, or high pressure using the thresholds −1 and +0.75 s.d.,
respectively. The category medium pressure was further subdivided into rising, stationary, and falling pressure using the thresholds ±0.2 s.d. This results in a clearly defined and small (41 cases) class representing vigorous frontal passages as well as five large classes.

Each of these five classes could be subdivided into nine subclasses according to
wind direction. However, this would result in a large number of classes, some of which represent very similar situations. We therefore combined subclasses according to the following rules: no class can have less than 30 members, classes to be combined must be neighboring (e.g. NW and W wind direction), if several options were possible, the one that produced the smallest within-class standard deviation for temperature was
chosen. Due to orographic wind channeling (see Fig. 1) SW and NW winds prevailed in all 5 pressure classes. This allows for some synoptic interpretation. For instance, high pressure with SW winds can occur with W or NW gradient wind (and correspondingly, temperatures are lower than for high pressure situation with other wind directions).

The resulting classification for the reference period is shown in Table 2. Figure 5
shows the corresponding anomalies of temperature and precipitation in the reference period. The final classification had 16 classes, with sizes between 36 ("low pressure, rest") and 222 ("high pressure, northerly wind"). Mean temperature anomalies for the classes ranged from −4.0 °C ("front") to +2.4 °C ("high pressure, rest"). Precipitation anomalies range from +3.4 mm d^{-1} ("front") to −1.8 mm d^{-1} ("high pressure, northerly
wind").

After the classification scheme was accepted, it was applied to the summer of 1816. Figure 6 shows the distribution of weather types in summer 1816 and in the reference period as a histogram. The main differences are the almost complete absence of the three high pressure situations in summer 1816 (with only one case), which in the

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reference period together account for 21 % of the days (corresponding to 20 days in an average summer). In contrast, the class "low pressure, southwesterly winds" was 3.5 times as frequent in 1816 as in the reference period. Hence, the "year without summer" of 1816 in Geneva can be explained by frequency shifts of only few weather types: an
5 absence of high pressure situation and a tripling of low-pressure situations.

Seasonal SLP reconstructions from Küttel et al. (2009) are consistent with this result. Figure 7 shows the corresponding anomalies for June-to-August with respect to the reference. A very large center with negative SLP anomalies appears over northern France. Geneva (dot in Fig. 7) was to the south of this center. This is expected from
10 an increase in low pressure situations and in situations with westerly geostrophic flow (which in Geneva could be channeled to southwesterly wind).

3.5   Contribution of weather types to temperature anomalies

How much of the afternoon cooling in summer 1816 can be reproduced from sampling corresponding weather types in the reference period? Figure 8 shows estimated
15 temperatures anomalies and precipitation sums (histograms of 10 000 repetitions) together with the actual values for summer 1816 as well as the mean values for summers in the reference period. While for temperature, the distribution is symmetric, it is slightly asymmetric for precipitation, indicating that the uncertainty is higher towards the high precipitation sums.
20 Out of 10 000 estimated 2 p.m. seasonal mean temperature anomalies, 99 % of the values are below zero (and hence below the reference period). The mean value is $-1.00\,°C$. Hence, there is no doubt that unusual weather types affected temperature in Geneva. However, the expected contribution of the weather types to the actually observed anomaly is only about one fourth. In fact, the actually observed anomaly is
25 well below the range of the Monte Carlo simulations. One might be tempted to attribute the remainder to direct volcanic effects. However, there might also be other effects that are not captured by the classification. The weather types capture an (unknown) mesoscale and not necessarily large-scale or small-scale effects.

To test this, we applied the same procedure (but now sampling only the mean values of a class) to all years in the reference period (during which no specific forcing was operating) and also to the summers of 1809, 1810, 1811, 1815, and 1817. Results are shown in Fig. 9. For temperature, there is a clear correlation between the artificial and the observed temperature anomalies that reaches 0.72 when including all years. This indicates that the not-captured part of the circulation effect on temperature correlates well with the captured part. In other words, about 50 % (in terms of variance) or 25 % (in terms of magnitude) of summer temperature anomalies can be explained by changing frequencies of weather types. The summer of 1816 lies close to a regression line drawn through the data points in the reference period (not shown). From this analysis we conclude that the temperature anomaly in Geneva in 1816 is not inconsistent with only a change in atmospheric circulation, although the uncertainty of the analysis is larger, leaving room for substantial non circulation-related cooling. At the same time, it is important to note that the temperature anomaly predicted only from the weather types is more than twice as negative as in any other case in the reference period.

We also analyzed whether or not there are significant differences between temperature anomalies in 1816 and the reference period within the same weather type. We performed the Wilcoxon rank sum test for all classes for which at least seven days were available in 1816. With one exception ("Rising pressure, northeasterly wind"), all classes exhibited a significantly lower mean temperature in 1816 compared to the reference period (Table 2). This analysis again suggests that not all of the cooling can be captured by the weather type frequencies, which can be due to an inadequate classification or a "missing" mechanism.

3.6 Contribution of weather types to precipitation anomalies

The same analyses were performed with respect to precipitation. Of the 10 000 estimated precipitation sums for summer 1816 (Fig. 8), 94 % are higher than the reference period mean. Hence, there are indications that unusual weather types contributed to

the precipitation surplus in Geneva in summer 1816, but the uncertainty is much larger than in the case of temperature. The uncertainty range includes the observed value.

Applying the procedure to all years (Fig. 9) we also find correlations between observed and predicted precipitation, but compared to the analysis for temperature correlations these are much lower and only significant for the reference period (not for the full period). Only 25 % of the interannual precipitation variability can be explained by changed weather types. The summer of 1816 falls within the relation found in the reference period and hence is not inconsistent with only a change in atmospheric circulation. However, as for temperature, it is important to note that the precipitation amount predicted for summer 1816 only from the weather types far exceeds any other value in the 1799–1821 period. The Wilcoxon test for within-class differences revealed significant differences only for one class ("front"). Hence, we have no evidence to falsify the hypothesis that the precipitation anomalies are caused by atmospheric circulation.

3.7   Contribution of weather types to cloud cover anomalies

We used the same methodology, albeit with the shorter calibration period, to estimate the fraction of cloud-free days (not shown). This variable could be well reproduced from weather types (estimated for 1816: 19.3 %, observed: 16.3 %, reference period: 25.2 %). According to the Monte Carlo simulation, the estimated fraction deviates significantly ($p < 0.01$) from the reference but not from the observed value.

4   Discussion and conclusions

We have digitized sub-daily meteorological data from the station Geneva in order to analyze the "Year Without Summer" of 1816. We chose a sub-period of the record which was found to be homogeneous after the correction of one (known) error. Comparing the YWS 1816 to the remainder of that period (1799–1821) reveals that the coldness of the summer 1816 was most prominent in the afternoon. The entire temperature

distribution function was shifted by almost 4 °C towards lower values with no apparent change in variability. In contrast, early morning temperatures show a significant decrease in the variability, but no changes in negative extremes and a smaller change for the mean.

5   Possible causes for changes between 1816 and the reference period include direct radiative changes (due to volcanic aerosols or clouds), changes in the mesoscale circulation (e.g. the frequency of weather types), and changes in the large-scale climate system (e.g. a cooling of the oceans). The mechanisms are not independent and hence hardly separable. Although an attribution of the causes is not possible using only ob-
10 servational data, they still provide interesting insights which, if well characterized, can be used in model comparisons.

    Analyzing cloud information suggests that an increase in cloud cover was mainly responsible for time-of-day characteristics of the temperature change. But what changed the clouds? A simple weather type classification (according to pressure, pressure
15 tendency, and wind direction) well explains the changes in cloud cover. About one fourth of the deviation in the seasonal mean afternoon temperature can be explained by changes in weather type (i.e. the mesoscale circulation). Although this may seem a small fraction, it corresponds exactly to the expected fraction of explained variance for any anomalous year. Importantly, the amount of weather-type-related cooling was
20 much larger than in other years and the within-type differences of afternoon temperature were significant in most cases. For precipitation, our analysis shows that the 80 % increase in summer precipitation can be explained solely by a higher frequency of precipitation, while no change could be found in the 24-h intensity of precipitation (including the occurrence of extremes).

25 In all, the results show that the year without summer was not characterized by extreme weather (the tails of the distributions did not change much except for cold afternoons), but extreme climate (i.e. the statistics of weather types changed). The analysis shows that the local-to-regional circulation plays a dominant role in that all climatic anomalies are statistically consistent with only a change in circulation. Historical

analyses show that in Switzerland, strong tropical volcanic eruptions are often followed by a "Year Without Summer" with very similar weather as in the summer of 1816 (Pfister, 1999; Fischer et al. 2007), suggesting a mechanism linking tropical volcanic forcing to persistent regional circulation and cloud cover anomalies over Western Europe in summer.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/7/3745/2011/cpd-7-3745-2011-supplement.zip.

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Table 1. Effect of clouds on temperature. Averaged summertime (June–August) temperature anomalies (˚C) at sunrise and at 2 p.m. as well as their difference (diurnal temperature range, DTR) for days with clear sky (both sunrise and 2 p.m.) or fully overcast days (both sunrise and 2 p.m.) during a short reference period (1812–1814 and 1818–1821, i.e. the period with relatively reliable cloud observations) and in summer 1816. Row 5 shows the average temperature anomaly for the sum of overcast and clear days for 1816 assuming the mean values from the short reference in the first two rows and the number of fully overcast days (21) and fully clear days (15) from 1816. Row 6 is the same but using the mean values from the year 1816 itself. The lowest row shows the difference between the two. All temperature anomalies are with respect to the long reference period.

period	sky	sunrise	2 p.m.	DTR
short reference	overcast	0.22	−5.06	−5.28
short reference	clear	−1.77	1.04	2.81
1816	overcast	−0.92	−6.96	−6.05
1816	clear	−3.40	−1.47	1.93
1816 estimated from short reference	overcast + clear	−0.61	−2.52	−1.91
1816 observed	overcast + clear	−1.95	−4.67	−2.72
difference	overcast + clear	−1.34	−2.16	−0.82

Table 2. Weather type classification. Note that days classified as "fronts" could theoretically also fit in other categories, but were attributed to "front" (in practice this occurred only rarely). The last column indicates whether significant ($p < 0.05$) differences were found within this weather type between 1816 and the reference period according to a Wilcoxon test (y = yes, n = no, − = not enough cases).

Class	p	dp/dt	wind	Sig.
Front	$x < -2.5$ or:	$x < -2.5$ or $x > 2.5$		y
High pressure, northerly wind	$x > 0.75$		NW, N, NE	−
High pressure, southwesterly wind	$x > 0.75$		SW	−
High pressure, rest	$x > 0.75$		Rest	−
Low pressure, northerly wind	$-2.5 < x < -1$		NW, N, NE	y
Low pressure, southwesterly wind	$-2.5 < x < -1$		SW	y
Low pressure, rest	$-2.5 < x < -1$		Rest	−
Rising pressure, northerly wind	$-1 < x < 0.75$	$x > 0.2$	N	−
Rising pressure, northeasterly wind	$-1 < x < 0.75$	$x > 0.2$	NE	n
Rising pressure, southwesterly wind	$-1 < x < 0.75$	$x > 0.2$	SW	y
Rising pressure, rest	$-1 < x < 0.75$	$x > 0.2$	Rest	−
Falling or stationary pressure, northerly wind	$-1 < x < 0.75$	$x < 0.2$	N	−
Falling or stationary pressure, northeasterly wind	$-1 < x < 0.75$	$x < 0.2$	NE	y
Stationary pressure, southwesterly wind	$-1 < x < 0.75$	$-0.2 < x < 0.2$	SW	−
Falling pressure, southwesterly wind	$-1 < x < 0.75$	$x < -0.2$	SW	−
Falling or stationary pressure, rest	$-1 < x < 0.75$	$x < 0.2$	E, SE, S, W, NW, calm	−
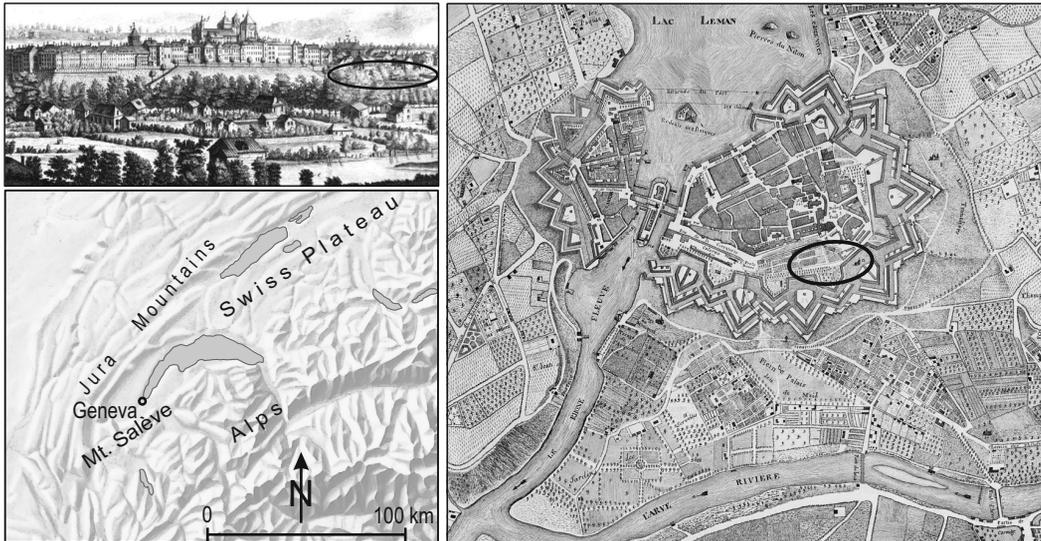
Fig. 1. Approximate location of the weather station of Geneva in 1799–1821 in a contemporary view (top left) and map (right) of the city. The bottom left figure shows the topography of the region (relief: Eidgenössische Erziehungsdirektorenkonferenz).
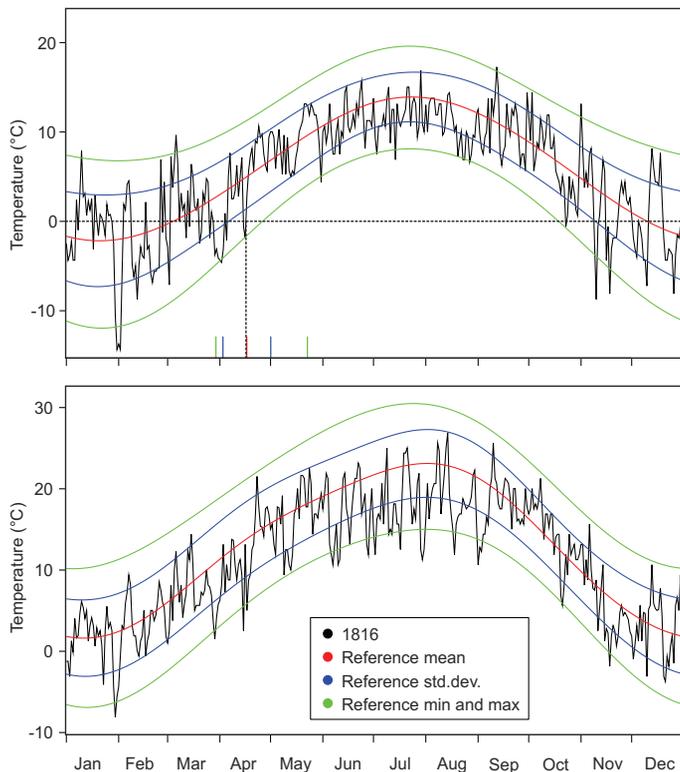
Fig. 2. Time series of daily values of temperature at sunrise (top) and 2 p.m. (bottom) in the year 1816 (black) as well as for the average of the reference period (red). The green lines denote ±1 standard deviation from the mean, the blue lines give the minima and maxima for the reference period. Note that all annual cycles from the reference period were obtained from the statistics for each calendar day. They were then smoothed by fitting the first two harmonics of the annual cycle.
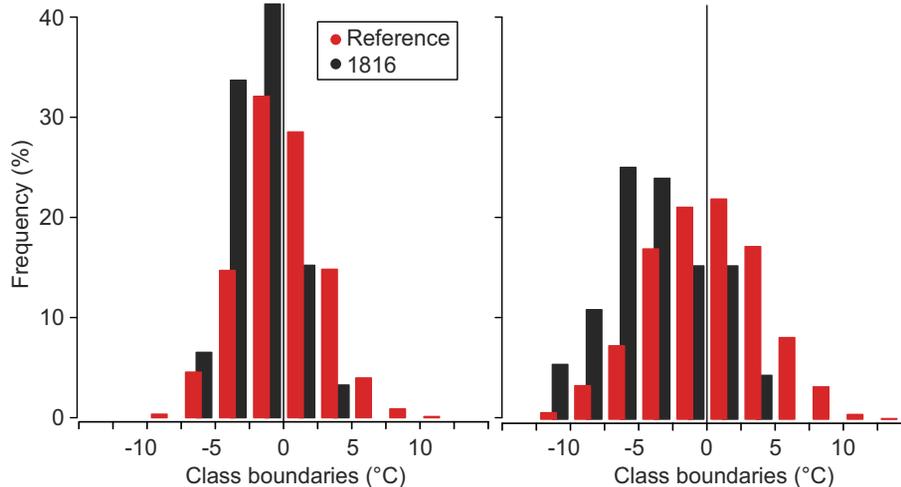
Fig. 3. Histograms showing the frequencies of occurrence (in percent) of temperature anomalies at sunrise (left) or 2 p.m. (right) in the summer months (June to August) of 1816 (black) and in the reference period (red).
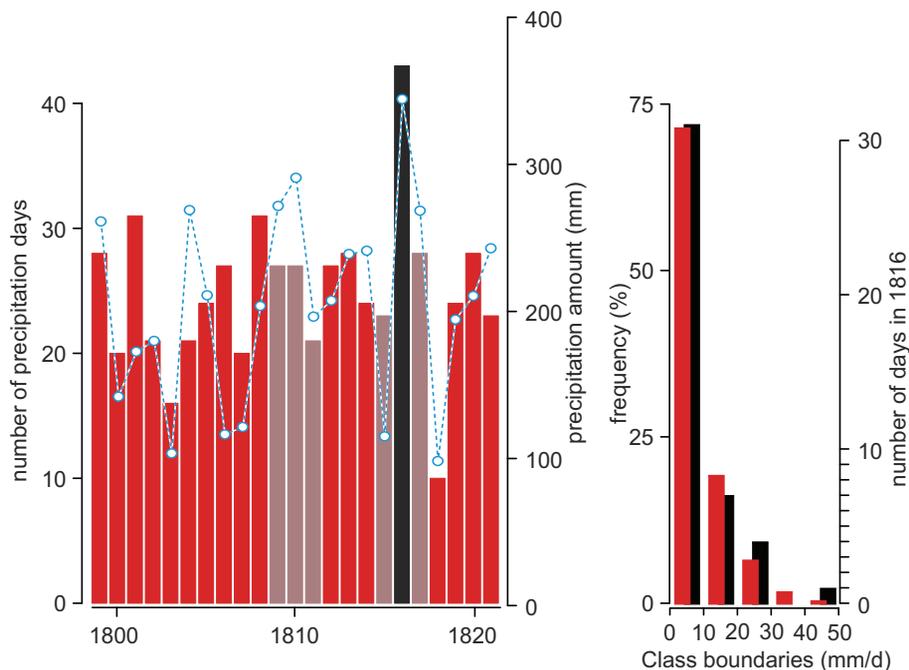
Fig. 4. (left) Precipitation sums (blue line, right scale) and number of rainy days (bars, left scale) in summer (June to August) from 1799–1821. The years that were excluded from the reference period are shown in grey, 1816 in black. (right) Histogram showing the frequency of occurrence (left scale: percent, right scale: number of days for 1816) of precipitation amounts in the summer months (June to August) of 1816 (black) and in the reference period (red). Note that precipitation amounts < 0.1 mm were excluded.
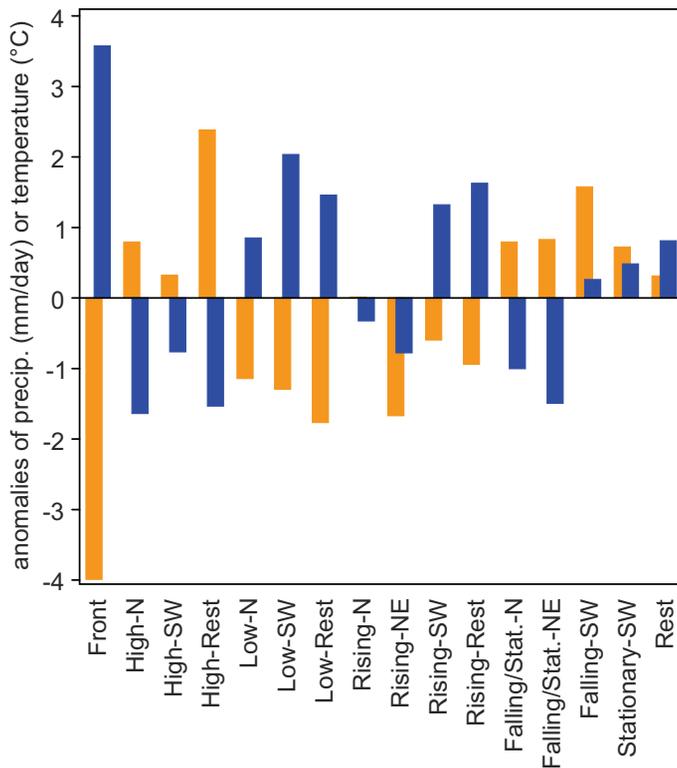
Fig. 5. Temperature anomalies (orange) and precipitation (blue) averaged for each weather type for the summer months (June to August) in the reference period. Note that for visualization purposes, precipitation is plotted as anomalies from the seasonal mean whereas the sampling operates with absolute values.

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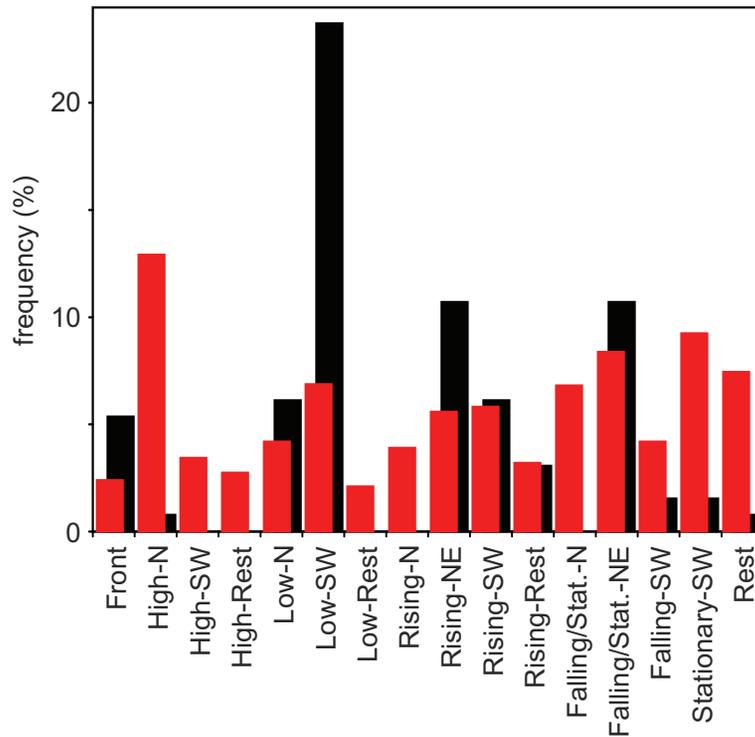
Fig. 6. Histogram showing the frequency of occurrence (percent) of weather types in the summer months (June to August) of 1816 (black) and in the reference period (red).

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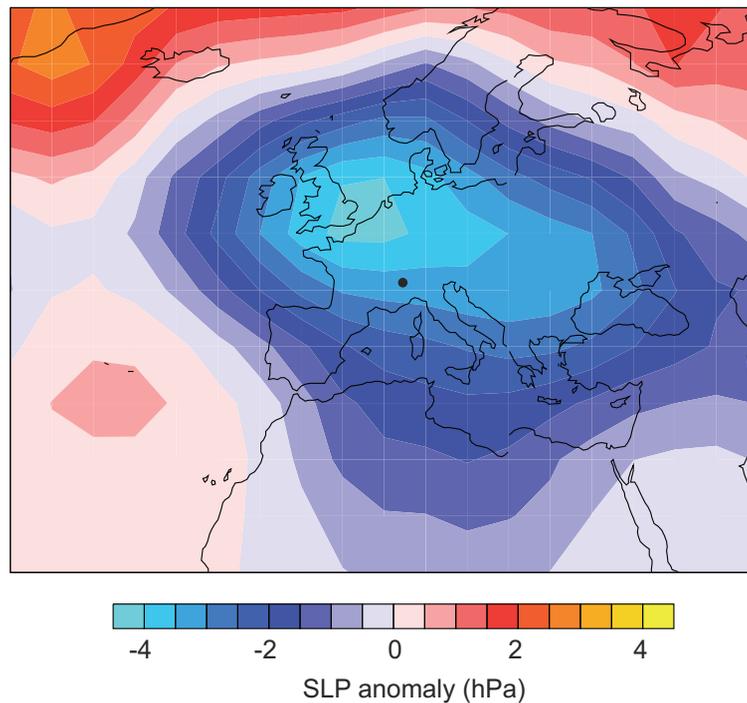
Fig. 7. SLP anomaly for summer (June to August) 1816 with respect to the reference period. The dot marks the location of Geneva.
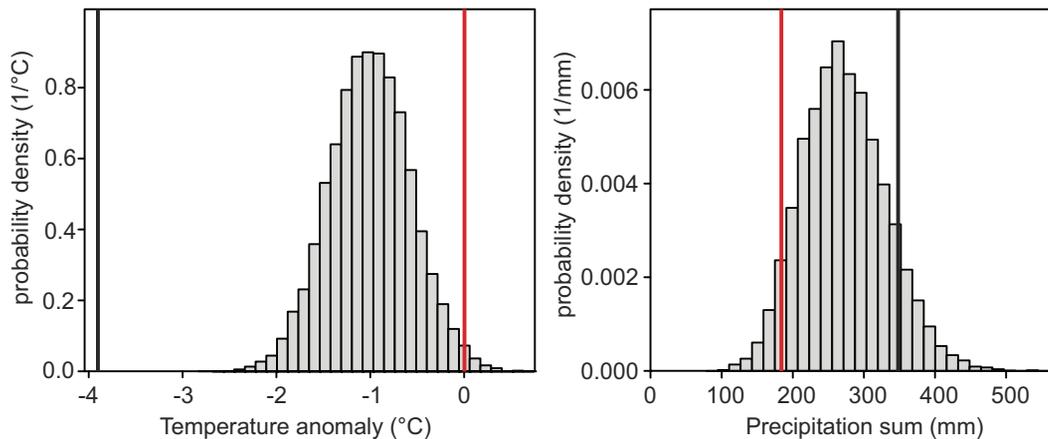
Fig. 8. Histogram showing 10 000 artificial temperature anomaly averages (left) and precipitation sums (right) for the summer of 1816 based on weather types for 1816 and sampling from these weather types in the reference period. The black and red lines denote the observed values for the year 1816 and the reference period, respectively.
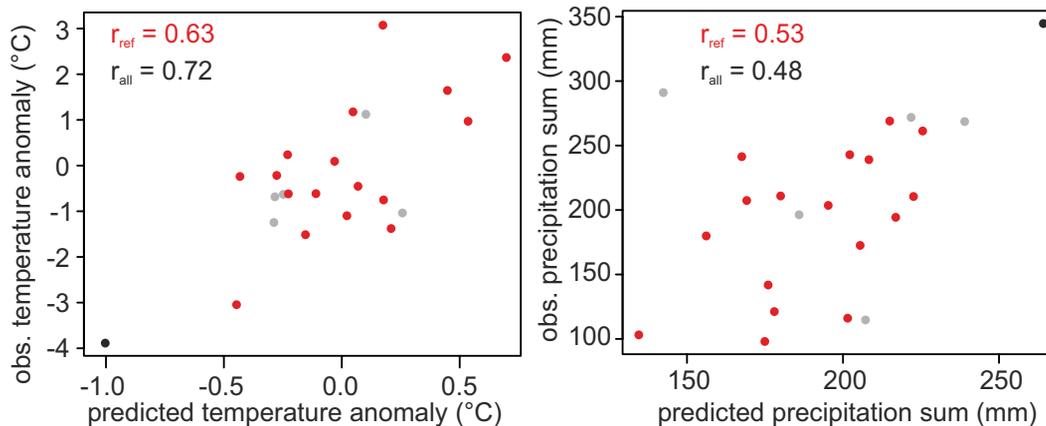
Fig. 9. Scatter plot showing the observed temperature anomalies (left) and precipitation sums (right) as a function of their predicted values based only on the weather types information. The years in the reference period are indicated in red, the years that were excluded from the reference period are shown in grey, 1816 in black. Correlation coefficients are shown for only the reference period (red number) and all years (black number).

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