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The year-long unprecedented European heat and drought of 1540 – a worst case

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Abstract The heat waves of 2003 in Western Europe and 2010 in Russia, commonly labelled as rare climatic anomalies outside of previous experience, are often taken as harbingers of more frequent extremes in the global warming-influenced future. However, a recent

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reconstruction of spring–summer temperatures for WE resulted in the likelihood of significantly higher temperatures in 1540. In order to check the plausibility of this result we

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investigated the severity of the 1540 drought by putting forward the argument of the known soil desiccation-temperature feedback. Based on more than 300 first-hand documentary

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weather report sources originating from an area of 2 to 3 million km^2, we show that Europe was affected by an unprecedented 11-month-long Megadrought. The estimated number of precipitation days and precipitation amount for Central and Western Europe in 1540 is significantly lower than the 100-year minima of the instrumental measurement period for spring, summer and autumn. This result is supported by independent documentary evidence about extremely low river flows and Europe-wide wild-, forest- and settlement fires. We found that an event of this severity cannot be simulated by state-of-the-art climate models.

1 Introduction

The need for climate change information at the regional to local scale is one of the key issues within the global change debate. Such information is necessary in order to assess the impacts of climate change on human and natural systems and to develop suitable adaptation and mitigation strategies at the national level (Giorgi et al. 2009). Knowledge of past climatic extremes is a research priority to derive predictive points of reference for adaptation and loss reduction (Ciscar et al. 2012). In view of global warming (GW) it is predicted that heat waves in the future will be more intense, more frequent and longer lasting (Meehl and Tebaldi 2004; Seneviratne et al. 2012; Collins et al. 2013). Observational evidence indeed provides some support for an increasing frequency of hot extremes across the globe (Alexander et al. 2006; Hansen et al. 2012; Donat et al. 2013; Hartmann et al. 2013), contributing to the likelihood of extreme heat waves such as those in 2003 (Europe) and 2010 (western Russia) (Barriopedro et al. 2011). For Europe, the hot summer of 2003 is usually taken as a benchmark for GW-related extremes. For a review of the 2003 heat wave the reader is referred to García-Herrera et al. (2010). In a previous study Wetter and Pfister (2013) demonstrated from a long series of grape harvest dates (AD 1444–2011) that April–July (AMJJ) temperatures in 1540 both in France and Switzerland were likely significantly warmer than in 2003. Considering the significance of soil moisture deficits for the generation of record-breaking heat waves (e.g. Seneviratne et al. 2010; Mueller and Seneviratne 2012), estimates of seasonal precipitation are needed to validate and find the plausibility of the duration and magnitude of the record-breaking heat wave temperatures in 1540. Extreme droughts over recent centuries were analysed for the Czech Lands (Brázdil et al. 2013a) and for Switzerland (BUWAL 2004). Several authors have claimed that the drought of 1540 was outstanding (Pfister 1984; Pfister 1999; Glaser et al. 1999; Brázdil et al. 2013a). Casty et al. (2005) concluded that the years 1540, 1921 and 2003 were very likely to have been the driest in the context of the past 500 years in the Greater Alpine area. In the Czech Lands 1540 was the driest year and the driest summer season in the past 500 years (Dobrovolný et al. 2014).

In this paper we confirm these findings in a larger, European context. This paper is organised as follows: section two presents the methodology to reconstruct the variability and number of days with precipitation (NPD) as well as the seasonal and annual precipitation amount (PA) for 1540. Reconstruction results and the assessment of return periods of similar drought events to 1540 are presented in the third section. In the discussion widespread documentary evidence about the 1540 drought is presented to highlight the quantitative reconstruction results with more qualitative evidence. Conclusions are drawn in the final section.

2 Methodology

2.1 Reconstruction of number of days with precipitation in 1540

Written archives offer a broad spectrum of evidence on past weather, climate and their agricultural and societal impacts (Brázdil et al. 2010). In contrast to documentary evidence, proxy data from natural archives usually do not have an adequate resolution to unravel the heat and drought effects in mid-latitude warm extremes (Wetter and Pfister 2013). Chroniclers were mainly motivated by concerns about the human and environmental impacts of extreme events, which were thus extensively described (Pfister and Brázdil 1999). Here we address the intensity, persistence and impact of the 1540 drought using more than 300 documentary sources of weather reports, originating from Austria, Belgium, the Czech Republic, England, France, Germany, Hungary, Italy, the Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Spain, Sweden and Switzerland, that collectively represent an area of 2 to 3 million km^2 (Fig. 1; Supplementary Information, Table S1).

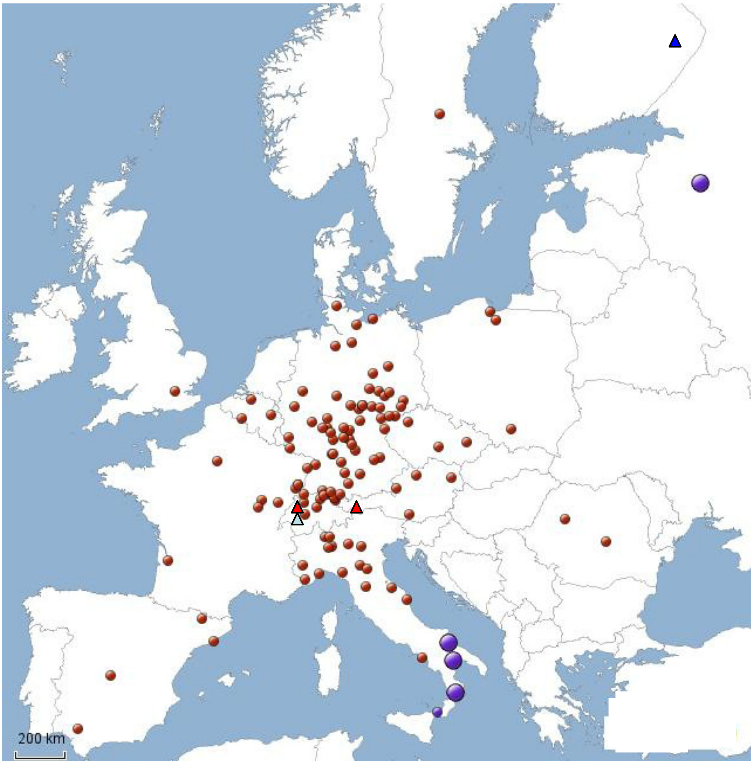

Fig. 1 Spatial distribution of 1540 documentary data related to the occurrence of drought. Dots: documentary data evidence (chronicler reports, official letters, rogation ceremonies for rain etc.) of drought (*red*) and abundance of precipitation (blue; in southern Italy the abundance of precipitation was only during spring). Triangles: red = warm anomaly; light blue = cold anomaly; blue = wet anomaly. Original documentary data plotted on the maps are found in Supplementary Information, Table S1)

Many chroniclers reported the date of rain spells and the quasi-rainless period in between as a proxy for drought severity. For 1540 they not only specified when but also in some cases how long and how intensively it rained, which provides an acceptable basis for assessing the number of precipitation days (NPD). In the absence of measured precipitation (P) for 1540 we collected such qualitative rainfall observations made by four chroniclers from Switzerland (situated in Basel, Zürich, Lucerne and Winterthur) and neighbouring Alsace (France) who kept track of the duration and yield of precipitation events. Regarding east central Europe, reliable data on precipitation frequency was obtained from the only weather diary so far known in Europe, kept by Marcin Biem, a theologian and president of the Cracow University (Supplementary Information, Table S1, section Poland, source 1). NPD and the temporal arrangement of precipitation days are shown in Table S2 (Supplementary Information, Table S2). Before the NPD were used for PA reconstruction the data was transformed from Julian to Gregorian calendar style.

2.2 Reconstructed precipitation amount

We estimated the amount of P (in mm) depending on the observed NPD through a hierarchy of statistical models (Tingley et al. 2012). These models are derived by analysing recent meteorological data from Cracow, Poland as well as four Swiss cities: Basel, Zürich, Lucerne and Schaffhausen. We consider these to be representative of the observation locations of the early chroniclers mentioned before. Preliminary analysis of the recent data shows different behaviour for the seasonal cycle of the precipitation (Supplementary Information, Fig. S1). While for Switzerland the seasonality is mostly determined by NPD, in Poland the seasonality is expressed in the dependence of monthly P on NPD. This can be interpreted as a strong shift in precipitation source – convective in summer versus frontal precipitation in spring and autumn. The model thus needs to be able to reflect not only the dependence on NPD, but additionally a possible seasonality factor. Moreover, when calculating averages over a number of stations, the fact that amount and NPD differ from place to place needs to be taken into account. For Switzerland, the reconstruction is based on observations at several locations and targets an area average, using the four Swiss stations in the instrumental period. Thus, a model needs to be introduced that first uses the NPD observed to estimate the NPD at the station sites and then uses the stochastic model to calculate the amount of precipitation. The full model is described in the supplementary information (Supplementary Information, Model). The model parameters are estimated through Bayesian inference (Gelman et al. 2003), using the data from the instrumental period. The results for the estimated parameters are shown in Fig. S2 (Supplementary Information, Fig. S2). As noted above, the shape is mostly independent of the season, while the scale parameter determining the centre of mass depends (mostly linearly) on NPD, as well as the season. We reconstruct P by drawing from this statistical model (the distribution), using the distribution of parameters derived in the inference step. For Poland (Cracow) we hold NPD to be the documented data of 1540. For Switzerland, we take the documented values and then create draws for NPD at the four stations to account for the possible differences over the area of study. Note that while there are some months with no observed precipitation, our model does not deny the possibility of precipitation at some location close by, leading to a higher spread of estimates for the area averaged precipitation compared to a reconstruction taking the NPD to be equal to the observed number and a larger uncertainty for Swiss P. See also Fig. S3 (Supplementary Information Fig. S3), showing the dependence of NPD at Basel, Lucerne and Schaffhausen during the instrumental period.

3 Results

The reconstructed NPD for Switzerland and Poland (Cracow) was considerably lower than that of the twentieth-century average and even below the absolute minima of the instrumental period in spring, summer and autumn. Data for January 1540 in Switzerland are not available. Thus the twentieth-century average of 10 precipitation days for January was included to calculate the annual NPD. The NPD obtained in this way is 81 % below the twentieth-century average and even 40 % below the driest year since 1864 (Supplementary Information Table S3). This result fits closely to a documentary-based precipitation reconstruction for 1540 in the Czech Lands that results in a deficit of more than 270 mm compared to the 1961–1990 mean (Brázdil et al. 2013b). The results of the reconstructed PA for Poland (Cracow) and Switzerland, averaged over the locations of Basel, Zürich, Schaffhausen and Lucerne, are displayed in Fig. 2a.

The median of P and associated 50 % and 95 % confidence intervals are shown as boxes and whiskers. The 50- and 100-year minimum PA based on instrumental data for 1901–2000 are presented (squares and triangles) to highlight the severity of the record-breaking anomaly. We conclude from Fig. 2a that PA in Switzerland remained significantly below 100-year minimum levels in 1540 throughout spring (MAM), summer (JJA) and autumn (SON). No similar event is documented within the instrumental period since 1864. In Poland the drought likewise persisted over three seasons, but it was less severe, as precipitation was possibly above the 100-year minimum (including upper uncertainty amounts). It has to be pointed out

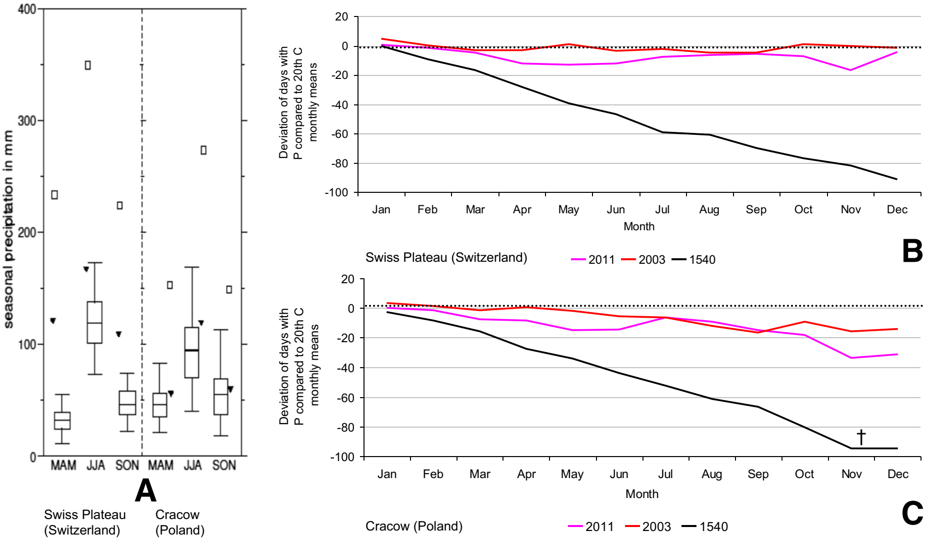

Fig. 2 Reconstructed seasonal precipitation amounts for spring, summer and autumn and cumulative deviations of 1540 NPD compared to the 20th-century mean, 2011 and 2003 .**a**: Median, upper and lower quartiles (*boxes*), 95 % uncertainties (whiskers) as well as 50 and 100 year minimum levels (*box and triangle*) of 20th century data for Swiss Plateau (northern Switzerland) average (*left*) and Cracow (*right*), **b**: compares cumulative deviations of NPD in Northern Switzerland in 2011, 2003 and 1540. NPD for 2003 and 2011 are taken from Federal Office of Meteorology and Climatology, MeteoSwiss (NPD were averaged over stations of Basel, Luzern, Schaffhausen and Zürich). Dotted line=20th-century mean of days with Precipitation≥1 mm, **c**: compares cumulative deviations of NPD in Cracow, Poland in 2011, 2003 and 1540. NPD for 2003 and 2011 are taken from the Center for Poland's Climate Monitoring. Dotted line=20th-century mean of days with Precipitation≥1 mm; † date of death of Marcin Biem: 19th Nov 1540

here that our PA estimates for Cracow are more conservative than the estimates from Limanówka (2001) (Supplementary Information, Table S4). Soil desiccation is a well-known driver for heat extremes in many regions of the world (Seneviratne et al. 2006; Hirschi et al. 2011; Mueller and Seneviratne 2012). It was also key in the sequence of events that drove the extreme 2003 heat wave (Ferranti and Viterbo 2006; Fischer et al. 2007; Jaeger and Seneviratne 2011). Evaporation uses more than half of the total net radiation at the land surface (e.g. Trenberth et al. 2009). If this latent energy flux is strongly reduced due to the lack of soil moisture (SM) availability, the sensible heat component of the land energy budget is increased, leading to higher air temperatures (Seneviratne et al. 2010). Moreover, SM displays memory effects with time scales up to several months (Vinnikov and Yeserkepova 1991; Koster and Suarez 2001; Orth and Seneviratne 2012), which in turn contribute to increased heat wave persistence (Lorenz et al. 2010). Sensitivity experiments suggest that the inter-annual variability of SM is the largest contributor to the persistence and intensity of heat waves (Jaeger and Seneviratne 2011). In the absence of SM feedbacks, summer 2003 would still have been warm, but it would have likely not been such a devastating event as it turned out to be (Fischer et al. 2007; Jaeger and Seneviratne 2011). In order to get a proxy for the degree of soil desiccation in 1540, we computed cumulative NPD anomalies from the 1901–2000 average of known drought years in the instrumental period for both Switzerland and Poland (Cracow) (Fig. 2b, c). In contrast to the recent droughts in 2011 and 2003, the 1540 drought was significantly more persistent and extreme in any single month except January, thus resulting in a severe annual NPD deficit.

To gain an insight into the extreme character of the 1540 drought, we have analysed the global simulation of six models conducted within the Climate Model Intercomparison Project Phase 5 (CMIP5) over the period 850 AD to 2005, driven by estimations of past atmospheric greenhouse trace gas concentrations, volcanism and variations in solar activity (Schmidt et al. 2011). These simulations are extended up to 2100, with forcing by the most extreme scenario of anthropogenic greenhouse gas concentrations (Representative Concentration Path scenario 8.5; Moss et al. 2010; Supplementary Information, Fig. S4). None of the six models simulates a succession of severe drought in spring, summer and autumn. Climate models simulate 1540-like years in the past millennium only if the seasonal precipitation thresholds are set 50 % higher than the 1850–2005 minima, whereas seasonal precipitation thresholds of the 2006–2100 period need to be raised by 30 %. This result may indicate that either the extreme character and thus low probability of occurrence of 1540-like droughts would require a larger simulation ensemble to produce one single drought year, or that models cannot simulate such extreme events with a reliable degree of probability.

4 Discussion

Several kinds of drought can be distinguished (Heim 2002; Tallaksen and van Lanen 2004; Seneviratne et al. 2012). The primary cause of a drought is the lack of precipitation over a large area and for an extensive period of time (i.e. meteorological drought). This water deficit propagates through the hydrological cycle and, together with evapotranspiration anomalies (e.g. Seneviratne et al. 2012; Sheffield et al. 2012), gives rise to different types of droughts. Hydrological drought is associated with precipitation shortfall on surface or subsurface water availability (i.e. streamflow, lake levels and groundwater). The term agricultural drought or soil moisture drought is used when soil moisture is insufficient to support crops (Seneviratne et al. 2012). Human impacts of drought are defined as socio-economic drought (Heim 2002; Tallaksen and van Lanen 2004). In the following sub-chapters we will unfold the 1540 drought event in a more qualitative way by highlighting the quantitative reconstruction results with selected and typical examples of the information included in the documentary evidence about the above-mentioned different basic drought types of the perennial drought in 1540 (Mishra and Singh 2010).

4.1 Meteorological drought

Previous studies have shown that late twentieth-century summertime heat and drought waves in Western Europe were often preceded by winter and spring rainfall deficits in Southern Europe (Vautard et al. 2007; Zampieri et al. 2009; Quesada et al. 2012; Stefanon et al. 2012). This kind of propagation pattern seems also to have prevailed in the case of the 1540 drought. According to chroniclers from Northern Italy, winter was "like in July" (Supplementary Information, Table S1, section Italy, source 3), with no rain falling from November 1539 to mid-April 1540 (Supplementary Information, Table S1, section Italy, source 1). Likewise, rogations for rain were held in October 1539 and March 1540 in Spain (Supplementary Information, Table S1, section Spain, sources 2 and 10). From a documentary data-based temperature reconstruction for Central Europe (Dobrovolný et al. 2010) it is concluded that the 1540 drought was the climax of a decade-long summer warming trend bearing comparison with that seen in the 1990s (Supplementary Information, Fig. S5). The summer of 1540, as the reconstruction by Jacobeit et al. (1999) illustrates, was characterised by a persistent diagonal south-west to north-east oriented blocking ridge of high pressure over continental Europe connected to the Azores High. The spatial distribution of drought and precipitation records indeed suggest that 1540 was dominated by a quasi-persistent high-pressure situation over Western and Central Europe surrounded by low pressure systems over the Atlantic and Western Russia. According to this meteorological situation, a multi-seasonal cold and wet spell likely should have prevailed in the region east of the anticyclone. Indeed, the famous chronicle of Novgorod (Western Russia) reports that "Springtime was cold and during all summer there were floods, and the rye did not grow and was frozen in spring, and all the meadows at the banks of the rivers and lakes were flooded […] In autumn there was a lot of rain, and the sun was not seen for 2 weeks until the eve before Filippov [15th November]" (Supplementary Information, Table 1, section Russia, source 1). Likewise, a dendroclimatic (TRW) series of drought-sensitive Scots pine (*Pinus sylvestris* L.) from south-eastern Finland indicates abundant (81 % percentile) precipitation in this year (Helama et al. 2009). In analogy to 2003, Switzerland was likely in the centre of the anomaly in 1540 (García-Herrera et al. 2010). Hans Stolz, a vinegrower and mayor of the small town of Guebwiller in neighbouring Alsace described in his chronicle using the customary Julian style that "February was warm and dry and … it only rained during the first three days in March but never snowed or rained in April. May was sunny and dry throughout. June was also dry, but it rained repeatedly in the end, but not much. July was torrid and dreadful until the end" (Supplementary Information, Table S1, section Switzerland, source 9; Fig. S6). Fridolin Ryff in Basel (Switzerland) counted three "short and feeble" rain spells between the "beginning of summer" and St. Martins Day (21st November), each lasting not more than two or three days (Supplementary Information, Table S1, section Switzerland, source 8). Heinrich Bullinger in Zürich insisted that it never rained for an entire day or an entire night between February and 29th September (Supplementary Information, Table S1, section Switzerland, source 23). Oeno-phenological proxy evidence suggests that August and September temperatures were likely at the same level as in 2003 (Wetter and Pfister 2013). Coherent narrative reports by independent contemporary chroniclers indicate that, unlike in 2003, the weather in the following months (October–December) was sunny and warm "like in April" until the end of the year, without any frost or snow (Brázdil et al. 2013a; Wetter and Pfister 2013).

4.2 Hydrological drought

Chronicler reports about the extremely low level of major water bodies confirm the record-breaking precipitation deficits assessed for Western and Central Europe (Fig. 3a).

Lake Constance, the second largest lake in Western Europe, dropped to such a low level in August 1540 that the lake floor, with its mountains and valleys, emerged close to the surface and the island of Lindau was connected to the coast so that people could walk around it (Supplementary Information, Table S1, section Germany II, source 4). This stage is close to the lowest recorded in the driest winters since 1550 (Pfister et al. 2006). It should be pointed out that winter low water levels of Lake Constance are comparatively common, because in this season precipitation, especially at higher altitudes, falls as snow. Melting of the stored winter snow in spring and early summer usually fills the lakes at the foothills of the Alps, so that the extreme late summer low water level in 1540, also considering the summer precipitation maximum in the Alps, was indeed a record-breaking event. Chroniclers described low water levels of rivers all over Western and Central Europe (Fig. 3a). Major rivers, such as the Rhine, Elbe and Seine, could be waded through in some places (Supplementary Information, Table S1, section Germany I, source 86 and section Netherlands and Belgium, source 6). Often, like in Basel, Collogne or Meissen, the descriptive information of low water levels is given with such a degree of accuracy that the rivers' low water level discharges can be reconstructed. In these cases they result, based on independent and different reconstruction and assessment methodologies, in only 10 % of the average instrumental period summer half-year discharge of each location (independent expertise according to methodologies by Herget and Meurs 2010; Wetter et al. 2011 and Prof. Dr. Uwe Grünewald; personal communication). In comparison, the discharge deficit of major German rivers in the hydrological summer half-year 2003 was only −47 % for the Elbe and −37 % for the Rhine (Bundesanstalt für Gewässerkunde 2006). Several chroniclers report that brooks and wells in 1540 dried out from late spring, including those that had never previously failed. Hans Salat reports that in the Swiss Plateau region this happened in July which suggests a substantial drop in groundwater levels. Digging for water more than 1.5 m deep in the dried-out bed of a small river in Canton Lucerne (Switzerland), did not yield a drop (Supplementary Information, Table S1, section Switzerland, source 5). Unlike in 2003, no thunderstorm was observed in summer 1540 (Supplementary Information, Table S1, section

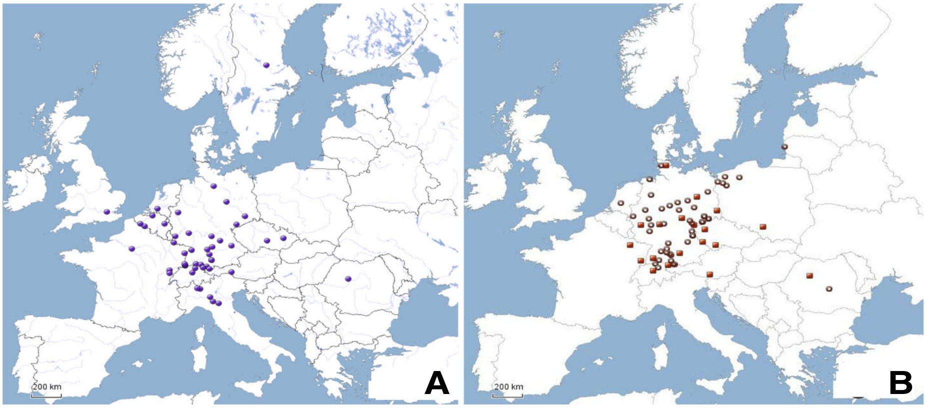

Fig. 3 Documentary evidence on low levels of rivers and lakes (**a**) and wild-, forest- (*squares*) and settlement fires (*circles*) (**b**) during the drought and heat wave in 1540. Original documentary data plotted on the maps are found in Supplementary Information, Table S1)

Switzerland, source 9). The Lucerne botanist, meteorologist and politician Renward Cysat emphasises in this context that Alpine meadows were literally "irrigated" every morning by abundant dew, possibly generated by the intensive evaporation of firn fields and glaciers during the day which, at that time, were in their advanced "Little Ice Age" position (Supplementary Information, Table S1, section Switzerland, source 22).

4.3 Agricultural drought and soil desiccation

Visual observations of extreme soil desiccation and soil cracking (Supplementary Information, Table S1, section Switzerland, source 22) confirm the hypothesis of a record-breaking soil moisture deficit in 1540. Some cracks were so wide that people could put their feet into them (Supplementary Information, Table S1, section Switzerland, source 20). The severity of the agricultural drought in 1540 may be assessed from the many reports describing acute feed and water shortages for cattle and dried-out vegetable gardens. Moreover, trees and vines suffered from drought stress. Pierre de Teysseulh, a capitular of the church of Limoges (central France), notes that "the grapes were like roasted and the leaves of the vines had fallen to the ground like after a severe frost" (Supplementary Information, Table S1, section France, source 20). Trees responded inconsistently to the record-breaking conditions, according to Battipaglia et al. (2010). In the MXD series of Norway spruce (*Picea abies*) from Tyrol (Esper et al. 2007; Battipaglia et al. 2010) the value for 1540 is extremely high, as in the *Picea abies* series from Lauenen (Bernese Oberland) (Schweingruber et al. 1988), both signifying warm conditions. According to chronicler Sebastian Fischer from Ulm (south Germany), leaves on the trees withered [at the peak of the worst heat wave] in early August and fell to the ground "as if it had been in late autumn." (Supplementary Information, Table S1, section Germany I, source 31). Drought effects may thus probably be the reason why tree-rings from Lötschental (Canton Valais in Switzerland) fail to indicate the record-breaking heat in 1540 (Büntgen et al. 2006; Fig. 1). Could it be that the Larch trees situated in the rain shadow of the Alps prematurely lost their needles under extreme drought stress like the leaf trees did in the plain? Likewise, 1540 does not stand out in the long silver fir (*Abies alba)* TRW chronology in southern Moravia which serves as an indicator for March to July precipitation (Brázdil et al. 2002). Finally, TRW extremes sometimes lag the responsible weather patterns by one or more years, such as for instance in AD 1541, when a large-scale growth depression lagged the extremely warm and dry climatic conditions of 1540. This response shift is well in line with the high first-order auto-correlative structure of the fir TRW data (Büntgen et al. 2011). Wetter and Pfister (2013) demonstrated that the reliability of proxies from the natural archives, such as grape harvest dates, may significantly fail, especially when dealing with climatic extreme events. The same caution, as we tried to demonstrate above, seems to be necessary when dealing with extremes based on tree ring reconstructions (TRW/MXD). Thus, extreme events indicated by proxies of the natural archives always should be double checked in the overlapping period with the evidence in the archives of society (approx. AD 1200 –present), which is usually very rich and most detailed in the case of such events.

4.4 Socio-economic drought

Cattle breeding, water power production (water mills) and water-based transportation suffered in particular. Countless domestic animals died from thirst, hunger or heat-stroke. Grain and wine harvests, both being heat and drought-resistant crops, were abundant, but the collapse of water power for mills led to skyrocketing prices for flour and bread (Supplementary Information, Table S1, section Switzerland, source 1). Navigation became difficult or impossible even on major rivers (Supplementary Information, Table S1, section Italy, source 12). The outstanding persistence and severity of heat and drought is further documented by a continent-wide outbreak of devastating wildfires in summer-wet Europe that is unique within the last 500 years (Pfister, in review). Likewise, town fires in Germany were more frequent in 1540 than in any other peace-time year since AD 1000 (Zwierlein 2011; Fig. 3b). Note that forest fires often start and grow at the time of maximum heat and drought stress (Verdú et al. 2012). In Portugal, temperatures of more than 40° C were measured during the peak of the heat wave in 2003, when large-scale forest fires broke out (Trigo et al. 2006). Similar high temperatures likely occurred during the heat wave in 1540 (Wetter and Pfister 2013). The continent was inundated from forest fire aerosols. Chroniclers Salat in Lucerne and Biem in Cracow noticed that the sky was filled with smoke so that the sun and the moon, looking reddish at their rising and setting, were shining pale (Supplementary Information, Table S1, section Switzerland, source 5 and section Poland, source 1). With regard to the vulnerability of present-day societies to extreme Megadroughts such as that in 1540, the case of summer 2003 – though it was likely rather moderate in comparison – may provide some hints as to socio-economic vulnerability. As well as the deaths of about 70,000, mostly elderly, people in Europe during the peak of the heat wave (Poumadère et al. 2005), the EU arable sector showed an overall slump in production of more than 10 % (García-Herrera et al. 2010), causing an approximate financial loss of 13.1 billion euros (ProClim 2005). Many power plants had to reduce their output capacity, some of them down to 60 %, as a consequence of too-low water levels (run-of-river power plants) and too-warm cooling water supply (thermoelectric power plants). Éléctricité de France, running 58 nuclear power plants, had to cut its electricity exports by more than half (Poumadère et al. 2005) when water temperatures exceeded 23 °C.

5 Conclusions

Based on widespread documentary evidence in Europe concerning weather in 1540, we demonstrated that the drought in 1540 was likely more extreme than similar events in the instrumental period. The meteorological drought was more persistent (11 months), leading to a cumulative annual deviation of NPD to about 90 to 95 days compared to the twentieth-century Western and Central European average. The hydrological drought was similarly extreme, with an assessed discharge deficit of about 90 % for rivers Rhine and Elbe and the complete desiccation of smaller watercourses. The record-breaking dimension of the Megadrought also corroborates the earlier result of Wetter and Pfister (2013) that the heat wave, respectively spring-summer temperatures in 1540, were likely more extreme than in 2003. Our analysis of CMIP5 simulations suggests that climate models are so far unable to simulate 1540-like droughts. Given the large spatial extent, the long duration and the intensity of the 1540 heat and drought, the return of such an event in the course of intensified global warming involves staggering losses, the dimension of which might be assessed by future economic analyses. In conclusion, the case of the 1540 Megadrought demonstrates that in particular palaeoclimatic evidence of the natural archives, such as tree-rings or grape harvest dates, may fail to detect record-breaking climatic outliers, whereas archives of society usually describe them in most accurate detail. More research also involving documentary evidence on record-breaking extreme events prior to AD 1500 is needed to better appreciate the nature of risk of such disasters.

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