Regional Environmental Change (2020) 20:19
https://doi.org/10.1007/s10113-020-01601-0

ORIGINAL ARTICLE

Extreme heat and drought in 1473 and their impacts in Europe in the context of the early 1470s

Chantal Camenisch[1,2] · **Rudolf Brázdil**[3,4] · **Andrea Kiss**[5] · **Christian Pfister**[1,2] · **Oliver Wetter**[1,2] · **Christian Rohr**[1,2] · **Antonio Contino**[6] · **Dag Retsö**[7]

Received: 26 December 2018 / Accepted: 2 December 2019

Abstract
Droughts and heatwaves are both dangerous natural hazards with a potential significant impact on human societies. In order to understand these hazards, it is important to examine such extreme events in the past. During the years 1471 to 1474, warm and dry weather conditions are described in most parts of Europe. Until now, these extraordinary years have not been examined in depth. Moreover, in spring 1473, a great drought and heat occurred in Europe. This heatwave facilitated a fast phenological development. During the summer and the autumn, temperatures were unusually high, and extremely dry weather conditions continued. In many places, the harvest began remarkably early, and there was abundant wine of a good quality. Fruit trees even bloomed for the second time in autumn. The heat and drought had a considerable impact on the environment and also caused damage to agriculture and society, including water shortages, harvest failures and rising food prices. The weather conditions of the years from 1471 to 1474 were outstanding during the fifteenth century and the heatwave and drought, as well as impacts on environment, economy, and society in the year 1473, were comparable to—if not more severe—than those in the year 1540. Learning from past climate anomalies like the 1473 drought in Europe is important for evaluating more recent and future climate extremes under increasing anthropogenic pressure.

Keywords Drought · Heat · Temperature · Precipitation · Human impact · Locusts · Wildfires

Introduction

Droughts and heatwaves belong to the most hazardous extreme weather events for human societies (van Loon et al. 2016; Wilhite and Pulwarty 2018; Labbé et al. 2019). Recent examples, such as the drought and heatwave in 2003 (Beniston 2004), in 2015 (Hoy et al. 2017; Laaha et al. 2017) and in 2018 (UFZ 2018) in

This article is part of the Topical Collection on *Societal Impacts of Historical Droughts*

✉ Chantal Camenisch
chantal.camenisch@hist.unibe.ch

Rudolf Brázdil
brazdil@sci.muni.cz

Andrea Kiss
kiss@hydro.tuwien.ac.at

Christian Pfister
christian.pfister@hist.unibe.ch

Oliver Wetter
oliver.wetter@hist.unibe.ch

Christian Rohr
christian.rohr@hist.unibe.ch

Antonio Contino
ntncontino@gmail.com

Dag Retsö
dag.retso@ekohist.su.se

1 Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

2 Institute of History, University of Bern, Bern, Switzerland

3 Institute of Geography, Masaryk University, Brno, Czech Republic

4 Global Change Research Institute, Czech Academy of Sciences, Brno, Czech Republic

5 Institute of Hydraulic Engineering and Water Resource Management, Vienna University of Technology, Vienna, Austria

6 Department of Earth and Marine Science, University of Palermo, Palermo, Italy

7 Department of Economic History and International Relations, Stockholm University, Stockholm, Sweden

Published online: 10 February 2020

Europe, show how strong such impacts on environment, economy and society can be.

Catastrophic droughts and heatwaves in Europe, similar to the recent ones, also occurred in the past, according to documentary data (Munzar 2004; Brázdil et al. 2013, 2016; Kiss and Nikolić 2015; Kiss 2017; Garnier 2019) as well as to dendroclimatological data (Cook et al. 2015; PAGES Hydro2k Consortium 2017). As an example of a particular hot and dry event, the year 1540 may be mentioned (Orth et al. 2016; Wetter et al. 2014; Wetter and Pfister 2013a). Several publications (Brázdil and Kotyza 1995; Camenisch 2015a; Glaser 2013) showed that extreme heat and drought patterns in Europe were recorded also in 1473, in the context of warmer and drier years between 1471 and 1474. This 1471–1474 period may be considered part of the so-called Little Ice Age (LIA) (e.g. Grove 1988; Matthews and Briffa 2005) whose climatic patterns in Europe were described for its different time sections in many papers based on a variety of data (e.g. Luterbacher et al. 2001; Oliva et al. 2018; Pfister et al. 2018; Brázdil et al. 2019). However, none of these papers deals specifically with the years 1471–1474.

The aim of the present paper is to close this gap by analysing the temperature and precipitation patterns of 1473 in the context of the years from 1471 to 1474 in Europe, applying the methods of historical climatology, and examining the impacts of the weather conditions on environment, economy and society. The results are discussed in a long-term context, comparing the year 1473 with 1540 and checking these results against reconstructions based on natural archives.

Data

The archives of society form the basis of any analysis in the field of historical climatology (Brázdil et al. 2005, 2010). The documentary evidence available for the late medieval period includes narrative sources, such as chronicles and annals, as well as administrative and legislative sources, including accounts or charters. These sources contain descriptions of weather conditions and their consequences. Also of value are proxy data, i.e. indirect information concerning events related to weather conditions, such as plant phenophases. The documentary texts frequently owe their origins to a monastic or ecclesiastic context; however, in the late Middle Ages, the number of laypersons among the authors was also growing (Rohr et al. 2018). Thus, for example, the Polish chronicler Jan Długosz (1415–1480) was a priest but also served as the Secretary of the Bishop of Cracow and as the diplomatic ambassador of the Polish King before he became the Archbishop of Lviv. Among other annals of the Kingdom of Poland Długosz wrote the “Annales seu cronicae incliti Regni Poloniae” (Bazkowski et al. 2005). In addition to records of political decisions, dynastic events and wars, these annals also contain descriptions of weather conditions. The documentary evidence discussed in this paper is drawn from Scandinavia; the Low Countries; areas corresponding to modern Germany; France and Switzerland; Austria as well as Bohemia; Silesia; Poland; Hungary; Slovakia; Romania; Serbia; Croatia; Spain; Italy; the Ukraine and Russia (Table 3 in the Appendix and Fig. 1).

Methods

In order to accurately use medieval texts, it is necessary to convert the data from the Julian calendar style to the modern Gregorian style by adding 9 days (Camenisch 2015a). The Gregorian calendar style will be used throughout the paper. In addition to this, it is necessary to consider different dates for the beginning of a new calendar year in order to avoid the multiplicity of separate occurrences in consecutive years (Rohr et al. 2018). Moreover, dealing with similar weather conditions, in a sequence of 4 years, it is necessary to remove possible dating errors. For example, in the case of the years 1471, 1472 and 1473, a very reliable and eye witness chronicler from Lorraine gives three distinct descriptions of dry and hot weather conditions in each of the 3 years. This is strong evidence that the dry and hot weather conditions in all consecutive years were not a simple dating error. Similar proof is available for the years 1473 and 1474 in central Europe. To analyse the existing documentary data, a reconstruction of temperature and precipitation has been made, based on the critical comparison of texts from the different areas reported in the ‘Data’ section.

Results

Weather patterns in Europe during 1471–1474

The year 1471

Sparse evidence from the winter 1470/1471 shows a very mild season (Camenisch 2015a). As Buisman (1996) points out, the ship traffic on the Scheldt area of Bergen op Zoom was never interrupted during this winter. Moreover, the chronicler Jehan Aubrion in Metz gives an account of the advanced plant phenology in March because of the mild temperatures in February and March (Larchey 1857). This mild weather continued in spring, according to the description of the plant phenological development (Camenisch 2015a). The Chronicon monasterii Campensis (Keussen 1869) mentions high temperatures that led to the earlier blooming of grapevines in mid-May. Furthermore, viticultural work in Lorraine began earlier than in other years (Larchey 1857). In Rotterdam, ripe cherries

Fig. 1 Map with locations, rivers and areas mentioned in the sources. Areas: Ardennes (ARD.); Rhineland (RH.L.); Black Forest (BL.F.); Burgundy (B.); Baden Württemberg (B.W.); Lombardy (LO.); Emilia-Romagna (EM.-RO.); Andalusia (AND.); Thuringian Forest (TH.F.); Bohemian Forest (BO.F.); Great Hungarian Plains (G.H.P.); Transylvania (TR.S)

were offered on the market as early as around 6 June (Buisman 1996). Outstandingly hot and dry weather during the summer of 1471 led to a very early harvest of grain, apple and grapes in Lorraine, Flanders and Holland (Camenisch 2015a).

Similarly, high temperatures and a lack of water were recorded in the area of Göttingen and the Black Forest (Glaser 2013). In Hungarian Sopron, near the Austrian border, a contemporary insertion to the local ‘Gerichtsbuch’ suggests that grapes were seen on the vines as early as 29 March and on 20 May, even ripe grapes had been observed (Házi and Németh 2005). A dry spell and high temperatures are also described in the Varnsdorf and Mimoň towns, both situated in the north of Bohemia and in Austrian Salzburg and in Polish Wrocław (Brázdil and Kotyza 1995). Also, in the Novgorod region, Russia, it was extremely dry, because not a droplet of rain fell from the sky during the entire summer (Borisenkov and Pasetskiy 1988). It was only in autumn that early short episodes of frost and snowfall set in in Lorraine (Camenisch 2015a) and thus ended the warm weather of the previous months.

The year 1472

The mild temperature and rather dry weather conditions are likely to have prevailed during the winter 1471/1472, although information on this season is sparse. A Zeeland source mentions no frost and only little precipitation for the entire winter (Camenisch 2015a). According to Buisman (1996), the ship traffic on the Scheldt River was probably not interrupted at any time during this winter. Similarly, shipping in ports of the south Baltic Sea in the Öresund straits and in Gdańsk started already by mid-February, i.e. 2 weeks before the average date in this region (Retsö and Söderberg, manuscript).

In the summer of 1472, temperatures were again higher than usual (Camenisch 2015a). Jehan Aubrion described June and July as miraculously warm months (Larchey 1857). Also, in the area of modern Germany, in Bohemia and in Silesia, summer was dry and hot (Brázdil and Kotyza 1995; Glaser 2013). Furthermore, droughts were reported in Russia (Borisenkov and Pasetskiy 1988) and in parts of Spain, especially in Andalusia, where no rain fell from September onwards (Montes Romero-Camacho 1995).

The year 1473

The year 1473 was outstanding in Europe from the viewpoint of temperature and precipitation. In Metz, the winter 1472/1473 started with moderate temperatures and rain, as stated by Jehan Aubrion (Larchey 1857). The temperature reconstructions of the Low Countries evaluate this winter either as normal (Buisman 1996) or rather mild (Camenisch 2015a). Similarly, normal, mild or very mild temperatures for this season follow from other reconstructions in modern Switzerland and Germany (Schwarz-Zanetti 1998; Glaser 2013). It is interesting to add that in today’s border area between Hungary and Slovakia, there was enough snow at the end of December 1472 to transport wood on sledges (13 Feb. 1473: HNA DL 17427 HNA DL 1473).

The water levels of the Morava and Danube Rivers were probably not significantly lower than usual in early March, as ships were ordered when the army of the Hungarian King Matthias Corvinus crossed the wetlands in the Marchegg area along the Danube, and its inflow into the Morava (HNA DL 1473). It was very warm in March and very hot in April in Metz.

During subsequent months, the temperatures remained high, as reports from England and Lorrain suggest (Aston 1994; Larchey 1857). The Danish Roskilde annals speak of a ‘severely hot and burning summer’ in 1473 (Rørdam 1873), and in the monastery of Kamp in the Rhineland, a chronicler emphasises that no one could remember a similar heat (Keussen 1869). The temperatures were even higher than in Italy or Lombardy as Philippe de Vigneulles—another chronicler from Metz—adds, and it is stated that not even older people had experienced something similar in their lives (Bruneau 1932). Because of the detailed description of plant phenology by Jehan Aubrion and also Philippe de Vigneulles, the 1473 weather conditions can be assumed to be reliable. Many further reports from the area of the Low Countries mention high temperatures in spring and summer, and an advanced growth of plants (Camenisch 2015a). All available medieval chroniclers used the phenological descriptions to give proof of the exceptional weather events in 1473 (‘Impacts on the environment’ section). In Bohemia, the heat was outstanding and lasted for a period of about three and a half months (Brázdil and Kotyza 1995). The hot weather was also mentioned in Austria, Württemberg and Poland, where the chronicler Jan Długosz referred to the unprecedented heat and the lack of rain that prevailed in Europe in this year (Brázdil and Kotyza 1995; Bazkowski et al. 2005; Kiss and Nikolić 2015).

Thus a considerable drought was mentioned in many parts of Europe. Across Western Europe, independent sources report 4 or 5 months without noteworthy precipitation in many locations (Ilgen 1895). In Spain, terrible and devastating drought that started in September 1472 lasted for several months and—at least in the area of Sevilla—no rain fell from September 1472 until May 1473 (Mackay 1981; Aston 1994; Montes Romero-Camacho 1995). Drought reports are also available from Italy (Borghi 1861) and from the Lower Rhône Valley in France, where a lack of water—due to the previous very dry and hot months—was reported at the end of August (Rossiaud 1994). Even in England, a lack of precipitation was reported, although there was probably no actual drought (Kington 2010). The chronicler Pierre Impens from Leuven writes that ‘tanta inaudita et insolita siccitas totum fere orbem afflixit’ (i.e. an unprecedented and anomalous drought afflicted the whole world) (Kervyn de Lettenhove 1876). In Zierikzee, no rain was reported from May to 10 October, and almost no rain fell for 5 months in Soest, with a statement that for more than 5 weeks, there was not a single raindrop at all (Buisman 1996; Ilgen 1895). Glaser (2013) also presents evidence showing similar outstanding dry weather patterns in the area of modern Germany. No rain fell for at least 9 weeks in Basel and for 12 weeks in Zürich (Bernoulli 1895; Dierauer 1900). In Wrocław, the drought lasted from 2 May until 20 November, and Bohemia suffered at least for three and a half months of the drought. More drought reports exist from Austria and Poland (Brázdil and Kotyza 1995; Buisman 1996). The mid-sixteenth-century Swiss chronicler Lycosthenes (1557), and a seventeenth-century chronicle from Ľubica in modern northeastern Slovakia (all applying late-medieval source evidence), reported on the extraordinary drought of 1473. Długosz and Lycosthenes stated as a fact the occurrence of a 'great drought' in (medieval) Hungary. Furthermore, the chronicle from Ľubica suggested that there was a great heat and drought from 15 June to 10 November (Kiss and Nikolić 2015; Kiss 2017). It seems that 1473 was generally extreme in most parts of the Carpathian Basin, but more in the north and somewhat less severe in the south (Kiss 2017). In western Russia, there was a similarly severe drought in 1473 (Borisenkov and Pasetskiy 1988).

The year 1474

A description of the winter 1473/1474 by Jehan Aubrion mentions the prevailing rainy weather during this season with no frost and almost no cold spells (Larchey 1857). In addition, ship traffic on the Scheldt River was not interrupted during the winter (Buisman 1996) which meant that no drifting ice occurred due to the normal to mild temperatures. In the Baltic Sea area, the shipping season seems to have started early; in Gdańsk, at least by mid-February and by early March, the Bay of Riga (in present-day Latvia) was ice-free. Similarly, the ice break-up process in the Stockholm archipelago of Sweden and, on the sea of Åland, was notably shorter than in previous years (Retsö and Söderberg, manuscript). In the eastern and south-eastern part of the Great Hungarian Plain (Oradea: today's western Romania), a swift attack of Ottoman troops, reported by a contemporary domestic chronicle (Florianus 1884) in cold winter weather, suggests dry conditions in early/mid-February (Kiss and Nikolić 2015).

The year of 1474 was reported as a dry year in England (Kington 2010) and in Mediterranean France (Rossiaud 1994). Also, in Poland and Bohemia, and perhaps in Württemberg, the weather conditions were again dry from spring to autumn (Brázdil and Kotyza 1995). The Italian chronicler Antonio Bonfini, who lived in Hungary from the 1480s onwards, mentions in his Hungarian chronicle, a great shortage of water and perennial drought in 1474, when springs dried up, and water levels of major rivers were so low that the Turkish troops could easily cross them and attack the southern areas, i.e. present-day northern Serbia, southern Hungary and northern Croatia (Kulcsár and Kulcsár 1976; Kiss and Nikolić 2015; Kiss 2017). In autumn, the Hungarian king Matthias took advantage of the dry weather when he conducted a military campaign against the Polish King in Silesia. The contemporary Silesian chronicler, Peter Eschenloer, mentions the low water level of the Odra River in early October at Krapkowice, where the Polish army crossed the river (Roth 2003; Kiss 2017). The Polish chronicler Jan Długosz also refers to the drought before he mentions a flood of the Odra, probably around November (Bazkowski et al. 2005). Furthermore, the council of the Swedish realm issued a statute in August 1474, where the use of watermills was regulated because of repeated droughts, presumably causing a lack of water. The wording indicates that the phenomenon had occurred for a number of the previous years (Hadorph 1676, no. 9).

Impacts of extreme weather during 1471–1474

The effects of dry and hot weather conditions on environment, human economy and society are various, and dependent upon the extension, duration and sequence of the weather pattern. In particular, dry and hot weather conditions can have very positive but also very negative impacts on the outcomes of agricultural production. This means that extremely hot and dry anomalies can turn into negative consequences for economy and society. Moreover, as extremes only occur rarely, people are less prepared for these types of weather conditions and the weather impacts and thus do not necessarily have adequate coping strategies.

Impacts on the environment

The year 1471 As Glaser (2013) shows for the area of modern Germany, the hot and dry weather had a significant impact on the level of different water bodies, such as that brooks and streams dried up and large rivers could be crossed without danger. The same occurred in the north of Bohemia where rivers dried up (Brázdil and Kotyza 1995). In May 1471, *a very hard year* is mentioned in a letter from Åbo (Turku), Finland (Hausen 1890 no. 625). It is unclear what exactly is referred to, but the wording is typical in Scandinavian medieval sources for situations of climatically induced stress.

In the same year, plant growth was advanced in several places, for example, in the Low Countries, Lorraine and in the area of modern Germany. The grain harvest was generally early and abundant. In Metz, ripe grapes were already available on 31 July, and on 12 September, people could buy new cider in Bruges. In Rotterdam, the wheat and rye harvests were already accomplished on 3 August; on 1 August wine grapes were ripe, and on 7 September, new cider was sold in Rotterdam (Camenisch 2015a). It seems that the fruits harvested in Göttingen were worm-eaten, but the wine quality was very good (Glaser 2013).

The year 1472 Not many specific drought and heat impacts on the environment are known for the year 1472. However, it is clear that the water level of the Odra River was very low (Brázdil and Kotyza 1995). The grain and wine harvest were most probably early and very good again (Glaser 2013; Le Roy Ladurie 2004; Dierauer 1900). In September, an ongoing epidemic disease was already mentioned in the area of present-day southern Hungary and northern Serbia (3 Sep. 1472: Kiss 2020) and in France and Burgundy (Kervyn van Lettenhove 1870).

The year 1473 In 1473, the lack of water was even more evident than in 1471. In Leuven, in the Ardennes and also in Basel, wells dried up (Kervyn de Lettenhove 1876; Bernoulli 1895). The same occurred in Lombardy and Emilia-Romagna (Borghi 1861; Tatti 1743). Furthermore, in Metz, the Meuse River dried out to form a narrow stream, in the words of Jehan Aubrion (Larchey 1857): 'Mil iiiic iiiixx et xiij. [...] Grant chailleur. […] Et tellement que la ripvier de Mezelle n'estoit en aulcuns lieux point plus large que ung russiaulx.', which translates to the effect that there was a great heat which was of such a magnitude that the Meuse River was in no place bigger than a small stream. In Bohemia, rivers and brooks dried up as well as in Poland, where a lack of drinking water was reported (Brázdil and Kotyza 1995). According to Lycosthenes, also in (medieval) Hungary, rivers dried up and even the Danube became easily crossable (Kiss and Nikolić 2015). Furthermore, in western Russia, rivers became shallow (Borisenkov and Pasetskiy 1988). The water in Zierikzee in the southern Low Countries started to smell as there was no rain for a long time (Buisman 1996).

As with the two previous years, the plant growth and ripening was very early in 1473. The fruit trees in Lombardy were already in bloom at the end of February and in Augsburg on 26 March. In Lorraine, the lilies of the valley (*Convallaria majalis*) were blooming on 10 April. On the same day, fruit sets of vines and fruit trees appeared. On 30 April, the grain plants were in bloom in Liège. In Lorraine, the cherries were ripe on 9 May, and 1 day later, ripe strawberries were sold on the market in Metz. In Soest, the pea harvest started on the last day of May and at the same time, the first *verjus* (juice of unripe grapes) was sold. By the end of June, vines were harvested in Lombardy and Emilia-Romagna and also in Dijon, where the harvest started on the exceptionally early date of 29 August. In Liège, the hay harvest and the harvest of grain, apples and nuts were reported to be 1 month earlier than usual. The grain harvest in Augsburg took place around 14 July and in Baden and in Württemberg, the vintage occurred already in August and the wine quality was very good. On 15 August, new French wine was sold in Bruges, and also in October at several places in the Low Countries. In western Russia and in Lombardy, a second bloom of fruit trees was described (Tatti 1743; Bonora 1862; Camenisch 2015a; Glaser 2013; Borisenkov and Pasetskiy 1988; Le Roy 2004). These examples of advanced phenological phases (Table 1) from so many European places demonstrate the unusual weather conditions.

On the other hand, for many sorts of plants, the drought of 1473 meant great stress. In the Ardennes, which is commonly a rather wet area, old trees desiccated and died, and roots were erased by drought, as a chronicler of the nearby Liège recounts (Kervyn de Lettenhove 1876). A similar phenomenon was reported in Ľubica (Schmauk 1889; Kiss and Nikolić 2015). Also, in Lombardy the woods looked as if they had burned (Tatti 1743).

Different information is available in the sources and the literature concerning the quantity of the harvest. In the Low Countries, some chroniclers emphasise that grain, fruit and vegetable harvests were very small because of the heatwave and the drought. Other authors did not give information on harvest quantity or even mentioned a good harvest (Camenisch 2015a). The further to the east, the more descriptions of harvest failure prevail. In the area of modern Germany and Switzerland, only little hay, grain and fruit grew (Glaser 2013; Dierauer 1900). Harvest failure was also reported in Bohemia, where cereals, beetroot, cabbage and other crops perished completely (Brázdil and Kotyza 1995), and in western Russia (Borisenkov and Pasetskiy 1988). Cattle suffered from the heat and drought as not enough grass and hay was available, and in some regions, there was even a shortage of drinking water (Brázdil and Kotyza 1995; Camenisch 2015a; Glaser 2013). Moreover, in Italy, harvest failures of grain and

Table 1 Comparison of vine phenological data in 1473 and 1540 for Metz (M—white variety), Beaune (B—Pinot Noir), Zürich (Z—white variety) and Schaffhausen (S), DOY—Day of the year (Litzenburger 2011; Labbé et al. 2019; Pfister, Rohr 2020, https://echdb.unibe.ch/selection/search/en/)

Year	Flower ends	DOY	Veraison	DOY	Ripe grapes	DOY	Harvest white variety	DOY	Harvest red variety	DOY
1473	Jun 09 (Z)	162			Jul 11 (Z)	192	Aug 25 (Z)	239		
			Jul 08 (M)	189			Aug 13 (Z)	226	Sep 05 (B)	249
1540			Jul 05 (S)	187	Jul 16 (Z)	198	Sep 10 (Z)	254	Sep 03 (B)	247

vines were reported and cattle died due to a lack of water and grass (Borghi 1861; Bonora 1862; Mafrici 1994). Similar reports exist in Spain, where in Sevilla and Jerez de la Frontera harvest failure occurred. Due to the lack of grass, people there even stripped the straw from the roofs of houses and cabins in order to feed the cattle (Montes Romero-Camacho 1995). Because temperatures remained high in autumn, even a second bloom of fruit trees was observed, and cherries were harvested twice during the year (Camenisch 2015a; Tatti 1743).

The wildfires which raged in many places in Europe represent another serious heat and drought impact on the environment. The woods of the Bohemian Forest burned for 18 weeks (Hansen 1887); in the Thuringian Forest, the woods burned for a long time; and in the Black Forest, there was a wildfire for about 6 days (Frensdorff et al. 1892). A few kilometres to the west of Antwerp, an enormous bushfire occurred around 10 August, which was out of control. The fire produced an ash cloud, which hurt people's eyes and caused them to panic (Buisman 1996). In Poland, the soil was burned by fire even below the earth's surface (Brázdil and Kotyza 1995). Jan Długosz mentioned fires in many settlements in this year, while Lycosthenes (1557) also describes wildfires in Hungary. Furthermore, in Russia, forests and towns were on fire (Borisenkov and Pasetskiy 1988). In Metz, two granaries caught fire and burned because of the dry and hot weather. It would appear that corn weevils found ideal conditions to reproduce fast in the granaries, which led to considerable losses of the stored grain (Bruneau 1932).

The epidemic disease of 1472, mentioned above, continued in 1473, as was reported in the Low Countries (Borman 1902). Many of the sources link the disease to the heat. Further charter evidence from medieval Hungary, regarding the area of present Berehove and Mukachevo in modern south-western Ukraine, and from the west-central Great Hungarian Plain in modern central Hungary, shows an epidemic disease most probably in 1473 (and before) and certainly in 1474 (1474, 1475: Kiss 2020). Moreover, in the Low Countries, people died of the heat, most likely of heatstroke and circulatory collapses (Buisman 1996). Similar cases occurred in England, where people died while harvesting in the heat (Aston 1994).

The year 1474 According to Bonfini, springs dried up in Hungary in 1474, and also the main rivers of the country showed very low water levels; in this year, probably the southern part of the country was more affected (Kulcsár and Kulcsár 1976; Kiss and Nikolić 2015). In Bohemia and Poland, the infernal heat caused damage to the grapes. Therefore, only little wine but of good quality was produced in this year. The fruit harvest was abundant (Brázdil and Kotyza 1995).

Furthermore, in 1473, the heat and drought favoured the increase, growth and spread of locusts. A chronicler from Melk in Austria gives an account of a locust invasion in 1474 which came from Moldova and most probably reached the area of Linz through Transylvania, Hungary and Bohemia. The locusts caused damage in most of central Europe until 1476 (Pertz 1851; Rohr 2009, 2010; Brázdil et al. 2014) and in Hungary until 1480 (Florianus 1884; Kiss and Nikolić 2015).

Impact on the economy

The year 1471 In the Black Forest area, the lack of water in 1471 provoked problems with the grinding of flour in the water mills (Glaser 2013). Because the harvest was good in most places, it can be assumed that the food supply situation was positive for people, and food prices were probably rather low, despite missing evidence in the sources.

The year 1472 As mentioned above, the hay, grain and grape harvests of 1472 were good at least in Switzerland and again the prices were obviously rather low (Dierauer 1900).

The year 1473 In 1473, several sources mention harvest failure (as already discussed in the 'Impacts on the environment' section). In certain different areas, prices for food, notably for grain and vegetables, were high, especially in Germany and Sweden but probably not in France (Camenisch 2015a; Brázdil and Kotyza 1995; Glaser 2013; Le Roy Ladurie 2004; Franzén and Söderberg 2006). Clearly, apart from the harvest failure, granary weevils could also have some influence on food prices. In the case of the 1470s, these weevils are mentioned, although it is not clear how strong this impact was. In spite of the description of high food prices, no reports on dearth or famine are known for most parts of Europe, neither in 1473 nor in 1474. The reason for this is perhaps that the harvests in 1471 and 1472 were very good and plenty of stocks prevented society from a crisis. Parts of southern Europe, Spain and Italy for example, are an exception, because their people suffered from severe grain and bean harvest failures caused by drought, and consequently a famine occurred (Mackay 1981; Borghi 1861).

Apart from the harvest size, other factors could also influence the availability of food. The watermills could not operate because of the low water levels (Brázdil and Kotyza 1995; Bernoulli 1895). The low water levels, such as at the Meuse River, made trade routes no longer passable (Larchey 1857). This was a problem for the transport of heavy and bulky goods, such as grains. Similar problems can be assumed for the Danube River and the rivers in Poland or Bohemia as well.

Although no economic impact of the wildfires is described, it may be assumed that the destruction of timber and the losses of wild game and of their habitat in 1473 also had economic consequences for the owner of the woods. Moreover, in the late Middle Ages, the functions of forests were manifold and were not only limited to the exploitation of timber (Radkau 2007).

Impacts on society

The year 1473 To cope with heat and drought and to secure the ending of these extreme weather conditions, people prayed for God's help. For this purpose, rogations were organised by the church to beg for rain, for example in Augsburg (Frensdorff et al. 1892).

In Spain, where the drought caused terrible harvest failure, people blamed the "Conversos"—former Jews that became Christians—for their misery and burned them on the stake. The reason was that people believed that they were punished for the sins of parts of the society, and therefore, they wanted to destroy the origin of the sins in order to receive God's pardon (Mackay 1981). This type of behaviour is also known in relation to cold and wet weather anomalies and their consequences (Behringer 2010; Camenisch 2018).

The year 1474 In February 1474, Ottoman troops took advantage of the cold and dry weather conditions for an extraordinary quick military campaign, when they suddenly crossed the Danube and devastated Oradea (Nagyvárad) in the eastern and south-eastern parts of the Great Hungarian Plain (Florianus 1884). Moreover, the low water levels of the Danube, Drava and Sava Rivers weakened the natural defence system of medieval Hungary and Croatia, and the southern areas were prone to swift Turkish attacks and devastation (Kiss and Nikolić 2015). Such campaigns were only successful when dry weather conditions were prevailing. The low water levels of the Odra River, and the dry and hot conditions in early October, made military operations easier in Silesia; the Polish troops, for example, were able to easily cross the Odra near Krapkowice (Roth 2003; Kiss 2017).

Discussion

The long-term context of 1471–1474

The sources introduced here represent strong evidence for the proposed chronology of the weather conditions in the years between 1471 and 1474. This is due to the fact that in most cases, the descriptions are independent from each other, and some of them contain recurring records of heat and drought from consecutive years. Dating errors are therefore not very probable. The fact that all these chroniclers underline their descriptions with physical and phenological information shows that they wanted to emphasise their reports of high temperatures as not just an individual occurrence, but something that could be compared with other less outstanding seasons.

A look into climate reconstructions of the fifteenth century shows how remarkable the years between 1471 and 1474 were. In a seasonal temperature and precipitation reconstruction of the Low Countries based on the documentary data (Camenisch 2015a, 2015b), only two spring seasons of the fifteenth century were evaluated as extremely warm seasons: 1420 and 1473. With regard to the summer seasons, four extremely dry summers occurred in 1422, 1424, 1442 and 1473, and three extremely hot summers were observed in 1471, 1473 and 1492. The extremely dry autumn seasons are documented for the years 1442 and 1473. In addition, the climate reconstructions by Buisman (1996) and by Shabalova and van Engelen (2003) show the singularity of the year 1473 because in these reconstructions; only the extended summer seasons (May to September) of 1420, 1422 and 1473 were evaluated as extremely warm. A further documentary-data–based temperature reconstruction by Glaser and Riemann (2009) confirms a short warm period in the second half of the fifteenth century which included the 1470s.

A comparison of the years from 1471 to 1474, as reconstructed from documentary data with reconstructions based also on natural proxies, shows that the drought period also appears there. For example, Cook et al. (2015) reconstructed a summer self-calibrated Palmer Drought Severity Index (scPDSI) from tree-rings in form of the Old World Drought Atlas (OWDA). From their results (Fig. 2c) follows that the 1473 summer drought affected almost all of Europe, with the exception of Spain, where the documentary data suggest a drought period between September 1472 and May 1473 and not during the summer. Moreover, the dry summer season in 1474 was reconstructed for the southern Carpathian Basin (Fig. 2d). Apart from the OWDA, a reconstruction based on the isotope analysis of speleothems from north-east Hungary (Siklósy et al. 2009) suggests a general warm and dry period around the 1470s. Below average precipitation in parts of Europe is also shown in the OWDA for the summer seasons in 1471 (Fig. 2a) and 1472 (Fig. 2b). This means that the documentary evidence of drought (and heat) is verified by other independent natural proxies.

Regarding the climatic context of the dry and hot period in the first half of the 1470s, it is important to emphasise that these extreme weather events occurred during the LIA, in a period after the extremely cold 1430s (Camenisch et al. 2016), and before the very wet and cold years at the beginning of the 1480s and the 1490s (Camenisch 2018). This is an important difference related to the extremely dry and hot weather conditions that have occurred in more recent times, for example, in 2003 (Beniston 2004), in 2015 (Hoy et al. 2017; Laaha et al. 2017) and in 2018 (UFZ 2020) in the time of recent global warming.

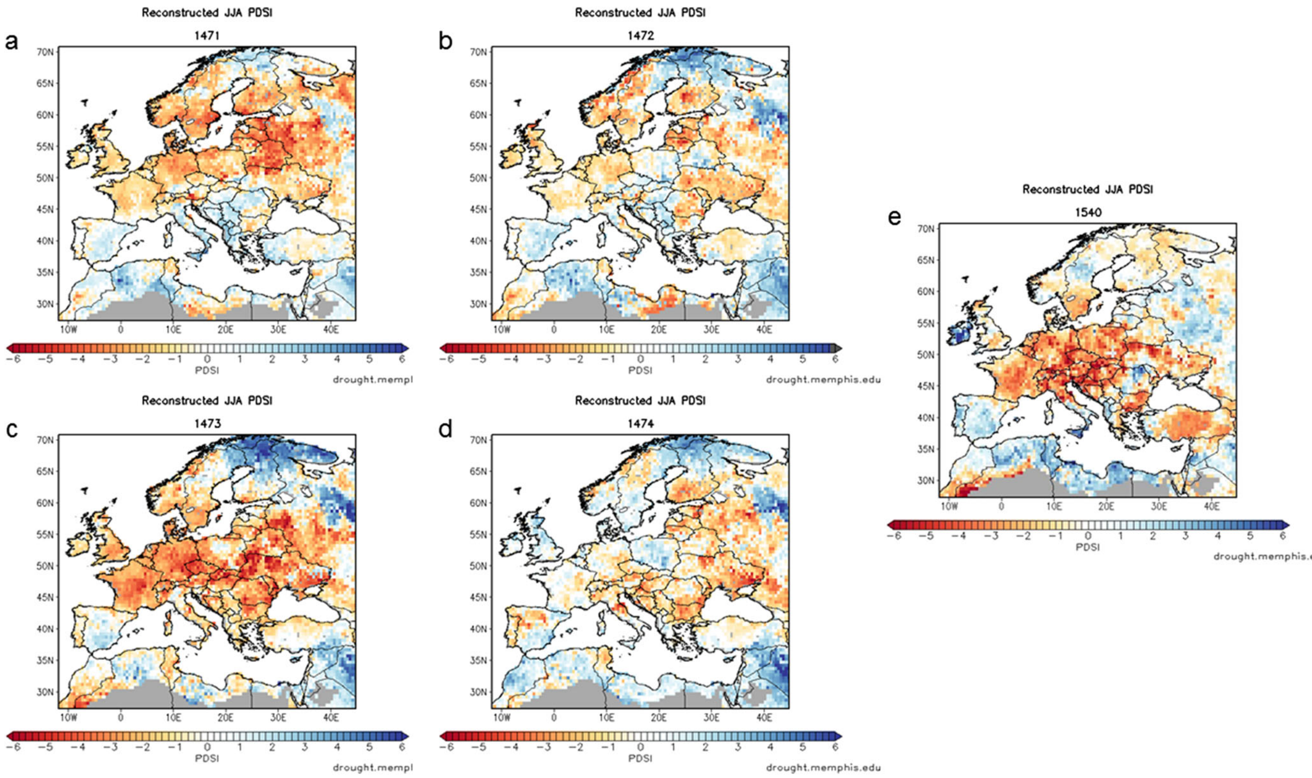

Fig. 2 Values of summer self-calibrated Palmer Drought Severity Index (scPDSI) for 1471 (**a**), 1472 (**b**), 1473 (**c**), 1474 (**d**) and 1540 (**e**) in the European area as derived from tree-rings in OWDA (Cook et al. 2015)

Heats and droughts of 1473 in comparison with 1540

The outstanding warmth and drought in 1473 is roughly assessed below with reference to the analogous case in 1540 (Wetter et al. 2014; Wetter and Pfister 2013b). The monthly and seasonal temperature estimates for central Europe from 1500 are found in Dobrovolný et al. (2010) while monthly measured temperatures for Paris are provided by Rousseau (2015). Both series are available from the Euro-Climhist database (Pfister and Rohr 2020, https://echdb.unibe.ch/selection/search/en/).

The estimates for 1473 are attempted using phenological observations (Templ et al. 2018) in combination with the narrative evidence. The most relevant are the phenological data on stages in the development of vines, such as bud-burst, flowering, veraison (i.e. the colour change of the grapes) and the official opening of the grape harvest ban (Labbé et al. 2019). In his pioneering synthesis concerning the climatic, economic and cultural history of the French city of Metz, Litzenburger (2015) compiled a set of dates of vine phenology, from 1420 to 1526, including relevant evidence concerning 1473. The Metz vineyards are situated at altitudes between 160 and 250 m. Comparable evidence is available from the Swiss Plateau situated at altitudes between 400 and 450 m (Table 1).

In 1473, the flowering of vines in the Zürich area ended at the latest, on 9 June (Table 1). A corresponding date in the instrumental period is found for the year 1868, which in Paris saw the warmest month of May between 1659 and 2010. The stage of veraison in 1473 was observed in Metz on 8 July, 52 days earlier than that of the fifteenth century average (Litzenburger 2015), and 3 days later, the first grapes were already eaten and found ripe in Zürich (Table 1).

The vines in Metz were somewhat more advanced than those in Zürich, due to the lower altitude of the vineyards. Today, the white grape cultivars, such as varieties of Chasselas or local white vines such as the *Räuschling* in eastern Switzerland, are harvested 10 to 14 days earlier than red Pinot Noir grapes (personal communication by Andres Altwegg, Brugg). Probably this was also the case of the white *Fromental* variety in Metz (personal communication by Laurent Litzenburger). Due to the lower altitude of Metz, these grapes were picked 12 days earlier than the *Räuschling* grapes in Zürich. Both the vintage dates of 13 August in Metz and 25 August in Zürich are probably the earliest ones documented for white varieties in central Europe. The Pinot Noir grapes in Beaune were picked from 3 September (Table 1), i.e. 3 weeks later than in 2003 (Labbé et al. 2019), which was probably because of the extraordinary dry conditions. The oenological research established that under the conditions of

Table 2 Comparison of summarized weather patterns and impacts on environment, economy and society for the years 1471, 1472, 1473 and 1474

	1471	1472	1473	1474
Weather conditions	- Mild winter and spring - Very dry summer	- Mild and dry winter - Dry and very hot summer	- Very mild spring - Extremely hot and extremely dry summer (several months of drought and heat wave)	- Wet and mild winter - Dry spring and autumn - Very hot and dry summer (Eastern Central Europe)
Impacts on environment	- Springs and brooks dried up, low water levels - Advanced plant phenology - Good harvest	- Low water level of rivers - Early and good harvest	- Springs, brooks and rivers dried up - Very low water levels Lack of drinking water - Advanced plant phenology - Second bloom of fruit trees - Trees died - Wildfires - Harvest failure/in few places good harvest	- Springs dried up - Low water levels of rivers - Good harvest - Little wine but of good quality - Locusts
Impacts on economy	- Water mills could not operate, grinding hampered - Probably moderate or low food prices	- Low prices for hay, grain and wine	- Water mills could not operate, grinding hampered - Trade disrupted on water ways - High grain and vegetable prices - Famine (Spain and Italy)	
Impacts on society			- Rogation ceremonies for rain - Processes against scape goats	- Impact on military campaigns

extreme heat and drought, the development of grapes can be slowed down or stopped (Keller 2016).

The year 1540 was the warmest year in the central European temperature series between 1500 and 2010 (Dobrovolný et al. 2010). Concluding from the precipitation and drought indices reconstructions for Switzerland, Poland and the Czech Lands (Brázdil et al. 2016; Wetter et al. 2014), it was also the driest. The comparison with 1473 draws an outline summarised from Pfister et al. (2018).

The winter in 1540 was moderate, whereby December and February were warm, albeit not as extreme as in 1473. March was entirely dry and sunny, but ice was found every morning because of persistent cold winds, which contrasts with the description of a record warmth in 1473. April and May were consistently sunny and extremely hot, whereby drought effects are mentioned in contrast to 1473. In early June 1540, the vines had caught up with 1473, considering the end of flowering (Table 1). The heatwave in 1540 persisted for 45 days from 23 June to 7 August, when the drought was broken by a rain-spell. The drought in 1473 began somewhat later, but it lasted considerably longer, and the defoliation of trees was probably more pronounced. In analogy to 1473, a second bloom of fruit trees was registered in autumn, including the reports of cherries reaching maturity for a second time. November and December were extremely warm in both years.

The impacts of both droughts and heatwaves on environment, economy and society look rather similar. In both years, 1473 and 1540, wells and brooks dried up and water levels of major European rivers were low (Table 2). In addition, feed and water shortage were described in both drought years, along with perished cattle, drought stress of trees and vines, wildfires and disruptions of water-based transport and the use of water mills (Wetter et al. 2014). A remarkable difference concerns the agricultural production, because in 1540 grain and wine harvests were abundant, whereas in 1473, in many places, grain harvest failures occurred. In regard to the geographical extent, the duration, the plant phenological advance and the severity of impacts, it seems probable that the 1473 drought and heatwave were even more severe than that of 1540. This also suggests a similar comparison according to the maps of 1473 and 1540 of the OWDA (Fig. 2c, e).

Context of impacts of 1471–1474

The described impacts of extreme weather patterns in 1471–1474 (see the 'Heats and droughts of 1473 in comparison with 1540' section) fit with the simplified Climate-Society-Interaction-Model developed by Daniel Krämer and Christian Pfister (Krämer 2015; Luterbacher and Pfister 2015), which shows how the interaction between extreme weather conditions and society worked. In this model, extreme weather—such as a drought—causes first order impacts on a bio-physical level. These first order impacts include food production, water availability and so on. In the case of a drought, it means that mainly grain, fruit and wine production—the availability of food and water are concerned. On the second level of impact, prices of food and transportation are affected. The epidemic and epizootic diseases spread. Malnutrition and a decline in demographic growth are the consequences on the third level of impact. On the fourth level of impact, the cultural responses, such as crisis interpretation, cultural memory and religious rituals might follow.

There is a strong link between drought and heat and epidemic diseases: especially the plague, dysentery, smallpox and different fevers are mentioned in this context (Garnier 2019). Depending on the disease, heat, drought and low water levels could favour the spread of vectors, such as rats and the development of the pathogenic germs or viruses (Campbell 2016; Pfister 2007, 2018). Unfortunately, it is not possible to determine what type(s) of disease spread during the 1470s, because the expression *pestis* used by the medieval authors is not limited to plague (Curtis and Roosen 2018), and because no descriptions of symptoms are available for the 1470s.

Clearly, weather conditions also have a strong impact on the life cycles of insects. In most cases, there is no evidence on these in the written sources of the late Middle Ages. In some cases when the insects appear in very large numbers, or when they are damaging harvest or stored food in a significant way, they are mentioned. The granary weevil (*Sitophilus granarius*)—a flightless weevil who is specialised in living in stored grain—belongs to arable agriculture, presumably as long as it already exists (Plarre 2010). Warm weather conditions favour the development of the weevil and the frequency of reproduction with it. These conditions can harm the quality and quantity of stocks to a considerable extent (Jacobs and Calvin 2001).

Hot and dry weather during a whole year or season also seems to play an important role concerning the invasion of migratory locusts (*Locusta migratoria*) in central Europe. The development of the locusts is determined by different factors. In particular, the locusts have two manifestations: during their solitary phase, they live alone and do not represent any danger. This changes when the solitary phase transforms into the gregarious phase. At the beginning of this phase, the number of locusts increases rapidly, and they can form huge swarms. While the younger insects hop close to the ground in swarms, the older ones fly off the swarms.

According to the 'Impacts on the environment' section, a large locust invasion hit central Europe after the extremely hot and dry year of 1473, similarly as after 1540. The locust invasions in central Europe are well documented for some years from the fourteenth to the eighteenth century (e.g. 1338–1341, 1470s, 1540s, 1690s, 1740s). The transformation from a solitary to a gregarious phase presumably took place in the Black Sea region in modern southern Russia, and then the eastward journey to the Carpathian Basin and further on to Austria, northern Italy, Moravia, Silesia, Bohemia, southern and central Germany. Thus, easterly and south-easterly winds obviously favoured those movements. Concerning weather conditions in the target areas, Brázdil et al. (2014) found that during the years in which the locust outbreaks took place, the seasonal temperature and precipitation patterns in central Europe showed no particular climatic features compared with the years without them. Regarding Italy, Camuffo and Enzi (1991) suggested that great locust outbreaks were usually preceded by mild winters. Moreover, it could be assumed that the drought periods might be a trigger for the transformation process to a gregarious occurrence in the origin country and in the transition areas, where the locusts lay eggs on the ground. As the larvae develop, and in the consecutive year, it is possible that the locust plague appear again and move forward. This is true, in particular, if locusts can survive a mild winter, dropping into a state of lethargy and being able to renew activity (Camuffo and Enzi 1991 for Italy) such as during the mild winters of 1472/1473 and 1473/1474. On the contrary, when the weather changes to very wet and cold, the locusts rapidly disappear, as some reports mention (Rohr 2009, 2010). In this way, the weather during the locust invasions is not decisive, but obviously the very dry and hot conditions in the origin and transition regions, combined with relatively mild winters, in the years before, are of importance.

Conclusions

In 1473, most parts of Europe experienced extreme droughts and heat, which had a considerable impact on the natural environment, agriculture and society. The adverse impacts included the desiccation of water sources, devastating and long-lasting wildfires, cattle suffering hunger from lack of water and fodder and direct impacts on humans in the form of losses in grain, fruit and vegetable production. These patterns occurred in a sequence of hot and dry seasons between 1471 and 1474. Thus, in 1471, the hot and dry period was remarkable, whereas 1472 seemed to be less outstanding. In 1474, a dry period was reported mainly in central Europe. The documentary evidence shows that weather conditions of the first half of the 1470s were remarkable in relation to the entire fifteenth century. This period of warm and dry weather can also be confirmed through the temperature or hydroclimate reconstructions based on tree-ring and speleothem data. A direct comparison of the descriptions of the weather conditions and the heat and drought impacts on environment, economy and society and the OWDA maps even suggest that 1473 was comparable with, if not more severe than, the outstanding year of 1540.

Acknowledgements R. Brázdil acknowledges support by the Czech Science Foundation, project no. 17-10026S. We acknowledge Laurent Litzenburger (Nancy, France) for sharing his Metz data and Astrid E.J. Ogilvie (Boulder, USA) for language editing and proofreading. The paper is a contribution to the PAGES (Past Global Changes) Climate Reconstruction and Impacts from the Archives of Societies (CRIAS) working group.

Appendix

Table 3 Analysed primary and secondary sources by regions according to Eurovoc

Northern Europe (Sweden, Norway, etc.)	
Retsö and Söderberg, manuscript	Secondary source
Rørdam 1873	Primary source
Hadorph 1676	Primary source
Hausen 1890	Primary source
Franzén and Söderberg 2006	Secondary source
Western Europe (Germany, France, Belgium, the Netherlands, Switzerland, Austria, etc.)	
Buisman 1996	Secondary source
Glaser 2013	Secondary source
Camenisch 2015a	Secondary source
Larchey 1857	Primary source
Brázdil and Kotyza 1995	Secondary source
Schwarz-Zanetti 1998	Secondary source
Aston 1994	Secondary source
Keussen 1869	Primary source
Bruneau 1932	Primary source
Ilgen 1895	Primary source
Rossiaud 1994	Secondary source
Northern Europe (Sweden, Norway, etc.)	
Retsö and Söderberg, manuscript.	Secondary source
Kervyn de Lettenhove 1876	Primary source
Bernoulli 1895	Primary source
Dierauer 1900	Primary source
Kington 2010	Secondary source
Le Roy Ladurie 2004	Secondary source
Hansen 1887	Primary source
Frensdorff et al. 1892	Primary source
Litzenburger 2015	Secondary source
Southern Europe (Spain, Italy, etc.)	
Montes Romero-Camacho 1995	Secondary source
Mackay 1981	Secondary source
Borghi 1861	Primary source
Tatti 1743	Primary source
Mafrici 1994	Secondary source
Central and Eastern Europe (Czech Republic, Poland,Hungary, Slovakia, Romania, Serbia, Croatia, Ukraine, Russia, etc.)	
Bazkowski et al. 2005	Primary source
Házi and Németh 2005	Primary source
Brázdil and Kotyza 1995	Secondary source
Borisenkov and Pasetskiy 1988	Secondary source
Retsö and Söderberg, manuscript	Secondary source
Kiss and Nikolić 2015	Secondary source
Kiss 2017	Secondary source
Florianus 1884	Primary source
Kulcsár and Kulcsár 1976	Primary source
Roth 2003	Primary source

Table 3 (continued)

Schmauck 1889	Primary source
HNA DL 17427	Primary source
HNA DL 45521	Primary source
Pertz 1851	Primary source
Rohr 2009	Secondary source
Rohr 2010	Secondary source

References

Aston M (1994) On death. Perceptions of society in late medieval England. In: Horrox R (ed) Fifteenth-century attitudes. Cambridge University Press. Cambridge, pp 202–225

Bazkowski C, Kowalczyk M, Ożóg C, Prożyńska C, Turkowska D, Wyrozumski G (eds) (2005) Joannis Dlugossii Annales seu Cronicae incliti regni Poloniae. Polska Akademia Umiejętności, Cracow

Behringer W (2010) A cultural history of climate. Polity Press, Cambridge

Beniston M (2004) The 2003 heat wave in Europe: a shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys Res Lett 31/2:L02202. https://doi.org/10.1029/2003GL018857

Bernoulli A (ed) (1895) Die Anonyme Chronik der Burgunderkriege 1473–1479. In: Bernoulli A (ed) Basler Chroniken, vol. 5. S. Hirzel, Leipzig, pp. 499–527

Bonora A (ed) (1862) Chronica Civitatis Placentiae Johanni Agazzari et Antonii Francisci Villa. Pietro Fiaccadori, Parma

Borghi C (ed) (1861) Cronaca Modenese di Jacopino de' Bianchi detto de' Lancellotti. Pietro Fiaccadori, Parma

Borisenkov YP, Pasetskiy VM (1988) A thousand-year history of unusual natural events (in Russian). Mysl, Moskva

Borman C (1902) Chronique d'Adrien d'Oudenbosch. Cormaux, Liège

Brázdil R, Kotyza O (1995) History of weather and climate in the Czech Lands, vol. 1, Period 1000-1500. Geographisches Institut ETH Zürich, Zürich

Brázdil R, Pfister C, Wanner H, von Storch H, Luterbacher J (2005) Historical climatology in Europe—the state of the art. Clim Chang 70:363–430. https://doi.org/10.1007/s10584-005-5924-1

Brázdil R, Dobrovolný P, Luterbacher J, Moberg A, Pfister C, Wheeler D, Zorita E (2010) European climate of the past 500 years. New challenges for historical climatology. Clim Chang 101:7–40. https://doi.org/10.1007/s10584-009-9783-z

Brázdil R, Dobrovolný P, Trnka M, Kotyza O, Řezníčková L, Valášek H, Zahradníček P, Štěpánek P (2013) Droughts in the Czech Lands, 1090-2012 AD. Clim Past 9:1985–2002. https://doi.org/10.5194/cp-9-1985-2013

Brázdil R, Řezníčková L, Valášek H, Kiss A, Kotyza O (2014) Past locust outbreaks in the Czech Lands: do they indicate particular climatic patterns? Theor Appl Climatol 116(1–2):343–357. https://doi.org/10.1007/s00704-013-0950-9

Brázdil R, Dobrovolný P, Trnka M, Büntgen U, Řezníčková L, Kotyza O, Valášek H, Štěpánek P (2016) Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501. Clim Res 70: 103–117. https://doi.org/10.3354/cr01380

Brázdil R, Kiss A, Řezníčková L, Barriendos M (2019) Droughts in historical times in Europe, as derived from documentary evidence. In: Herget J, Fontana A (eds) Palaeohydrology. Traces, tracks and trails of extreme events. Springer, Cham, pp 65–96

Bruneau C (1932) La chronique de Philippe de Vigneulles, vol. 3, De l'an 1473 à l'an 1499. Société d'histoire et d'archéologie de la Lorraine, Metz

Buisman J (1996) Duizend jaar weer, wind, en water in de Lage Landen, vol 3. Van Wijnen, Franeker, pp 1450–1525

Camenisch C (2015a) Endlose Kälte. Witterungsverlauf und Getreidepreise in den Burgundischen Niederlanden im 15. Jahrhundert. Schwabe, Basel

Camenisch C (2015b) Endless cold. A seasonal reconstruction of temperature and precipitation in the Burgundian Low Countries during the 15th century based on documentary evidence. Clim Past 11:1049–1066. https://doi.org/10.5194/cp-11-1049-2015

Camenisch C (2018) Two decades of crisis: famine and dearth during the 1480s and 1490s in Western and Central Europe. In: Collet D, Schuh M (eds) Famines during the Little Ice Age (1300–1800): socionatural entanglements in premodern societies. Springer, Cham, pp 69–90

Camenisch C, Keller KM, Salvisberg M, Amann B, Bauch M, Blumer S, Brázdil R, Brönnimann S, Büntgen U, Campbell BMS, Fernández-Donado L, Fleitmann D, Glaser R, González-Rouco F, Grosjean M, Hoffmann RC, Huhtamaa H, Joos F, Kiss A, Kotyza O, Lehner F, Luterbacher J, Maughan N, Neukom R, Novy T, Pribyl K, Raible CC, Riemann D, Schuh M, Slavin P, Werner JP, Wetter O (2016) The 1430s: a cold period of extraordinary internal climate variability during the early Spörer minimum with social and economic impacts in North-western and Central Europe. Clim Past 12:2107–2126. https://doi.org/10.5194/cp-12-2107-2016

Campbell BMS (2016) The great transition: climate, disease and society in the late medieval world. Cambridge University Press, Cambridge

Camuffo D, Enzi S (1991) Locust invasions and climatic factors from the Middle Ages to 1800. Theor Appl Climatol 43:43–73

Cook ER, Seager R, Kushnir Y, Briffa KR, Büntgen U, Frank D, Krusic PJ, Tegel W, van der Schrier GJ, Andreu-Hayles L, Baillie M, Baittinger C, Bleicher N, Bonde N, Brown DM, Carrer M, Cooper RJ, Čufar K, Dittmar C, Esper J, Griggs CB, Gunnarson B, Günther B, Gutiérrez E, Haneca K, Helama S, Herzig F, Heussner KU, Hofmann J, Janda P, Kontic R, Köse N, Kyncl T, Levanič T, Linderholm HW, Manning SW, Melvin TM, Miles D, Neuwirth B, Nicolussi K, Nola P, Panayotov M, Popa I, Rothe A, Seftigen K, Seim A, Svarva H, Svoboda M, Thun T, Timonen M, Touchan R, Trotsiuk V, Trouet V, Walder F, Ważny T, Wilson RJS, Zang C (2015) Old World megadroughts and pluvials during the common era. Sci Adv 1/10:e1500561. https://doi.org/10.1126/sciadv.1500561 http://drought.memphis.edu

Curtis D, Roosen J (2018) Dangers of noncritical use of historical plague data. Emerg Infect Dis 24(1):103–110

Dierauer J (1900) Zürcher und Glarner Fortsetzung 1425-1433. 1460-1478. In: Dierauer J (ed) Chronik der Stadt Zürich. Mit Fortsetzungen. Adolf Geering, Basel, pp 226–271

Dobrovolný P, Moberg A, Brázdil R, Pfister C, Glaser R, Wilson R, van Engelen A, Limanówka D, Kiss A, Halíčková M, Macková J, Riemann D, Luterbacher J, Böhm R (2010) Monthly, seasonal and annual temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. Clim Chang 101(1–2):69–107. https://doi.org/10.1007/s10584-009-9724-x

Florianus M (1884) Chronica Dubniciense cum codicibus Sambuci Acephalo et Vaticano, cronicisque Vindobonensi picto et Budensi accurate collatum. M. Taizs, Leipzig

Franzén B, Söderberg J (2006) Svenska spannmålspriser under medeltiden i ett europeiskt perspektiv. Historisk tidskrift 126(2): 189–214

Frensdorff F, Lexer M, Roth F (eds) (1892) Anonyme Chronik von 991–1483. In: Die Chroniken der schwäbischen Städte, vol. 3. S. Hirzel, Leipzig, pp 445–530

Garnier E (2019) Historic drought from archives: beyond the instrumental record. In: Iglesias A, Assimacopoulos D, Van Lanen HAJ (eds) Drought. Science and Policy. Wiley, Hoboken, pp 45–67

Glaser R (2013) Klimageschichte Mitteleuropas. 1200 Jahre Wetter, Klima, Katastrophen, 3rd edn. Wissenschaftliche Buchgesellschaft, Darmstadt

Glaser R, Riemann D (2009) A thousand-year record of temperature variations for Germany and Central Europe based on documentary data. J Quat Sci 24/5:437–449

Grove JM (1988) The Little Ice Age. Routledge, London and New York

Hadorph J (1676) Dahle laghen, then i forna tijder hafwer brukat warit öfwer alla Dalarna och them som in om Dala råmärken bodde, Stockholm

Hansen J (1887) Chronik des Dietrich Westhoff von 750–1550. In: Die Chroniken der westfälischen und niederrheinischen Städte. S. Hirzel, Leipzig, pp 147–478

Hausen R (ed) (1890) Registrum ecclesiæ Aboensis eller Åbo domkyrkas svartbok, med tillägg ur Skoklosters codex Aboensis. Finlands statsarkiv, Helsingfors

Házi J, Németh J (eds) (2005) Gerichtsbuch/Bírósági könyv 1423–1531. Győr-Moson-Sopron Megye Soproni Levéltára, Sopron

HNA DL: Hungarian National Archives (HNA), Collection of medieval documents (DL), cat, no. 17427 and no. 45521, Official letters of the palatine Mihály Guti Ország to the vice-count and county judges of Hont County, 13 February and 28 March 1473

Hoy A, Hänsel S, Skalák P, Ustrnul Z, Bochníček O (2017) The extreme European summer of 2015 in a long-term perspective. Int J Climatol 37:943–962. https://doi.org/10.1002/joc.4751

Ilgen T (ed) (1895) Auszüge aus den Soester Stadtbüchern. In: Die Chroniken der westfälischen und niederrheinischen Städte, vol. 3, S. Hirzel, Leipzig, pp 1–176

Jacobs S, Calvin D (2001) Weevils on stored grains. Entomological notes. The Pennsylvania State University, College of Agricultural Sciences. Cooperative extension, University Park, PA

Keller M (2016) The science of grapevines, anatomy and physiology, 2nd edn. Academic Press, Amsterdam

Kervyn de Lettenhove JM (ed) (1876) E scriptis Petri monachi Bethleemitici chronica excerpta. In: Chroniques relatives à l'histoire de la Belgique sous la domination des Ducs de Bourgogne, vol. 3. F. Hayez, Brussels, pp 339–468

Kervyn van Lettenhove JM (ed) (1870) Chronique d'Adrien de But complétée par les additions du même auteur. In: Chroniques des religieux des Dunes, Jean Brandon – Gilles de Roye – Adrien de Brut. F. Hayez, Brussels, pp 211–710

Keussen H (1869) Chronicon monasterii Campensis ordin. Cisterciensis. Annalen des historischen Vereins für den Niederrhein 20:261–360

Kington JA (2010) Climate and weather. Collins, London

Kiss A (2017) Droughts and low water levels in late medieval Hungary II: 1361, 1439, 1443–4, 1455, 1473, 1480, 1482(?), 1502–3, 1506: documentary versus tree-ring (OWDA) evidence. J Environ Geogr 10:43–56. https://doi.org/10.1515/jengeo-2017-0012

Kiss A (2020) A dynamic interplay of weather, biological factors and socio-economic interactions: late 15th-century-early 16th-century crises in Hungary. In: Kiss A, Pribyl K (eds) the dance of death in late medieval and renaissance Europe: environmental stress, mortality and social response. Routledge, Abingdon, pp 125-145.

Kiss A, Nikolić Z (2015) Droughts, dry spells and low water levels in medieval Hungary (and Croatia) I: the great droughts of 1362, 1474, 1479, 1494 and 1507. J Environ Geogr 8(1–2):11–22. https://doi.org/10.1515/jengeo-2015-0002

Krämer D (2015) "Menschen grasten nun mit dem Vieh". Die letzte grosse Hungerkrise der Schweiz 1816/17. Schwabe, Basel

Kulcsár M, Kulcsár P (eds) (1976) Antonius de Bonfinis. Rerum Ungaricarum decades. Akadémiai Kiadó, Budapest

Laaha G, Gauster T, Tallaksen LM, Vidal J-P, Stahl K, Prudhomme C, Heudorfer B, Vlnas R, Ionita M, Van Lanen HAJ, Adler M-J, Caillouet L, Delus C, Fendekova M, Gailliez S, Hannaford J, Kingston D, Van Loon AF, Mediero L, Osuch M, Romanowicz R, Sauquet E, Stagge JH, Wong WK (2017) The European 2015 drought from a hydrological perspective. Hydrol Earth Syst Sci 21: 3001–3024. https://doi.org/10.5194/hess-21-3001-2017

Labbé T, Pfister C, Brönnimann S, Rousseau D, Franke J, Bois B (2019) The longest homogeneous series of grape harvest dates, Beaune 1354–2018, and its significance for the understanding of past and present climate. Clim Past 15:1485–1501. https://doi.org/10.5194/cp-15-1485-2019

Larchey L (ed) (1857) Journal de Jehan Aubrion, bourgeois de Metz, avec sa continuation par Pierre Aubrion. F. Blanc, Metz, pp 1465–1512

Le Roy Ladurie E (2004) Histoire humaine et comparée du climat. Canicules et glaciers XIIIe-XVIIIe siècles. Fayard, Paris

Litzenburger L (2015) Une ville face au climat. Metz à la fin du Moyen Âge (1400–1530). Presses Universitaires de Nancy, Nancy

Luterbacher J, Pfister C (2015) The year without a summer. Nat Geosci 8: 246–248. https://doi.org/10.1038/ngeo2404

Luterbacher J, Rickli R, Xoplaki E, Tinguely C, Beck C, Pfister C, Wanner H (2001) The Late Maunder Minimum (1675–1715) – a key period for studying decadal scale climatic change in Europe. Clim Chang 49(4):441–462. https://doi.org/10.1023/A:1010667524422

Lycosthenes C (1557) Prodigiorum ac ostentorum chronicon. Henricus Petri, Basileae

Mackay A (1981) Climate and popular unrest in late medieval Castile. In: Wigley TML, Ingram MJ, Farmer G (eds) Climate and history. Studies in past climates and their impact on man. Cambridge University Press, Cambridge, pp 356–376

Mafrici MV (1994) Calabria Ulteriore (1266–1860). In: Galasso G, Romeo R (eds) Storia del Mezzogiorno. Le Province VII. Edizioni del Sole, Rome, pp 95–237

Matthews JA, Briffa KR (2005) The 'Little Ice Age': re-evaluation of an evolving concept. Geogr Ann 87:17–36. https://doi.org/10.1111/j.0435-3676.2005.00242.x

Montes Romero-Camacho I (1995) Política y Economía en la Campiña Sevillana: la Producción Agraria en la Comarca de Osuna. Aproximación a su Estudio a Través de las Rentas Decimales. In: Iglesias Rodríguez JJ, García Fernández M (eds) Osuna Entre los Tiempos Medievales y Modernos. Siglos XII–XVIII. Universidad de Sevilla, Sevilla, pp 135–181

Munzar J (2004) Extreme droughts in Central Europe in the pre-instrumental period. Morav Geogr Rep 12:13–23

Oliva M, Ruiz-Fernández J, Barriendos M, Benito G, Cuadrat JM, Domínguez-Castro F, García-Ruiz JM, Giralt S, Gómez-Ortiz A, Hernández A, López-Costas O, López-Moreno JI, López-Sáez JA, Martínez-Cortizas A, Moreno A, Prohom M, Saz MA, Serrano E, Tejedor E, Trigo R, Valero-Garcés B, Vicente-Serrano SM (2018) The Little Ice Age in Iberian mountains. Earth-Sci Rev 177:175–208. https://doi.org/10.1016/j.earscirev.2017.11.010

Orth R, Vogel MM, Luterbacher J, Pfister C, Seneviratne SI (2016) Did European temperatures in 1540 exceed present-day records? Environ Res Lett 11:114021

PAGES Hydro2k Consortium (2017) Comparing proxy and model estimates of hydroclimate variability and change over the common era. Clim Past 13:1851–1900. https://doi.org/10.5194/cp-13-1851-2017

Pertz GH (1851) Continuatio Mellicensis. In: Monumenta Germaniae Historica. Scriptores, vol 9. Hahn, Hannover, pp 501–535

Pfister C (2007) Bevölkerungsgeschichte und historische Demographie 1500–1800, 2nd edn. Oldenbourg, München

Pfister C (2018) The "Black Swan" of 1540. Aspects of a European megadrought. In: Leggewie K, Mauelshagen F (eds) Climatic change and cultural transition in Europe. Brill, Leiden, pp 156–196

Pfister C, Rohr C (eds) Euro-Climhist. Information system on the history of weather and climate, http://www.euroclimhist.unibe.ch . doi: https://doi.org/10.7892/boris.73059. Accessed 30 January 2020

Pfister C, Brázdil R, Luterbacher J, Ogilvie AEJ, White S (2018) Early modern Europe. In: White S, Pfister C, Mauelshagen F (eds) The Palgrave handbook of climate history. Palgrave Macmillan, London, pp 265–295

Plarre R (2010) An attempt to reconstruct the natural and cultural history of the granary weevil, Sitophilus granarius (Coleoptera: Curculionidae). Eur J Entomol 107/1:1–11. https://doi.org/10.14411/eje.2010.001

Radkau J (2007) Holz – wie ein Naturstoff Geschichte schreibt. Oekom Verlag, München

Rohr C (2009) "Sie seind krochen wie ain kriegsordnung". Heuschreckenplagen im Land Tirol im Spätmittelalter und in der Frühen Neuzeit. Tiroler Heimatblätter 84(1):20–25

Rohr C (2010) Zur Wahrnehmung, Deutung und Bewältigung von Heuschreckenplagen in Mitteleuropa im Spätmittelalter und in der Frühen Neuzeit. In: Klein T, Prass R, Rau S, Schladitz L (eds) Umweltgeschichte in globaler Perspektive. Vortragsreihe des Historischen Seminars der Universität Erfurt im Sommersemester 2010, http://www.db-thueringen.de/servlets/DerivateServlet/Derivate-23892/Rohr_Heuschreckenplagen.pdf

Rohr C, Camenisch C, Pribyl K (2018) European middle ages. In: White S, Pfister C, Mauelshagen F (eds) The Palgrave handbook of climate history. Palgrave Macmillan, London, pp 247–263

Rørdam H (ed) (1873) Historiske kildeskrifter og bearbejdelser af dansk historie især fra det 16. aarhundrede, R 1, vol. 1. Gad, Kjøbenhavn

Rossiaud J (1994) Réalités et imaginaire d'un fleuve: recherches sur le Rhône medieval, PhD thesis, vol. 8, Université Paris I, Paris

Roth G (ed) (2003) Peter Eschenloers Geschichte der Stadt Breslau, vol 2. Waxmann, Münster

Rousseau D (2015) Fluctuations des dates de vendanges bourguignonnes et fluctuations des températures d'avril à septembre de 1378 à 2010. In: Camberlin P, Richard Y (eds) Climat. Système & interactions. XXVIIe Colloque de l'Association Internationale de Climatologie, 2-5 juillet 2014 – Dijon, pp 746–752

Schmauk M (1889) Supplementum analectorum terrae Scepusiensis, Pars II. Typogr. Episcopalis, Szepesváraljae

Schwarz-Zanetti G (1998) Grundzüge der Klima- und Umweltgeschichte des Hoch- und Spätmittelalters in Mitteleuropa. Studentendruckerei, Zürich

Shabalova MV, van Engelen AFV (2003) Evaluation of a reconstruction of winter and summer temperatures in the Low Countries, AD 764–1998. Clim Chang 58(1–2):219–242. https://doi.org/10.1023/A:1023474032539

Siklósy Z, Demény A, Szenthe I, Leél-Őssy S, Pilet S, Lin Y, Chuan-Chou S (2009) Reconstruction of climate variation for the last millennium in the Bükk Mountains, Northeast Hungary, from a stalagmite record. Időjárás 113(4):245–263

Tatti L (1743) Degli annali sacri della città di Como raccolti, e descritti dal P.[adre] D.[on] Primo Luigi Tatti Ch[ierico] Regolare della Congregazione di Somasca. Decade 1–3, appendice alla terza deca degli annali di Como. Per gli eredi di Nicolò Caprani Stampatori della Città, Como

Templ B, Koch E, Blomgren K, Ungersböck M, Paul A, Scheifinger H, Rutishauser T, Busto M, Chmielewski FM, Hájková L, Hodzić S, Kaspar F, Pietragalla B, Romero-Fresneda R, Tolvanen A, Vučetič V, Zimmermann K, Zust A (2018) Pan European phenological database (PEP725). A single point of access for European data. Int J Biometeorol 62(6):1109–1113. https://doi.org/10.1007/s00484-018-1512-8

UFZ (2018) https://www.ufz.de/index.php?de=44429 , last visited 31 January 2020

Van Loon AF, Stahl K, Di Baldassarre J, Clark J, Rangecroft S, Wanders N, Gleeson T, Van Dijk AIJM, Tallaksen LM, Hannaford J, Uijlenhoet R, Teuling AJ, Hannah DM, Sheffield J, Svoboda M, Verberein B, Wagener T, Van Lanen HAJ (2016) Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. Hydrol Earth Syst Sci 20:3631–3650. https://doi.org/10.5194/hess-20-3631-2016

Wetter O, Pfister C (2013a) An underestimated record breaking event. Why summer 1540 was likely warmer than 2003. Clim Past 9(1): 41–56. https://doi.org/10.5194/cp-9-41-2013

Wetter O, Pfister C (2013b) Spring-summer temperatures reconstructed for northern Switzerland and southwestern Germany from winter rye harvest dates, 1454-1970. Clim Past 7:1307–1326. https://doi.org/10.5194/cp-7-1307-2011

Wetter O, Pfister C, Werner JP, Zorita E, Wagner S, Seneviratne SI, Herget J, Grünewald U, Luterbacher J, Alcoforado MJ, Barriendos M, Bieber U, Brázdil R, Burmeister KH, Camenisch C, Contino A, Dobrovolný P, Glaser R, Himmelsbach I, Kiss A, Kotyza O, Labbé T, Limanówka D, Litzenburger L, Nordli Ø, Pribyl K, Retsö D, Riemann D, Rohr C, Siegfried W, Söderberg J, Spring JL (2014) The year-long unprecedented European heat and drought of 1540 – a worst case. Clim Chang 125:349–363. https://doi.org/10.1007/s10584-014-1184-2

Wilhite DA, Pulwarty RS (2018) Drought and water crises. Integrating Science, Management, and Policy. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp 3–20

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.