CHAPTER 5

The "Black Swan" of 1540: Aspects of a European Megadrought

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Abstract

This paper provides coherent evidence on what Europe might expect in the case of a worst-case heat and drought event. The record-breaking heat in 1540 was an analogous case to the 2003 event, albeit more intense, longer lasting and affecting a larger area—extending from France to Poland and from Italy to Germany, also including Spain and Morocco. Both in Switzerland and in Poland, precipitation in spring, summer, and autumn was below twentieth century averages. Discharge deficits of ninety percent were assessed for major rivers. Due to the extreme soil dessication, maximum temperatures in early August probably rose above 40°C. By then, forest and settlement fires were ravaging throughout continental Europe.

Premodern societies were surprisingly resilient to extreme conditions, notwithstanding the widespread dysentery, cattle mortality, and forest fires. The majority of the impact of a 1540-like event on present societies would be caused by the resulting severe water shortage and its cascading across interlinked systems. In particular, fossil and nuclear energy production, which depend on a sufficient amount of cooling water, would be significantly affected. Such a shortage might entail longer-lasting power blackouts with disruptive impacts on societies and economies.

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* Acknowledgements are due to the Oeschger Centre for Climatic Change Research at the University of Bern for providing a workplace and logistic support, Dr. Ursula Bieber, University of Salzburg for providing evidence on Russia, Dr. Antonio Contino, University of Palermo, for providing evidence on Italy, Prof. Dr. Adriaan de Kraker, Free University, Amsterdam for providing information about dysentery in 1540, Dr. Franz Mauelshagen, Potsdam, for the critical and constructive lecture on the text, Tamara Widmer, Institute of History, University of Bern, for bibliographical and clerical work, and Prof. Dr. Alfred Johny Wüest, Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Switzerland for providing information on green algae in Mediterranean rivers.

> What is surprising is not the magnitude of our forecast errors, but our absence of awareness of it.
>
> NASSIM TALEB[1]

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1 Black Swans and Hot Summers

A "black swan" is an outlier outside the realm of normal expectations carrying an extreme impact. Nassim Taleb, who coined the metaphor with regard to the global financial crisis, notes in this context, that most people expect all swans to be white because that's what their experience tells them; a black swan is by definition a surprise, at least outside a zoo, where black swans from Australia may be kept. Our minds are designed to retain, for efficient storage, past information that fits into a compressed narrative, but we are blind with respect to randomness, particularly to large deviations.[2] Taleb distinguishes between two different kinds of black swans. The *narrated* black swan, present in the current discourse, is overestimated, while the *implausible*[3] black swan, about which nobody talks, is underestimated and may thus come as a surprise.[4] To face the black swan, "you need a story to displace the story".[5]

With regard to climatic change, the implausible black swan is as a low-probability, high-impact event of an unimaginable magnitude. Studying the past is the best way to derive credible scenarios for such extremes, because what has already happened in the past may happen again. A recent World Bank study expects that extreme heat waves, that without global warming would be expected to occur once in several hundred years, will be experienced during almost all summer months in many regions.[6] Most climate scientists would argue that the well-known European heat wave in summer 2003 meets this

1 Taleb, Nassim N., *The Black Swan: The Impact of the Highly Improbable* (London: Allen Lane, 2007), XXV.

2 Taleb, *The Black Swan*, XX.

3 This term was coined by the author.

4 Taleb, *The Black Swan*, XX.

5 Ibid., XXXI.

6 World Bank, ed., "The Turn Down Heat: Why a 4°C Warmer World Must be Avoided," Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics, published November 2012, accessed November 20, 2014. <http://www.worldbank.org/en/topic/climatechange/publication/turn-down-the-heat-climate-extremes-regional-impacts-resilience>.

criterion. In this context, they would probably refer to the study by Isabel Chuine and co-authors published in the renowned journal *Nature*. The authors conclude from a series of grape harvest dates in Dijon (France) that the heat from April to August was probably "higher than in any other year since 1370".[7] Their findings are supported by Ulf Büntgen and co-authors who concluded from a series of tree-ring maximum latewood density measurements made in the inneralpine dry valley of Lötschental (Canton Valais, Switzerland) that the summer of 2003 was the warmest since AD 755.[8]

The summer of 2003 thus corresponds to the narrated black swan. However, was it really the worst case documented in the past centuries? García-Herrera and co-authors concede in their review article that "several summers, such as 1420 or 1540 and a few others, were as warm as or even warmer than 2003".[9]

Two recent papers demonstrate that the obsession of many scientists with summer 2003 obscured the view of the event in 1540. Not only was the heat wave in 1540 much longer, more extended and more severe than in 2003;[10] to make things worse, the associated drought persisted for eleven months, affecting most of continental Europe.[11] Several authors claimed that the drought of 1540 was outstanding (Pfister, Glaser et al., Brazdil et al. and Dobrovolný et al.).[12] Carlo Casty and co-authors concluded that the years 1540, 1921, and 2003

7 Chuine, Isabelle et al., "Historical Phenology: Grape Ripening as a Past Climate Indicator: Summer Temperature Variations Are Reconstructed from Harvest Dates since 1370," *Nature* 432 (2004): 289-290.

8 Büntgen, Ulf et al., "Summer Temperature Variation in the European Alps: A.D. 755-2004," *Journal of Climate* 19 (2006): 5606-5623.

9 García-Herrera, Ricardo et al., "A Review of the European Summer Heat Wave of 2003," *Critical Reviews in Environmental Science and Technology* 40.4 (2010): 267-306, accessed April 4, 2017 doi:10.1080/10643380802238137.

10 Wetter, Oliver, and Christian Pfister, "An Underestimated Record Breaking Event—Why Summer 1540 Was Likely Warmer than 2003," *Climate of the Past* 9 (2013): 1-16, accessed April 6, 2017. doi:10.5194/cp-9-41-2013; Wetter, Oliver et al., "The Year-Long Unprecedented European Heat and Drought of 1540—A Worst Case," *Climatic Change* 125 (2014): 349-363, accessed April 6, 2017. doi:10.1007/s10584-014-1184-2.

11 Wetter et al., "The Year-Long Unprecedented European Heat and Drought," 351.

12 Pfister, Christian, *Das Klima der Schweiz von 1525 bis 1860 und seine Bedeutung in der Geschichte von Bevölkerung und Landwirtschaft*, 2 Vols. (Bern: Paul Haupt, 1984); Pfister, Christian, *Wetternachhersage: 500 Jahre Klimavariationen und Naturkatastrophen 1496-1995* (Bern: Haupt, 1999); Glaser, Rüdiger et al., "Seasonal Temperature and Precipitation Fluctuations in Selected Parts of Europe During the Sixteenth Century," *Climatic Change* 43.1 (1999): 169-200, accessed April 5, 2017. doi:10.1023/A:1005542200040; Brázdil, Rudolf, "Fir Tree-Ring Reconstruction of March-July Precipitation in Southern Moravia (Czech

were very likely the driest in the Greater Alpine area in the context of the last five hundred years,[13] while the year 1540 is not mentioned by Pauling and co-authors among the driest seasons in their gridded multi-proxy-reconstruction for Europe.[14]

The evidence for 1540 taken from documentary data offers a broad spectrum of evidence on past weather and climate and their societal impacts.[15] It is described in a sample of 312 first-hand documentary weather reports originating from continental Europe. Most chroniclers were mainly concerned about precipitation and its human and environmental impacts, which are thus more extensively discussed than temperature.[16]

The present study is organised as follows: The second section summarises the course of the European summer heat wave of 2003 discussing the pattern of temperature anomalies and drought from multiple perspectives and addressing the role of the main contributing factors involved in the occurrence of this event. The third section describes how contemporary chroniclers and diarists witnessed the course and the consequences of the 1540 event distinguishing between meteorological, hydrological, agricultural and socio-economic drought. It is then explained how spring-summer temperatures and seasonal precipitation were assessed for 1540. The fourth section compares the socio-economic impacts of the extreme events in 1540 and 2003, and discusses the vulnerability of present-day societies in the face of a recurrent 1540-like megadrought.[17] The final section summarises the results and the main lessons that can be drawn from the study.

doi:10.3354/cr020223; Dobrovolný, Petr et al., "Precipitation Reconstruction for the Czech Lands, AD 1501-2010," *International Journal of Climatology* 2 (2014), accessed April 6, 2017, doi:10.1002/joc.3957.

13 Casty, Carlo, et al., "Temperature and Precipitation Variability in the European Alps since 1500," *International Journal of Climatology* 25 (2005): 1825-1880.

14 Pauling, Andreas et al., "Five Hundred Years of Gridded High-Resolution Precipitation Reconstructions over Europe and the Connection to Large Scale Circulation," *Climate Dynamics* 26.4 (2006): 387-405, accessed April 6, 2017. doi: 10.1007/s00382-005-0090-8.

15 Brázdil, Rudolf et al., "European Climate of the Past 500 Years: New Challenges for Historical Climatology," *Climatic Change* 101 (2010): 7-40, accessed April 6, 2017. doi: 10.1007/s10584-009-9783-z.

16 Pfister, Christian, and Rudolf Brázdil, "Climatic Variability in Sixteenth-Century Europe and its Social Dimension: A Synthesis," *Climatic Change* 43.1 (1999): 5-53, accessed April 6, 2017. doi: 10.1023/A:1005585931899.

17 The term "megadrought" is used here to denote an extreme drought extending over several seasons. In the US southwest, where droughts are common, the term is used for per-

2 The Heat Wave in Summer 2003

The atmospheric circulation in summer of 2003 was characterised by a northward displacement of the Azores anticyclone which shielded the continent from the Atlantic depressions. The shift led to consecutive episodes of intense anti-cyclonic anomalies, particularly for the months of June and August. The extensively heated continental surface induced strong meridional (South-North) air flow components which intensified the already elevated temperatures.[18]

The summer of 2003 set new standards for heatwaves and heat-periods within large parts of Europe. The largest anomalies (+4 to +5°C) were measured in a strip extending from Southern France over the Alps to the Adriatic Sea, while other parts of Central Europe still experienced anomalies of +2 to +4°C. It was the hottest summer since the beginning of instrumental measurements in most of Germany[19] with average maximum temperatures up to 30.4°C (Karlsruhe).[20] In the centre of the anomaly (Switzerland) the summer average temperature was 4 to 5.5°C higher than in the 1961-1990 reference period, surpassing the warmest summer since the beginning of systematic instrumental measurements (1864) by 2 to 3°C. Likewise, the highest average summer temperature anomaly in France was 5.3°C in Lons-le-Saunier, situated in the plain west of the Jura Mountains.[21] Maximum temperatures exceeding 30°C were measured in Basel on 51 days.[22] Two distinct periods of exceptional heat occurred during the season: the first in June and the second in the first half of August. In June, the duration of the heat was exceptional, rather than the maximum temperatures. During the August heatwave, France, Germany, Switzerland and the UK experienced record-breaking maximum temperatures.[23] In Portugal, the historical record of absolute extreme temperatures was surpassed in early August with anomalies of up to 11°C in the central sector of the country.[24] Precipitation in spring and summer 2003 was substantially below average

"Megadroughts in Southwestern North America in ECHO-G Millennial Simulations and their Comparison to Proxy Drought Reconstructions," *Journal of Climate* 26 (2013): 7636.

18 García-Herrera et al., "A Review," 277-279.

19 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode 2003 in Deutschland: Ursachen – Wirkungen – Folgen*, Mitteilungen, Nr. 27 (Koblenz, 2006).

20 Wahl, Laurent et al., "Les canicules de l'été 2003: Un événement météorologique exceptionnel dans le quart nord-est de la France," *Revue géographique de l'est* 45.2 (2005): 67-77.

21 Ibid., 70.

22 Ibid., 69.

23 García-Herrera et al., "A Review," 269.

within a zone extending from the Pyrenees over Southern France, Southern Germany, Switzerland, Austria and Northern Italy to the Northern Balkans.[25] Monthly precipitations in France, Switzerland and in Germany were below average from February to October with a maximum deficit of fifty percent in June.[26] The smallest deficits were measured in May, July and September.[27] In France, they were between 20 and 55 percent in summer. However, the summers of 1921, 1964, 1976 were much drier in this country.[28] Likewise, spring and summer in Switzerland were not particularly dry considering that spring precipitation in 2003, since the beginning of regular measurement in 1864, ranks 14th in Geneva and 43rd in Zürich. The values for summer are 16th in Zürich and 51st in Geneva.[29] The authors of a study by the Swiss Office for the Environment and the National Weather Service MeteoSwiss concluded that the summer half year in 1921, 1929, 1944 was drier than 2003, to a considerable extent also in 1947 and 1976, and that 1540 was probably even drier.[30] In summer the drought also affected the Czech Republic, Slovakia and parts of Romania. Annual precipitation deficits in Austria were twenty to thirty percent with substantial regional differences.[31] The conditions under which temperatures rise to record breaking levels were investigated after the 2003 event.[32] There is consensus that soil moisture-temperature interactions were a

25 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode 2003*, 21.

26 Wahl et al., "Les canicules," 10; Bundesamt für Umwelt, Land und Landschaft (BUWAL), "Hitzesommer 2003: Synthesebericht 2005," accessed March 28, 2017. <https://web-beta.archive.org/web/20160802130808>/<http://www.occc.ch/products/heatwave03/PDF_D/Hitzesommer03_d.pdf>.

27 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode 2003*, 21

28 Wahl et al., "Les canicules," 69.

29 Values from Begert, Michael, Thomas Schlegel, and Walter Kirchhofer, "Homogeneous Temperature and Precipitation Series of Switzerland from 1864 to 2000," *International Journal of Climatology* 25.1 (2005): 65-80. doi:10.1002/joc.1118. Updated from Meteo Schweiz.

30 BUWAL, Auswirkungen des Hitzesommers 2003 auf die Gewässer. Schriftenreihe Umwelt 369 (Bern 2004), 20.

31 Eybl, Jutta et al., *Trockenheit in Österreich im Jahr 2003: Ein hydrologischer Situationsbericht* (Wien: Bundesministerium für Land und Forstwirtschaft, Umwelt und Wasserwirtschaft Abteilung VII/3, 2004), 1/11, accessed November 20, 2014. <https://www.google.de/search?q=Trockenheit+in+%C3%96sterreich+im+Jahr+2003%3A+Ein+hydrologischer+Situationsbericht+&ie=utf-8&oe=utf-8&client=firefox-b-ab&gfe_rd=cr&ei=cfvlWKCFPLLVXqW6tPAB>.

32 See the review article by Seneviratne, Sonia I. et al., "Investigating Soil Moisture—Climate

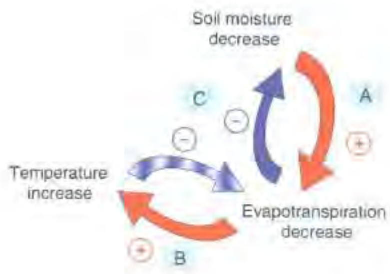

FIGURE 5.1
Processes contributing to soil moisture–temperature coupling and feedback loop

key driver in the sequence of events that led to the exceptional heat wave in August, 2003. In temperate climates, a considerable part of incoming shortwave radiation is generally used for evapotranspiration, i.e. for driving the so-called latent heat flux. The remaining sensible heat flux impacts air temperature. In case of an initial strong soil moisture deficit, which may occur after a dry spring, the share of sensible heat increases with the higher position of the sun in early summer, leading to higher air temperatures. This leads to a higher evaporative demand, and thus to a potential increase in evapotranspiration despite the dry conditions, possibly leading to a further decrease in soil moisture (figure 5.1[33]).

Sensitivity analyses suggest that, given climatologic mean soil moisture and similar continental-scale circulation, the 2003 summer (June, July, August) surface temperature anomalies would have been reduced by around forty percent. Thus, in the absence of soil moisture feedbacks, summer 2003 would still have been warm, but it would not have been such a devastating event as it turned out to be.[34]

Large rivers dropped to low levels. The discharge deficit of major German rivers in the hydrological summer half-year (April to September) was more than fifty percent for the river Meuse, situated in the Western part of the country, and for the river Odra situated in the North-eastern part, while it was somewhat lower for the Elbe (−47 percent) and the Rhine (−37 percent), fed by melt-water from the Alpine firns and glaciers.[35] However, the year 2003 does not rank among the smallest annual values in many very long German discharge-series.[36]

33 Seneviratne et al., "Investigating Soil Moisture."

34 Fischer, Erich M. et al., "Soil Moisture–Atmosphere Interactions during the 2003 European Summer Heat Wave," *Journal of Climate* 20 (2007): 5097. doi:10.1175/JCLI4288.1.

35 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode 2003*, 77.

Lake Constance, the largest lake in Central Europe, dropped to the lowest monthly average level in August and September registered since 1866. Likewise, the level of Lake Maggiore (Southern Switzerland/Northern Italy) was extremely low in July and August. The strong insulation and the extreme temperatures warmed the watercourses up massively. Water temperatures of 26°C were measured in the High Rhine at the climax of the heat wave on 12th August leading to the death of 52,000 graylings (*Thymallus thymallus L*).[37] Temperatures in the German catchment area of the Rhine were even up to 28°C.[38] It was estimated that Alpine glaciers lost five to ten percent of their total mass. The freezing limit rose above 4,500 metres above sea level for ten days, which resulted in anomalous thawing and degradation of mountain permafrost and thus a destabilisation of Alpine rock walls.[39]

Large forest fires were not registered in continental Europe, in contrast to the Mediterranean region. The 2003 fire season in Portugal represents an outlier year considering the outstanding total burned area of roughly five percent of the Portuguese territory.[40]

3 The Year 1540—an Evidence-based Worst Case Scenario

The first part of this section presents a set of documentary narratives describing the mega-drought of 1540. The focus is put on Northern Switzerland, Eastern France and Southern Germany, from where the most detailed weather descriptions are available. Probably this region was—like in 2003—situated in the centre of the anomaly. It may then become clear from these narratives why both grape-harvest dates and tree rings failed to adequately indicate the record-breaking heat wave in 1540. Subsequently it is outlined how seasonal temperature and precipitation were assessed and in what sense these results are physically coherent. With regard to dating it needs to borne in mind that the Julian style was still generally in use in 1540. The Gregorian reform was only introduced step by step after 1582. Julian dates are converted to Gregorian style

37 ProClim-Forum, and Plattform of the Swiss Academy of Sciences, "Hitzesommer 2003," 8, accessed March 29, 2017. <http://proclimweb.scnat.ch/products/heatwave03/PDF_D/Hitzesommer03_d.pdf>.

38 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode 2003*, 168.

39 García-Herrera et al., "A Review," 295.

40 Trigo, Ricardo M. et al., "Atmospheric Conditions Associated with the Exceptional Fire Season of 2003 in Portugal," *International Journal of Climatology* 26.13 (2006): 1741-1757.

by adding ten days, which is, of course, not possible, when descriptions refer to an entire month.

Documentary sources, being understood as physical units of man-made information on weather and climate, may contain two different kinds of data, namely, narrative accounts on (unusual) weather spells and weather-induced disasters on the one hand, and references to (bio) physical proxy evidence such as vegetation advances or delays in the boreal summer half year and the presence or absence of frost, ice and snow-cover on the other hand. Narrative accounts put biophysical observations within their meteorological context by shedding light on the interplay of different weather elements, such as heat, frost, wetness and drought and their impact on ecosystems and societies, which is particularly important for the analysis of record-breaking extreme events. With regard to 1540, the analysis of the megadrought mainly draws on coherent narrative accounts, while the assessment of the related heat wave draws on biophysical evidence.

Another important distinction is related to the agents who kept the sources distinguishing between individuals and institutions. Individuals were mainly motivated by concerns about the human impacts of extreme events. In doing so, chroniclers referred to (bio) physical proxy evidence as quasi-objective indicators that could be compared over time.

Institutions such as monasteries and town administrations provided public services within given territorial structures. Their office holders laid down year-by-year records on weather-dependent resources and activities, such as the time of grape and grain harvests, often for several centuries. Institutional evidence thus has the advantage, in comparison to narrative accounts, of providing continuous, quantitative and largely homogenous series of biophysical proxy data, similar to evidence from archives of nature.[41] For the present analysis, institutional proxy data in the form of grape harvest dates provide the framework for the assessment of temperatures. Prior to the French revolution, vine-growers were not free to harvest at will. They had to wait for an order by the municipality to begin the harvest.[42] In the weeks preceding the harvest, the vineyards were banned, i.e. guarded day and night. The main reason for the

41 Pfister, Christian et al., "Documentary Evidence as Climate Proxies," "White Paper" written for the Proxy Uncertainty Workshop in Trieste, 9-11 June, 2008, accessed November 6, 2013. <http://www.pages.unibe.ch/index.php/products/2029-proxy-data-uncertainties-white-paper-documentary-evidence-as-climate-proxies>.

42 Garnier, Emmanuel et al., "Grapevine Harvest Dates in Besançon (France) between 1525 and 1847: Social Outcomes or Climatic Evidence?" *Climatic Change* 104.3-4 (2011): 703-727. doi:10.1007/s10584-010-9810-0

vintage ban was preventing theft or clandestine harvesting before the owners of the vineyards and the beneficiates of tithe (i.e. taxes) could monitor the correct delivery of their dues. The date on which the grape harvest was enabled was noted down in the protocols of the community and communicated to all parties concerned.[43]

Subsequently, some narrative descriptions of the megadrought are presented.[44] Severe drought was reported from 312 chronicles representing an area of two to three million km² ranging from France to Poland including the London Basin and from Tuscany to the Northern border of Germany (figure 5.2[45]). Marc Stefanon and co-authors worked out a set of six typical European heat wave patterns for the period 1950 to 2009. The spatial location and dimension of the 1540 pattern agrees best with the pattern for "Western Europe" except that the drought in 1540 extended further east to Poland and farther south to the entire Po valley[46] (figure 5.2[47]).

Based on a network of 165 tree-ring series from the Alps, Italy, Spain, Morocco, Algeria, Greece, and Turkey, Nicault and co-authors reconstructed the widely-used Palmer Drought Severity Index for the larger Mediterranean land area over the last five hundred years.[48] Their reconstruction supports the documentary-based outstanding drought in the Alps, Italy and France. In addition, it points to severe drought in Southern Spain, Morocco, Algeria, and parts of Libya (figure 5.3[49]).

Summer 1540, as the reconstruction by Jacobeit and co-authors (figure 5.4[50]) illustrates, was characterised by a persistent diagonal South-west to North-East

43 Wetter and Pfister, "An Underestimated Record Breaking Event," 43.

44 Observations taken from Pfister, *Das Klima der Schweiz*, 138-140; Glaser et al., "Seasonal Temperature," 193.

45 Wetter et al. "The Year-Long Unprecedented European Heat and Drought of 1540," 352.

46 Stefanon, Marc, Fabio D'Andrea, and Philippe Drobinski, "Heatwave Classification over Europe and the Mediterranean Region," *Environmental Research Letters* 7 (2012): 1-9, doi:10.1088/1748-9326/7/1/014023.

47 Nicault, Antoine et al. "Mediterranean Drought Fluctuation during the Last 500 Years Based on Tree-Ring Data," *Climate Dynamics* 31 (2008): 227-245. doi: 10.1007/s00382-007-0349-3.

48 The Index developed in 1965 by the US Meteorologist Wayne Palmer is based on a supply-and-demand model of soil moisture assessed from precipitation and temperature (cf. Wikipedia, "Palmer Drought Index," accessed December 23, 2014. <http://en.wikipedia.org/wiki/Palmer_Drought_Index>).

49 Nicault et al, "Medterranean drought," 7.

50 Jacobeit, Jucundus et al., "European Surface Pressure Patterns for Months with Outstanding Climatic Anomalies during the Sixteenth Century," *Climatic Change* 43.1 (1999): 201-221. doi:10.1023/A:1005540131683806

FIGURE 5.2 *Spatial dimension of the extreme drought in 1540*

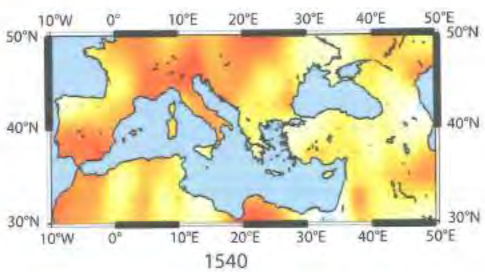

FIGURE 5.3 *Spatial dimension of the extreme drought in 1540 in the larger Mediterranean land area based on tree-ring evidence*

oriented ridge of high pressure over continental Europe connected to the Azores high widely blocking the passage of frontal zones into continental Europe.[51] According to this large-scale blocking situation, a multi-seasonal cold and wet spell might have prevailed in the region east of the anticyclone. Indeed, the famous chronicle of Novgorod (Western Russia) reports that

51 Jacobeit et al., "European Surface Pressure Patterns."

FIGURE 5.4 *Reconstructed monthly surface pressure patterns for 1540*

> 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 two weeks until the eve before Filippov [15th November].[52]

Most chroniclers reported the date of the main rain-spells and the quasi-rainless period in between as a proxy for drought severity. For example, no rain fell in England "from June [about 10th July] to eight days after Michaelmas" [18th October].[53] In Louny (Bohemia), it only rained on 8th August within the period between 26th May and 13th October.[54] People in Northern Italy were worst affected, because it did also not rain between October 1539 and early April 1540.[55] In Varese Liguria (La Spezia, Italy) not a drop fell between mid-April and 30th June [10th July], when it rained for two days. Then the terrible drought

52 *Novgorodskija i pskovskija lětopisi* [The Chronicles of Novgorod and Pskov]. *Polnoe sobranie russkich letopisej* [Complete Edition of the Russian Chronicles], vol. 4, trans. Ursula Bieber (Saint Peterburg: v tipografii Ėduarda Praca, 1848, reprinted Düsseldorf: Brückner 1973), 303.

53 "This yeare was a hott sommer and drie, so that no raine fell from June till eight daies after Michaelmas" (19th September n. st.). Wriothesley, Charles, *A Chronicle of England during the Reigns of the Tudors, from A.D. 1485 to 1559*, ed. William Douglas Hamilton (Westminster: J.B. Nichols and Sons, 1875), 45.

54 Glaser et al., "Seasonal Temperature," 193.

55 "Chronicon Pontremulense ab Anno MDXXVI usque ad annum MDXLIII a Joanne Maria De Ferrariis–vulgo Ser Marione," in Sforza, Giolio, ed., *Memorie e documenti per servire alla Storia di Pontremoli* (Lucca: Giusti, 1887), 38.

returned until 1st to 3rd [11th to 13th] August, afterwards persisting until the end of the year leaving all rivers completely dry.[56]

Four chroniclers from Switzerland and Alsace also mention the dates of short rain spells. Fridolin Ryff in Basel counted three "short and feeble" rain spells between the "beginning of summer" and St. Martin's Day [21st November], each lasting not more than two or three days.[57] Adelberg Meyer in the same town got ten precipitation days between February and 21st November.[58] Heinrich Bullinger in Zürich reports six rain-days between February and 29th September insisting that it never rained for an entire day or an entire night.[59] Hans Stolz, being a vine-grower and mayor of the small town of Guebwiller (Alsace), was the most continuous chronicler in Western Central Europe in the second quarter of the sixteenth century. He wrote about 1540: "February was warm and dry throughout. The month of March except the first three days, when it rained, was consistently dry and sunny, but ice was found every morning."[60] Ulrich Meyer (Winterthur) reports persistent cold winds,[61] probably related to a strong Siberian anticyclone dominating the weather in Central Europe at that time. April and May were sunny throughout and completely rainless. At the end of May, the grass in the Swiss Plateau had dried out and the level of brooks and small rivers was already so low that many mills stopped working. Temperatures during that time were extreme, concluding from the rapid development of vegetation. Cherry trees flowered around 10th April in Ancy-sur-Moselle (France). One month later, cherries in the same region were

56 Relazione dell'origine et successi della terra di Varese [Varese Ligure] descritta dal R.P. Antonio Cesena l'anno 1558, (La Spezia: Academia lunigianese di Scienze Giovanni Cappellini, 1982), 36.

57 "Dasz esz von anfang desz sumersz [June 1st] bisz Martini (11th/21th Nov) nit über drümol regnet; so esze schon regnet, wert esz nit über zwen oder drü tag und necht lang und klein, senfft regen," Ryff, Fridolin, "Die Chronik des Fridolin Ryff 1514-1541, mit der Fortsetzung des Peter Ryff 1543-1585: Die Chroniken des Karthäuser Klosters in Klein-Basel 1401-1532," in *Basler Chroniken*, vol. 1, ed. Historische und Antiquarische Gesellschaft in Basel (Leipzig: S. Hirzel, 1872), 86.

58 "Die Aufzeichnungen Adelberg Meyers 374-1542," in *Basler Chroniken*, vol. 8, ed. Historische und Antiquarische Gesellschaft (Leipzig: S. Hirzel, 1902), 43.

59 Bullinger, Heinrich, "Diarium (Annales Vitae) der Jahre 1504-1574," in *Quellen zur Schweizer Reformationsgeschichte*, vol. 2, ed. Emil Egli (Basel: Basler Buch- und Antiquariatshandlung, 1904), 22.

60 Tschamser, Malachias, *Annales oder Jahrs-Geschichten der Baarfüsern oder Minderen-Brüdern S. Franc. ord. insgemein Conventualen genannt, zu Thann* (Colmar, 1864), 64.

61 "Die Aufzeichnungen Adelberg Meyers," 43.

already ripe.[62] The flowering of all grapes in Schaffhausen and in Biel-Bienne (Switzerland) had ended in the last days of May (prior to 10th June),[63] about five weeks earlier than usual. In early June, the heat was already unbearable, considering the fact that quarrymen in Besançon (France) got time off from hard physical work.[64] From 18th to 22nd June it was somewhat rainy.[65] Subsequently not a drop fell for 45 days until 6th August. Hans Stolz reports that "July was torrid and dreadful until the end".[66] People in Besançon (France), unable to stand the heat in the streets during the day, took refuge in cellars after 9 a.m.[67] The heat wave peaked in early August. On August 2nd, the town council of Ulm ordered the parsons to preach "about the hot and dry weather, begging God for rain".[68]

Trees came under drought stress as leaves withered and fell to the ground like in late autumn. Forest fires became rampant in many parts of the continent, such as in the Vosges mountains,[69] in the Black Forest,[70] in the Bohemian Forest, in Thuringia, in the Spessart mountains,[71] in Hungary and in Poland,[72] infernos that nobody could get under control. Reformer Martin Luther

62 Bouteiller, Ernest de, ed., *Journal de Jean le Coullon, 1537-1587* (Paris, Nancy: D. Dumoulin, 1881), 22.

63 Huber, Oswald, *Schaffhauser Chronik* 1521-1582, ed. Carl August Bächtold (Schaffhausen: Buchdruckerei H. Meier und Cie 1906), 95; Bähler, Arnold, ed., *Bendicht Rechbergers Bielerchronik 1524-1566* (Biel, 1902, reprinted 1989), 18.

64 Delsalle, Paul, *La Franche Comté au temps de Charles Quint* (Besançon: Presses Universitaires de Franche Comté, 2004), 58.

65 Baechtold, Jacob, *Hans Salat: Ein schweizerischer Chronist und Dichter aus der ersten Hälfte des XVI. Jahrhunderts: Sein Leben und seine Schriften* (Basel: Bahnmaier's Verlag, 1876), 56.

66 Stolz, Wolfram, *Die Hans Stolz'sche Gebweiler Chronik: Zeugenbericht über den Bauernkrieg am Oberrhein* (Freiburg i.Br.: Steinmann Druck und Verlag, 1979), 373.

67 Frossard, Anatoile, "Livre de raison de la famille de Froissard-Broissia de 1532 à 1701," in *Mémoires de la Société d'émulation du Jura* (published 1886), 46.

68 Pfister, Christian, "When Europe Was Burning: The Multi-Seasonal Megadrought of 1540 and the Arsonist Paranoia," in *Disasters, Risks and Cultures: A Comparative and Transcultural Survey of Historical Disaster Experiences between Asia and Europe*, ed. Gerrit Jasper Schenk (Heidelberg: Springer, 2016).

69 Tschamser, *Annales*, 65.

70 Spicker-Beck, Monika, Räuber, Mordbrenner, *Umschweifendes Gesind: Zur Kriminalität im 16. Jahrhundert* (Freiburg i.Br.: Rombach, 1995), 231.

71 *Chronik der Stadt Kitzingen*, Stadtarchiv Kitzingen, Manuscript, Msc. 314.

72 Glaser et al., "Seasonal Temperature," 193.

anticipated the far-reaching consequences of this calamity in terms of rising prices for timber.[73] School teacher Hans Salat writes:

> On Mary and Magdalene's day [31th July] I went to Solothurn. It was unbearably hot, everybody complained about water shortages. Forests were burning everywhere around. The sun and the moon, being reddish at their rising and setting, looked pale during the day, because the sky was dark of mist and smoke. Mount Pilatus [above Lucerne] could hardly been seen in the morning due to fog conditions like in autumn.[74]

Similarly, the inhabitants of Schneeberg (Saxony) complained about breathing in stinking smoke during the night emitted from forest fires.[75] The scientist Marcin Biem reported from Cracow (Poland) that the sun often retained a reddish colour throughout the day due to the presence of smoke in the air. Glaser and co-authors argue that this smoke was probably the effect of a cover of forest fire aerosols,[76] as was observed during the Russian drought in 2010. Likewise, town fires in Germany, according to a unique statistic of 8,200 events set up by Cornel Zwierlein, were more frequent in 1540 than in any other peace year since AD 1000.[77] This gives reason to believe that settlements became fire-prone at about the same rate as forests. No thunderstorm was observed in contrast to summer 2003.[78] On the other hand, the Lucerne botanist and

73 On 26th July/4th August Martin Luther wrote to his wife: "ist ym Düringer walt mehr denn tausent acker holtz abgebrand vnd brennet noch, dazü sind heüte zeitung, das der wald bey werda aüch angangen sey. Vnd an vil orten mehr, hilfft kein lesschen. das wil theür holtz machen." Luther, Martin, „Luther an seine Ehefrau" [Eisenach,] 16/26, Juli 1540, in *D. Martin Luthers Werke: Kritische Gesamtausgabe*, ed. Otto Clemen, Abt. Briefwechsel, vol. 9 (1540-1528), Februar 1542, Nr 3519 (Weimar: Hermann Böhlaus Nachfolger, 1941), 204-205.

74 "Um M. Magdalene [31. July n. st] gieng ich gen Soloturn [...] [es war] unbillich heiss, clagt sich all welt fast um wasser, was am uf- und nidergang sunn und man bluot rot; schinendn ouch ganz bleich, dann der himel was tunkel von itel hitznebel. Es brunnend die weld an vil orten, [...] an eim morgen was es uf der wyti nit anders von rouh und hitz, als im herbst mit nebel, dass man Pilatusberg kum sehen moht." Baechtold, *Hans Salat*, 56.

75 Melzer, Christian, *Bergkläufftige Beschreibung der Churfürstl. Sächß. freyen und im Meißnischen Ober-Erz-Gebirge löbl.* Bergk-Stadt Schneebergk (Schneeberg, 1684).

76 Glaser et al., "Seasonal Temperature," 193.

77 Zwierlein, Cornel, *Der gezähmte Prometheus: Feuer und Sicherheit zwischen Früher Neuzeit und Moderne* (Göttingen: Vandenhoeck & Ruprecht, 2011).

78 Concurrent observations by Ryff, "Die Chronik;" Stolz, *Die Hans Stolz'sche Gebweiler Chronik* and an anonymous chronicler from Lindau quoted in Burmeister, Karl Heinz, "'Der heiße Sommer' 1540 in der Bodenseeregion," in *Schriften des Vereins für Geschichte*

politician Renward Cysat reports eyewitness accounts that Alpine meadows were literally "irrigated" every morning by abundant dew. This effect was possibly generated by the intensive daytime evaporation of the then larger glaciated areas and the subsequent condensation during the night.[79]

Hans Salat reports that it rained in Lucerne for some days after 11th August so that meadows became green again.[80] Farther north the rain was more intensive and longer lasting causing floods in the Main, middle Rhine, Elbe and Danube River system.[81] Afterwards, rain spells were again sporadic for the rest of the year. Vine grower Hans Stolz noted a second bloom of fruit trees in early September 1540 in Alsace,[82] which reflects similar observations being made in Munich at the same time in 2003.[83] Based on observations of a record breaking second flowering of vines on 9th October and cherries reaching maturity for a second time in Lindau on the shore of Lake Constance[84] it is concluded that September and October were warmer than in 2003. The reports by several chroniclers agree that weather in the remaining part of the year was sunny and warm "like in April" without any frost and snow covering the ground until Christmas (Julian Style), i.e. 4th January 1541. At that time, several adults demonstratively swam across the Rhine at Schaffhausen (Switzerland)[85] to capture the attention of chroniclers. They were eager to include such physical evidence into their narratives to demonstrate how extraordinarily warm the water still was at the end of this longest known bathing period in European history.[86] Taking into account the preceding record-breaking spring-summer temperature anomaly and the outstandingly warm conditions until December 1540, we assume that water temperatures might have been at about 15°C at the end of the year which still is somewhat below comfortable water temperatures

des Bodensees und seiner Umgebung, vol. 126, ed. Jürgen Klöckler (Ostfildern: Jan Thorbecke, 2008), 61.

79 Cysat, Renward, "Stationes Annorum: Witterung, Missjahre, Teuerung," in *Collectanea Chronica und denkwürdige Sachen pro Chronica Lucernensi et Helvetiae*, Abt. 1, vol. 1, part 1, ed. Josef Schmid (Luzern: Diebold Schilling Verlag, 1969), 935.

80 Baechtold, *Hans Salat*, 61.

81 Glaser, Rüdiger et al., "The Variability of European Floods since AD 1500," *Climatic Change* 101 (2010): 235-256.

82 Stolz, *Die Hans Stolz'sche Gebweiler Chronik*, 374.

83 Wikipedia, "Hitzewelle 2003," last modified January 21, 2014, accessed April 6, 2017. <http://de.wikipedia.org/wiki/Hitzewelle_2003>.

84 Burmeister, "'Der heiße Sommer' 1540," 62.

85 Huber, *1521-1582: Schaffhauser Chronik*, 95.

86 Wetter and Pfister, "An Underestimated Record Breaking Event," 51.

for swimming.[87] Maximum water temperatures of the Rhine measured at this time of the year within the period 1978 to 2011 were about 11°C in December 2006 and about 9°C in January 2007.[88] Updated European averaged autumn and winter air temperature time-series indicate that temperatures for autumn 2006 and winter 2007 were likely the highest since 1540.[89]

Because reported dates of rainfall are not entirely consistent among the four key chroniclers, all rain-days mentioned at least by one chronicler were aggregated to get believable though perhaps overrated seasonal values. To be sure, values in spring, summer and autumn are even below the absolute minima of the instrumental period (since 1864). The annual estimate for 1540 including ten precipitation days for the missing January observation is forty percent below the lowest instrumental measurement since 1864. Reliable data on precipitation frequency from East Central Europe were obtained from the only weather diary so far known. It was kept by Marcin Biem, who was a theologian and president of the renowned Cracow University.[90]

Considering the cumulative deficit of precipitation days from the 1901-2000 average (figure 5.5[91]), the 1540 drought was significantly more persistent and extreme than the recent events in 2011 and 2003.

The amount of precipitation depending on the observed rain-days was estimated through a hierarchy of statistical models.[92] From figure 5.6[93] it is concluded that the precipitation in Western Europe remained significantly below one hundred-year minimum levels in 1540 throughout spring, summer and autumn. The reconstructed annual precipitation of 236 millimetres (24 percent) is somewhat below of the 'guesstimate' attempted by the author in 1984.[94] No event of similar severity is known within the instrumental period. In Poland, the drought likewise persisted over three seasons, but it was somewhat less severe, as precipitation was possibly above the one hundred-year minimum (including upper uncertainty amounts). The year 1540 is the warmest

87 Loc cit.

88 Data from the Swiss Federal Office for the Environment (FOEN).

89 Luterbacher, Jürg et al., "The Exceptional European Warmth of Autumn 2006 and Winter 2007: Historical Context, the Underlying Dynamics and its Phenological Impacts," *Geophysical Research Letters* 34.12 (2007): 1-6. doi:10.1029/2007GL029951.

90 Wetter, and Pfister, "An Underestimated Record Breaking Event."

91 Source: Wetter et al. "The Year-Long Unprecedented European Heat and Drought of 1540," 355.

92 Ibid., 354.

93 Temperature reconstruction based on the homogenised Swiss GHD series covering the period from 1444–2011.

94 Pfister, *Das Klima der Schweiz*, 138, guesstimated "a third at the most".

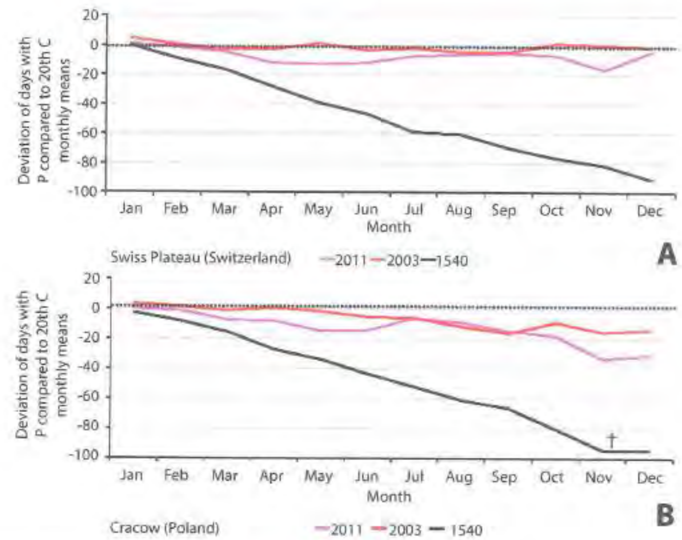

FIGURE 5.5 *Cumulative deviations of the number of precipitation days in 1540 in Northern Switzerland and in Cracow (Poland) in comparison with twentieth century values*

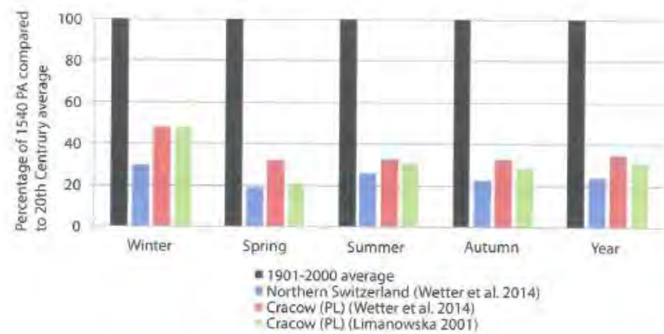

FIGURE 5.6 *Estimated 1540 seasonal precipitation in Northern Switzerland and in Cracow (percent) compared to the twentieth century*

since 1500 in the Central European temperature series[95] and the driest in the Czech Republic.[96] The 2015 Central European summer precipitation was the

95 Dobrovolný et al, "Monthly, Seasonal and Annual Temperature Reconstructions for Central Europe Derived from Documentary Evidence and Instrumental Records since AD 1500." *Climatic Change* 101.1-2 (2010): 69-107. doi:10.1007/s10584-009-9724-x.

96 Dobrovolný et al, "Precipitation Reconstruction for the Czech Lands, AD 1501-2010."

lowest on record since 1901.[97] In some locations the German Weather Service only measured half of the long-term mean.[98] However, the amounts measured for two Swiss stations substantially exceeded the estimates for summer 1540.[99]

A great number of observations about the level of lakes and rivers, i.e. the hydrological drought, are available. Lake Constance dropped to such a low level in August, 1540, that the lake floor with its mountains and valleys emerged over considerable distance. The island of Lindau was temporarily connected by a land bridge to the coast and people walked around it on the dry sea-ground.[100] The lake level was thus lower than in 2003. A woman named Anna Schmid was lucky enough to dig out a pot containing nine hundred silver coins from the time of Emperor Augustus.[101] This level of Lake Constance was close to the lowest ones recorded in the driest winters since 1550.[102] It should be pointed out that winter low water levels of Lake Constance are comparatively common, because in this season precipitation, especially in the 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. The discharge deficit of the river Rhine in Basel, still fed by melt-water from the then more glaciated Alps, was about ninety percent below its corresponding twentieth century mean value. Near Cologne, four hundred kilometres farther north, the relative discharge of the river was the same order of magnitude. The Rhine

97 Orth, René, Jakob Zscheischler, and Sonia I. Seneviratne, "Record Dry Summer in 2015 Challenges Precipitation Projections in Central Europe," *Scientific Reports* 6 (2016). doi: 10.1038/srep28334.

98 Deutscher Wetterdienst – Wetter und Klima aus erster Hand, "Deutschlandwetter im Jahr 2015," last modified December 30, 2015, accessed November 8, 2016. <https://www.dwd.de/DE/presse/pressemitteilungen/DE/2015/20151230_deutschlandwetter_jahr2015_news.html.

99 Bundesamt für Meteologie und Klimatologie Meteoschweiz, "Datenportal für Lehre und Forschung," Summer (JJA) 2015: Zürich 242 millimetre, Basel 191 millimetre, accessed May 13, 2017. <http://www.meteoschweiz.admin.ch/home/service-und-publikationen/beratung-und-service/datenportal-fuer-lehre-und-forschung.html>. Summer (JJA) 1540: 91 millimetre (estimated) (Wetter et al. 2014, Supplementaries, Table S4).

100 "Der See war im Sommer so klein, daß man rings um die Stadt gehen und im Wasser Berg und Thal sehen konnte." *Schnell'sche Chronik, Manuscript*. Stadtarchiv Lindau, Lit 29, 99.

101 Burmeister, "'Der heiße Sommer' 1540," 77.

102 Pfister, Christian, Rolf Weingartner, and Jürg Luterbacher, "Hydrological Winter Droughts over the Last 450 Years in the Upper Rhine Basin: A Methodological Approach," *Hydrological Sciences-Journal-des Sciences Hydrologiques* 51.5 (2006): 966-985. doi:10.1623/hysj.51.5.966.

downstream of Basel, the Seine near Paris and the Elbe near Meissen could be waded through in some places. The water of the river Meuse, being the second largest tributary of the Rhine, was green and unsuitable for drinking, due to a very slow flow and high water temperatures promoting the growth of green algae,[103] as is known from Mediterranean rivers in summer.[104] Around Liège, Belgium, cattle were seen wading in the nearly stagnant water.[105] Likewise, the Odra River "was green" according to a Czech source.[106] The flow of the river Thames in London was so feeble that the salt water penetrated further upstream than London Bridge. Navigation on the river Po in Northern Italy ceased completely. Smaller watercourses such as the river Doubs in France were completely dry.[107] In July, the water shortage became acute,[108] considering that fountains ran dry that so far had never failed. This shortage points to a substantial drop in ground-water tables. In Canton Lucerne, desperate people were digging for water 1.5 metres deep in the bed of a small river without finding a single drop.[109] People in Parma, Italy, had to cart water from river Po over a distance of twenty kilometres, because their wells were all dry.[110] Those in Avignon, Southern France had to get their water from the river Rhone.[111] All

103 "Aussi en fut la Moselle si courte, Que l'eaue à la Ville estoit très courte, Elle changea & devint si verde Qu'on en pouvoit en œuvre metre." The level of river Moselle was so low near the town [of Metz, Lorraine] that the water became green and could not be used any more (Calmet, Augustin, "Chronique de la noble cité de Metz: Preuves servant à l'histoire de Lorraine," in *Histoire de Lorraine*, vol. 3, ed. Augustin Calmet, François Jean-Baptiste Noël and Auguste Prost, col. Cccxxviij (Paris: Éditions du Palais Royal, 1973). (Interpretation provided by Prof. Dr. Alfred Johny Wüest, EAWAG, CH 6047 Kastanienbaum, Switzerland.)

104 Power, Mary E. et al., "Algal Mats and Insect Emergence in Rivers under Mediterranean Climates: Towards Photogrammetric Surveillance," *Freshwater Biology* 54.10 (2009): 2101-2115. doi:10.1111/j.1365-2427.2008.02163.x.

105 Buisman, Jan, and Aryan F.V. van Engelen, *Duizend jaar weer, wind en water in de lage landen*, vol. 3 (*1450-1575*) (Franeker: Van Wjnen, 1998), 466.

106 Brázdil, Rudolf et al., Climate of the Sixteenth Century in the Czech Lands, History of Weather and Climate in the Czech Lands (Brno: Masaryk University, 2013).

107 Delsalle, Paul, *La Franche-Comté*, 58.

108 At the end of July "giengend brunnen und wasser ab, so bi mentschen tenken nie abgangen warend". Baechtold, *Hans Salat*, 56.

109 Baechtold, *Hans Salat*, 56.

110 Sforza, G., ed., *Memorie e documenti per servire alla Storia di Pontremoli* (Lucca: Giusti, 1887), 59.

111 Mémorial d'Aix en Provence quoted in: Pichard, George, and Emeline Roucaute, "Sécheresses du Bas Rhone et invasions de sauterelles," accessed August 25, 2014. <http://histrhone.cerege.fr/squelettes/pdf/Chronologie_Secheresses_Bas_Rhone.pdf>.

this could be taken to imply that most people living some distance from lakes or large rivers were left high and dry. Local conflicts over water were probably frequent, but the respective local sources have so far hardly been examined under this context.

In conclusion, Western and Central Europe suffered from a dust-dry spring in 1540, which was then followed by a torrid summer and an almost rainless autumn, making 1540 to the worst drought year of the last five centuries. On the basis of these results, it becomes plausible that temperatures in 1540 might have been higher than in 2003, as will be subsequently demonstrated.

In a previous study, Wetter and Pfister investigated the severity of the heat wave going along with the megadrought. At first, the authors attempted an in-depth view of the Dijon vine harvest series from the archives. Firstly, it turned out that the outstanding heat wave in August 2003 could not have mattered for the Dijon grape harvest date of 15th August. According to the renowned oenologist John Gladstones, "temperatures of the first two or three growing season months [...] can usually predict quite closely the dates of [...] maturity to follow [...]. The later phenological intervals [...] tend to be constant from year to year".[112] Gladstone's observation agrees with the statistical analyses that August temperatures are not significant for the harvest date. Secondly, two historians, Thomas Labbé and Damien Gaveau, discovered through a critical reinterpretation of the Dijon series in the municipal archives that the correct harvest date for 1540 was 3rd September, instead of 4th October given by Isabel Chuine and co-authors.[113] Thirdly and most importantly, the beginning of grape harvest in 1540 was postponed in many places beyond grape maturity. Vine-growers in Schaffhausen (Switzerland) were "long waiting for rain to begin the harvest", as chronicler Oswald Huber relates. Nevertheless, he writes, "they finally tackled the work because the plants withered."[114] Vine growers at the shores of Lake Constance and in the Upper Alsace interrupted the vintage after picking the juicy grapes, because the remaining ones had already become raisins. The vintage was only resumed after a two-day rain spell on St. Michael's Day [8th October].[115] By waiting for rain, vine growers hoped to get more juice into the berries, as their income, regardless of prices, depended on the quantity of liquid they got from the wine press. The situation in France was hardly different.[116] Pierre de Teysseulh being 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."[117] The unintentional sweet-late vintage yielded a sherry-like wine, which made people rapidly drunk.[118]

Wetter and Pfister set up a long series of grape harvest dates for Switzerland (1444-2011) to re-assess temperatures in France and Switzerland in 1540. It turned out that grape harvest dates are not available for 1540 in Switzerland, probably because the current practice of the harvest ban could not be maintained under the extraordinary situation in that year. The likely date of full grape maturity in the Swiss Mittelland was thus estimated from grape phenological evidence to be between 12th and 24th August. The reconstruction of mean temperatures from April to July yielded an estimate of 4.7°C and 6.8°C (+/−0.5°C) above the 1901-2000 regional mean depending on the assumed value for full grape maturity.[119]

Even the lower of these estimates is significantly higher than the anomaly of +2.86°C measured for April to July temperatures in 2003 (figure 5.7[120]). In interpreting this result, it needs to be conceded that the two dates for full grape maturity underlying the temperature assessment are statistically shaky. Using climate model output based on the relationship between the number of dry days and temperatures, René Orth and co-authors recently re-examined the question whether the summer in 1540 was warmer than in 2003. The results suggest a high probability that maximum temperatures in 1540 exceeded those in 2003, whereas for mean temperatures, such a probability is rather low.[121] These results concur with the fact that August temperatures could not be statistically estimated. It is also consistent with the fact that widespread forest and settlement fires were observed towards the end of the rainless July 1540. In 2003 forest fires mainly ravaged in the Mediterranean basin, particularly in Portugal, where temperatures of more than 40°C were measured during the

112 Gladstones, John, *Wine, Terroir and Climate Change* (Kent Town: Wakefield Press, 2011), 7.

113 Labbé, Thomas, and Fabien Gaveau, "Les dates de bans de vendange à Dijon: Etablissement critique et révision archivistique d'une série ancienne," *Revue Historique* 657.1 (2011): 19-51. doi:10.3917/rhis.111.0019; Chuine, Isabelle et al., *Burgundy Grape Harvest Dates and Spring-Summer Temperature Reconstruction*, published by IGBP PAGES/World Data Center for Paleoclimatology, 2005, 2 Data Contribution Series #2005-007. Boulder Co. 2005.

114 Huber, 1521-1582: Schaffhauser Chronik, 95.

115 Burmeister, "Bodenseeregion," 64; Stolz, *Die Hans Stolz'sche Gebweiler Chronik*, 379.

116 Wetter et al., "The Year-Long Unprecedented European Heat and Drought of 1540," 359.

117 Leroux, Alfred, and Auguste Bosvieux, ed., "Extraits du Journal de Me Pierre de Teysseulh : chanoine de l'église de Limoges, 1533-1568," in *Chartes, Chroniques et Mémoriaux pour Servir à l'Histoire de la Marche et du Limousin*, ed. Alfred Leroux and Auguste Bosvieux (Tulle: Crauffon, 1886), 259.

118 Kessler, Josua, *Chronologie Santgallischer Begebenheiten vom Jahr 1540 bis Ende des Jahres 1645, Handschriften Nr. 74*, Manuscript (St. Gallen: Stiftsarchiv St. Gallen, n. d.).

119 Wetter, and Pfister, "An Underestimated Record Breaking Event," 41.

120 A questionable comparison of the outstandingly hot years 2003 and 1540.

121 Orth, René et al., "Did European Temperatures in 1540 Exceed Present-Day Records?," *Environmental Research Letters* 11.11 (2016). doi: 10.1088/1748-9326/11/11/114021.

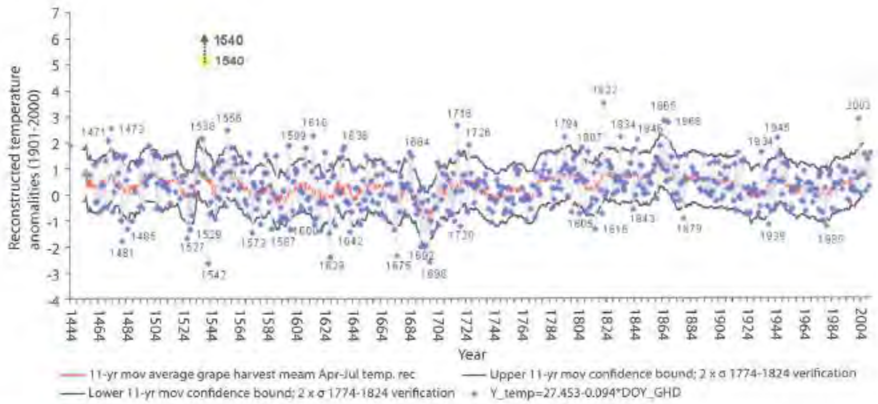

FIGURE 5.7 *Temperature reconstruction based on the homogenised Swiss GHD series covering the period from 1444-2004*

peak of the heat wave.[122] Similarly high temperatures might have been reached at the peak of the 1540 heatwave in Central Europe.

On the other hand, the conclusion that the period from April to July 1540 was warmer than in 2003 seems plausible considering the physical reasons for severe droughts and the outstanding environmental context of the event. Spring droughts are an important precondition for the triggering feedbacks of soil dessication and temperature underlying extreme heat waves. Undoubtedly, the spring drought in 1540 was longer lasting and more intense than in 2003 and it was then followed by the summer drought, which further intensified the feedback between soil dessication and temperature. Eye observations about extreme soil dessication and soil cracking confirm the hypothesis of a record-breaking soil moisture deficit. Some cracks were so wide that people could put their feet into them.[123] In contrast to 2003, the drought in 1540 persisted until the end of the year. Annual temperatures in 1540 for Germany, Switzerland and the Czech Republic estimated from documentary "Pfister indices" were 2.3°C (±0.4°) higher than in 1901-2000, which is the highest value since 1500.[124]

Several authors showed that summer heat waves in Central Europe are associated with a precipitation deficit in winter and spring in Southern Europe, as droughts in the South cause unusual low cloud cover which is then transported

122 Trigo et al., "Atmospheric Conditions."

123 Goldschmid, Johann Jakob, *Erzellung seltsammer Natur-Geschichten* [...] *so sich bey uns in der Statt Wintertur zugetragen haben* (*bis 1543*), vol. 3, Ms Fol. 3, Stadtbibliothek Winterthur.

124 Dobrovolný, Petr et al., "Monthly, Seasonal and Annual Temperature Reconstructions."

northward, enhancing existing anti-cyclonic conditions.[125] This cause-and-effect relationship can also be demonstrated for the 1540 megadrought. Chroniclers in Northern Italy report that winter 1540 was "like in July"[126] with no rain falling from 10th [20th] November 1539 to 6th [16th] April 1540, leaving wells dessicated.[127]

In conclusion, the record-breaking heat and drought of 1540 was an analog case to the 2003 event, but it was more intense, spatially more extended and longer lasting. This result was challenged by Büntgen and co-authors (2015) based on a large sample of tree-ring width measurements. The authors argued that Wetter and co-authors (2013, 2014) "probably overstated the intensity and duration of the 1540 drought event."[128] On the other hand, it needs to be noted that an earlier tree-ring study led by the same author trees demonstrated that a very small tring ring width emerges in 1541, which was interpreted as the lagged result of the severe drought in 1540.[129] This interpretation is supported by the tree-ring study of Nicault and co-authors who concluded that trees in the larger Mediterranean land area including the Alps suffered from a severe drought in 1540 (Figure 3).[130]

4 Vulnerabilities of Pre-modern and Present-day to Severe Drought

Climate impacts are joint products of the interaction of climate and society. Social vulnerability exists within human systems independently of external hazards. It determines whether a society is more or less vulnerable to climatic shocks. Under these premises, similar climatic impacts will have different

125 Stefanon, Marc, Fabio D'Andrea, and Philippe Drobinski, "Heatwave Classification over Europe and the Mediterranean Region," *Environmental Research Letters* 7 (2012): 1-9. doi:10.1088/1748-9326/7/1/014023.5.

126 Burigozzo, Giovanni Maria, "Cronaca di Milano dall'anno 1500 sino al 1544," in *Archivio Storico Italiano*, vol. 3, ed. G.P. Viesseux (Florence: Leo S. Olschki, 1842), 539.

127 Fossati, Francesco, ed., *Opere scelte di Benedetto Giovio* (Como: Fostinelli, 1887, reprint 1982), 36.

128 Büntgen, Ulf et al., "Limited Tree-Ring Evidence for a 1540 European 'Megadrought'. Commentary to Wetter et al. (2014)," *Climatic Change Letters* (2015).

129 Büntgen, Ulf, et al., "Combined Dendro-Documentary Evidence of Central European Hydroclimatic Springtime Extremes over the Last Millennium," *Quaternary Science Reviews* 30 (2011). doi:10.1016/j.quascirev.2011.10.010; Pfister, Christian, Wetter Oliver, et al., "Tree-Rings and People—Different Views on the 1540 Megadrought. Reply to Büntgen et al. (2015)," *Climatic Change Letters* (2015).

130 Nicault et al., "Mediterranean Drought Fluctuation," 7

socio-economic consequences under different sets of social conditions. Many different concepts of vulnerability are known in the literature. This analysis uses the generally applicable vulnerability scheme worked out by Hans-Martin Füssel, distinguishing between four groups of related vulnerability factors:

1. A focus of analysis such as an human-environment system, a geographical region or an economic sector;
2. an attribute of concern of the analysed system such as income or health;
3. a hazard which threatens attributes of the system; and
4. a temporal reference.

In a first step, the analysis explores the vulnerability of pre-modern societies to the megadrought. In the second step the vulnerability of key branches of present-day economies is investigated from the example of 2003. In the last step, the physical boundary conditions assessed from the analysis of the 1540 megadrought are used to consider the vulnerability of present-day societies for an extreme event of this magnitude.

Subsequently, the impacts of the megadrought on contemporaries are described. Water scarcity was the worst effect. Where wells and fountains were dry, people had to get water over considerable distances, usually at night.[131] For example, the residents of the small village of Goldiwil situated five hundred metres above the town of Thun (Canton Bern) had to get water from Lake Thun on donkeyback.[132] Well water was priced in some regions. In Lake Constance, upstream of the Rhine valley, it was more expensive than wine.[133] High mortality is reported in some chronicles, which, considering the heat and lack of water, might mostly have been caused by dysentery.[134] "Many people fell ill," we read in a chronicle from Gent (Belgium), "[...]and there was red melisoen [illness] which in particular affected people's defecation very much,

131 Cysat, "Stationes Annorum," 905.

132 Züricher, Gertrud, ed., Karl Friedrich Ludwig Lohners Chronik der Stadt Thun (Bern: Haupt, 1935), 74.

133 Walser, Gabriel, *Neue Appenzeller Chronick oder Geschichte des Landes Appenzell der Innern und Äussern Rhoden* (St. Gallen: Selbstverlag, 1740), 484.

134 "In Folge der grossen Hize des vorigen Jahres entstand in diesem eine höchst mörderische Krankheit, welche der grosse Tod genannt wurde und nach unverbürgten Nachrichten an 3.000 Personen in unserer Stadt, sowie zwei Fünftheile der Bewohner unserer Landschaft wegraffte." Cf. Im-Thurn, *Chronik der Stadt Schaffhausen*, 68. "In y latter ende of this moneth, was vniversally through the realme greate death, by reason of newe hote agues and Flixes, and some Pestilence." Cf. Holinshed, Raphaell, *The Description and Histories of* [illegible]

because many people died from mid-August until December which was caused by the great vehement heat."[135]

Three branches of the economy particularly suffered from the drought: agriculture, energy production and transportation. Watering of cattle and small livestock became critical. Animals were driven to drink over long distances up to and beyond ten kilometres.[136] Hay harvests completely failed and prices skyrocketed.[137] Cattle all over Europe died of thirst and hunger, as chroniclers from England, Alsace (France), Cologne (Germany) and Northern Italy reported.[138] In many cases, animals may have died from heat stroke. Many more were probably slaughtered. Hence, prices for milk and dairy products surged.[139] Spring grains, fruit and legumes failed completely. The harvest of winter grain, which was the major food crop, was satisfactory in Central Europe, because yields and related water needs were much below present-day values, but this crop failed in Northern and Central Italy, because the drought there already began in autumn 1539 leading to severe famine and widespread (e)migration.[140]

135 Anonymous, MS 2543, University Library Ghent, kindly provided by Adriaan de Kraker, Utrecht University. Likewise: Stolz, *Die Hans Stolz'sche Gebweiler Chronik*, 373, mentions "many people [in Alsace] dying from an epidemic".

136 "Das Baursvolck muoßt an etlichen enden weit her [...] mit dem Viehe zuotrencken/ fahren." Cf. Wurstisen, *Basler Chronik*, 79. "In divers partes of this realme the people caried their cattle six or seven miles to watter them." Cf. Wriothesley, *A Chronicle*, 123.

137 "Und ward das heuw thur, und das veche fast wolfeill." Anonymus, ed., "[...] Die Anonyme Chronik bei Schnitt, sammt Fortsetzung: 1495-1541 [...]," in *Basler Chroniken*, vol. 6, ed. Historische und Antiquarische Gesellschaft in Basel (Leipzig: S. Hirzel, 1902), 220.

138 For England: "Muche cattell died for lacke of water." In Grafton, Richard, *Grafton's Chronicle, or history of England [...] from the year 1189 to 1558, inclusive, Volume 2* (London: J. Johnsen, 1809), 475. For Guebwiller (Alsace): "Und starb vill vieh an etlichen orten wasserhalb." Stolz, *Die Hans Stolz'sche Gebweiler Chronik*, 376. For Cologne: "Vil beisten storben". Höhlbaum, Konstantin, ed., *Das Buch Weinsberg: Kölner Denkwürdigkeiten aus dem 16. Jahrhundert. Erster Band* (Leipzig: Dürr, 1886), 45. For Modena (Northern Italy): "Dominica a di 25 Questo dì [...] è stato et è uno excessivo caldo [...] fu uno secho antiquamente tanto grande che li poci [pozzi] se secorno per tutto el modoneso e moriva bestie assai de fame e de sete" (Sunday 25th July/4th August was an unbearable heat and a drought of such extent that the wells got dry in the entire region and animals died from hunger and thirst), in Borghi, Carlo, ed., *Tomasino de Bianchi detto de Lancellotti: Cronica Modenese, 1538-1540. Monumenti di Storia Patria delle province modenesi*, vol. 7 (Parma: Fiaccadori, 1868), 56.

139 Ryff, "Die Chronik," 86.

140 Many chronicles from Northern and Central Italy mention a terrible famine (for example, Borghi, *Tomasino de Bianchi detto de Lancellotti*,

Likewise, the transportation sector was affected. Waterways were important for transportation prior to the creation of railway networks. For example, preindustrial river transport before the early 19th century accounted for ninety percent of goods transported on the Middle Rhine.[141] Highly priced goods made up the lion's share of the upstream cargo and bulky goods dominated the downstream cargo.[142] Erich Weber demonstrated in his illustrative dissertation that river navigation on the Middle Rhine was impossible during "extreme low flows"[143] that were, however, above those described in 1540. The situation of river navigation was not much better on the High Rhine. The small transport ships between Lake Constance and Schaffhausen carried less than half their usual cargo,[144] whereas goods hauled downstream from Schaffhausen to the Basel Fair were entirely transported by land.[145] Navigation on the river Po and its tributaries in Northern Italy was discontinued in the drought until late November, at which time water levels were usually high due to abundant rains in the Apennine Mountains.[146]

The main energy source collapsed with the ebbing of water. For preindustrial societies, the worst effect of this situation was a standstill of mills except those within big rivers. Mills pulled by horse driven capstans were set up as a substitute in some places. In others, people resorted to the use of hand-mills. Surging prices for flour and bread and the lack of water resulted in life-threatening circumstances, especially for the poor.[147] Trades such as hammer-mills became idle leaving the workers unemployed and dependant on begging.[148]

141 Weber, Erich M., *Untiefen, Flut und Flauten: Der Güterverkehr auf dem Rhein zwischen 1750 und 1850: Die Modernisierung der vorindustriellen Rheinschifffahrt aus einer wirtschafts-, sozial- und umweltgeschichtlichen Perspektive betrachtet* (Bern: Selbstverlag, 2005), accessed November 20, 2013. <http://www.zb.unibe.ch/download/eldiss/05weber_e.pdf>.

142 Ibid., 429.

143 Ibid., 457.

144 "Der Rhein war so klein und dünn, dass die schiff nicht halb geladen mochten herab kommen". Huber, *1521-1582: Schaffhauser Chronik*, 96.

145 "Uff diese Baszler mesz diesz fierzigisten jorsz alle gutter über lant und mit wegen musten obenherab gfurt werden." Cf. Ryff, "Die Chronik," 86.

146 "Il fiume Po è in secca proprio nel periodo autunnale [che generalmente è caratterizzato da piene, legate alla piovosità degli Appennini e della Pianura Padana]." [River Po was dry in autumn, whereas usually it reaches high flood levels due to rainfall in the Appenin mountains and in the Po valley], in Borghi, *Tommasino de Bianchi detto de Lancellotti*, 58.

147 Glaser et al., "Seasonal Temperature," 192.

148 "Die Flössen/Mühlen und Hammer=Hütten [near Meissen, Germany] stunden müssig/ die Hammer=Arbeiter liessen betteln." Lehman, Christian, [...] *Historischer Schauplatz derer natürlichen Merckwürdigkeiten in dem Meißnischen Ober=Erzgebirge* (Meissen: Lankisch 1699).

Impacts on the natural environment are only casually mentioned. Oswald Huber reports that graylings (*Thymalus thymallus L.*) in the Rhine, unable to find zones with cool water, were caught by hand belly up in large numbers,[149] as was also reported for 2003.[150] Considering the drying up of most brooks and smaller rivers over large parts of continental Europe together with the extremely low level and warming up of major rivers, the multi-seasonal heat and drought in 1540 may have caused the greatest fish mortality in the second half of the last millennium. The congruent descriptions about stinking smoke made by Salat in Lucerne and by Biem in Cracow—two cities separated by a horizontal distance of nine hundred kilometres—bear witness to the fact that the fire disasters in 1540 affected a far larger area than any other known natural hazard such as a severe flood or a violent winter storm. Hence, large parts of Europe might well have had a peacetime maximum of town and village fires in 1540 in an analogy of Zwierlein's findings for Germany.[151] These calamities may have acted as a major break on economic development. According to Eric L. Jones, "net capital formation was held down in the preindustrial world, not merely by lower incomes and lower savings propensities, but by a weaker capacity to control and recover from natural and social calamity", including urban and rural fires.[152] The longer-term economic impact of the drought in 1540 was, in addition to burnt-down settlements, multiplied by large-scale destructions of forest and substantial losses of cattle, thereby reducing the availability of draught-power and manure needed for grain production over subsequent decades.

The long-lasting heat and drought promoted a widespread epidemic phenomenon called the "Big Death", which may have mainly consisted of dysentery and other intestinal diseases linked to contaminated water.[153] Following the extreme drought of 1719, a dysentery epidemic in France took 450,000 lives,

149 "Der Häwmonat war so häiss, dass die Jfer und Escher im Rhein ans land schwummen, kalt wasser zusuochen, und ehe sie wider recht ins wasser kommen mochten, fielen sie für grosser hitz an den ruggen, dass die fischer die in grosser menge mit den händen fiengen, waren faisst und guot." Huber, *1521-1582: Schaffhauser Chronik*, 96.

150 BUWAL, Auswirkungen des Hitzesommers 2003 auf die Gewässer, 137-139.

151 Zwierlein, *Der gezähmte Prometheus*, 104.

152 Jones, Eric L., *The European Miracle* (Cambridge: Cambridge University Press, 2003), 39.

153 Christian Pfister, "When Europe was Burning. The Multi-Season Mega-Drought of 1540 and the Arsonist Paranoia," in *Disasters, Risks and Cultures. A Comparative and Transcultural Survey of Historical Disaster Experiences between Asia and Europe*, ed. Gerrit J. Schenk, (Springer, in press.).

which corresponds to two percent of the French population at that time.[154] Assuming an equally excessive mortality in 1540, the "Big Death" may have killed about one million Europeans assuming a population of forty million people were affected by the drought.[155]

Climatic extremes and nature-induced disasters are known hotspots of cultural history. Thus, the environmental 'emergency situation' of 1540 entailed an emergency within society. The widespread forest and settlement conflagrations involved a loss of control over fire outside people's experience and beyond their imagination. Conspiracy theory offered plausible and convincing explanations. Settlement fires were frequently attributed to arsonist plots allegedly inspired by political opponents and put into effect by paid vagrants and beggars. In people's imagination, these groups living outside of parish structures formed a criminal counter-society hidden from the authorities and the public.[156] In the German Reich, the Schmalkaldian Alliance of Protestants blamed the League of Catholic Princes for setting towns aflame using paid "Mordbrenner" (murder arsonists). Organised arson was regarded as the most threatening political crime of the early modern period, as attacks were not directed toward individuals, but aimed at spreading insecurity and chaos within communities and territories, similar to terrorist attacks today.[157] Trials against alleged "terrorists" allowed the application of torture to learn the names of other members of the sect.[158] Gender stereotypes played an important role in the construction of the arsonist conspiracies. Even though there were of course itinerants of both sexes, the members of the imaginary arsonist gangs were all supposed to be male. Women were non-existent in the conspiracy. However, there was a competing picture of gender-specific crime, that of the witch.[159] Indeed, the disastrous "Witches Hammer," published in 1486 by Heinrich Kramer, propagated the idea that witches were in fact an occult sect enabled by their pact with the devil to commit horrible crimes against a fictitious collective in the form of crop destruction via hailstorms, untimely frost,

154 Lachiver, Marcel, Les années de misère: La famine au temps du Grand Roi, 1680-1720 (Paris: Fayard, 1991), 414-417.

155 Pfister, "When Europe was Burning"; de Vries, Jan, "Population," in *Handbook of European History 1400-1600. Late Middle Ages, Renaissance and Reformation*, vol. 1, ed. Thomas A. Brady, Heiko A. Oberman, and James D. Tracy (Leiden: Brill, 1995), 13.

156 Dillinger Johannes, "Organized Arson as a Political Crime: The Construction of a 'Terrorist' Menace in the Early Modern Period," *Crime, History & Societies* 10.2 (2006): 102-119.

157 Dillinger, "Organized Arson," 111.

158 Rummel, Walter, and Rita Voltmer, *Hexen und Hexenverfolgung in der Frühen Neuzeit*

and cold rains. Thus, there seems to have been a dichotomy between male arsonist conspiracy, blamed for "warm" disasters in the human realm, and female magic generating "cold" disasters in the natural world that needs to be further investigated.

In general, however, premodern societies were remarkably resilient considering the magnitude of the impact: epidemics, cattle mortality, water shortages, frequent settlement and forest fires and rising bread prices due to stalling mills. In contrast to Italy, famines could be avoided in Central Europe.

Agriculture, transportation and energy were also particularly vulnerable to heat and drought in 2003, leaving aside the death of about 70,000 mostly elderly people in Europe during the peak of the heat wave.[160] The EU arable sector showed an overall slump in production of more than ten percent[161] causing an approximate loss of US$12.3 billion.[162] Cattle breeding is not mentioned among the vulnerable branches of agriculture, apart from Germany, where the loss of feed on meadows was estimated at €1 billion. The French cattle industry suffered from a sixty percent drop of green fodder.[163] Inland navigation was restricted in analogy to 1540 due to the low level of major rivers. Ships on the river Rhine could only use twenty to thirty percent of their loading capacity. German railways were not able to fully compensate for the insufficient capacity of river transport, which led to delays and rising cost of transport.[164]

Energy is the Achilles heel of modern economies. A reliable electricity supply is the essential resource basis for modern life.[165] Thermal (fossil and nuclear) power plants are the most vulnerable energy producers, because they depend on an abundant water supply for cooling purposes. Electricity generation through fossil and nuclear thermal power plants requires about 100 l/kWh of freshwater for cooling purposes, process, and other supply water. Thermal power stations in Germany are using a staggering annual amount of 25 billion m^3 freshwater representing 64 percent of the average available surface water.[166]

160 Poumadère, Marc et al., "The 2003 Heat Wave in France: Dangerous Climate Change Here and Now," *Risk Analysis* 25.6 (2005): 1483-1494. doi:10.1111/j.1539-6924.2005.00694.x.

161 García-Herrera et al., "A Review," 292f.

162 SwissRe (ed.), "Natur- und Man-made-Katastrophen im Jahr 2003: Zahlreiche Todesopfer, vergleichsweise moderate Versicherungsschäden," *Sigma* 1.1 (2004): 10.

163 Food and Agriculture Organization of the United Nations, "Climate Change and Food Security: Risks and Responses," accessed November 10, 2016. <http://www.fao.org/3/a-i5188e.pdf>.

164 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode*, 175.

165 Ward, David M., "The Effect of Weather on Grid Systems and the Reliability of Electricity

Extreme temperature-related impacts, like unusually long periods of hot, dry weather, lead to a shortfall in water supply and high-river temperatures. Rising water temperatures first lead to a higher withdrawal of water in order to meet legal and environmental thresholds for the temperature of discharged water without large reductions in efficiency. If the higher amount of cooling water is still not sufficient, the energy conversion consequently needs to be reduced in order to meet environmental regulations. There are numerous examples in 2003, from the United States in 2002, Switzerland, Germany, and France, as well as in 2006 from France, Spain, and Germany, where high ambient water temperatures resulted in reduced power output at several thermal power plants.[167] Allowances were given to thermal power plants most severely affected by the heat wave in the federal state of Baden-Württemberg (Germany) to discharge cooling water into the rivers, which was beyond the limits of the environmental regulations.[168] Europe's main electricity exporter, "Electricité de France", running 58 nuclear power plants, had to cut its electricity exports more than half[169] when water temperatures exceeded 23°C the last day of the August heat wave. Most wind turbines stood still because it was almost windless. Water power stations couldn't compensate for the shortfalls because their capacity was equally reduced due to low water levels. Power exported from the Swiss storage power stations declined by twenty percent.[170] Power prices skyrocketed as a consequence, although power cuts and blackouts could be avoided. In conclusion, due to the enormous cooling water need of thermal (fossil and nuclear) power stations, energy production turned out to be particularly sensitive to long periods of hot and dry weather.

Though the recurrence probability of a 1540-like megadrought might be small, even in the course of intensified Global Warming, some considerations about the possible consequences of such a worst-case event are attempted. In comparison to most scenarios, which have mainly speculative character, the climatic and hydrological boundary conditions underlying the case of 1540 are evidence-based. It was demonstrated that the heat and drought in 1540 was more persistent than in 2003, lasting about eleven months. It was also more extensive, comprising Europe from the Atlantic to Poland and from Tuscany to the North Sea. Finally, the heat wave was also more intense, considering the

167 Sieber, Jeannette, "Impacts of, and Adaptation Options to, Extreme Weather Events and Climate Change Concerning Thermal Power Plants," *Climatic Change* 121.1 (2013): 55-66. doi:10.1007/s10584-013-0915-0.

168 [168] Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode*, 188.

drought-related extreme soil desiccation and its interactions with temperature, and also the continent-wide spread of forest fires.

The major impacts of a recurrent 1540-like worst-case event would be related to water scarcity and its multiple ripple effects across other interlinked systems. Inland navigation might have might have to be cancelled completely, considering discharge deficits of about ninety percent in large rivers. Railways would even less be able to compensate for the insufficient transport capacity of river navigation than in 2003. Besides severe crop failures, the megadrought would heavily affect cattle breeding and hence milk and meat production. There were about 65 million head of cattle in the EU in 2012. At a temperature of 28°C, which may be realistic for average conditions in summer 1540, a high-production cow consumes a daily amount of 110 to 130 litres of water. Even without any milk production, the animal still consumes 78 litres a day, while the need of feeder cattle is between 23 and 66 litres and that of calves somewhat less.[171] Assuming a moderate daily water need of fifty litres per animal, the forty million cattle living within the 1540 drought perimeter would want about two billion m^3 of water per day. There is still the question of how to feed forty million cattle from completely withered meadows. Probably, milk production would collapse and a considerable amount of cattle would have to be slaughtered. Forest fires might hardly be extinguished for lack of water and air traffic might be severely disturbed by widespread forest-fire aerosols.

Energy production would bear the brunt of the disaster. It is an open question how thermal power stations in Europe, consuming at present the lion's share of the average available surface water for cooling, might maintain their production capacity during a 1540-like megadrought. Besides the staggering quantitative deficit of about ninety percent, the water might be considerably warmer than in 2003. With regard to the situation in the federal state of Baden-Württemberg, which was most affected by the 2003 heat wave, scenarios of the consequences of further restrictions in cooling water availability envisaged a complete power failure (blackout) leading to massive disturbances in the integrated European network.[172] To what extent solar energy, in contrast to wind power, might compensate for the drastic reduction in thermal power and hydropower generation needs to be investigated. In any case, photovoltaic (PV) modules are not vulnerable to extreme drought. However, their output drops by about 0.5 percent for every 1°C increase in temperature. This means that

171 "Wasser – das wichtigste Futtermittel für Kühe," published by Tiergesundheit und mehr, last modified October 9, 2013, accessed April 6, 2017. <http://www.tiergesundheitundmehr.de/wasser-fuer-kuehe.pdfx>.

high ambient air temperatures in situations with high direct solar irradiation can have a significant impact on the maximum possible power output.[173] In the case of extraordinary supply situations, such as in summer 2003, the needed reserve power might be transmitted over greater distances. However, the transmission grid is only limitedly suited for substantial energy transmissions over large distances and over longer time periods.[174]

Whereas regional short-term power blackouts are experienced frequently around the world, societies are not ready to face large-scale, long-lasting power blackouts as might be experienced during a 1540-like megadrought. The 2003 blackout in the United States (which was, however, not climate-related), illustrates

> that after 3 to 6 hours without power most fuel stations and the refineries had to close down, leaving the public without fuel for cars or backup generators as the pumps did not operate. Most critical systems such as hospitals, water and sewage systems have backup power generation in place. However, these typically have only enough fuel for several hours to a maximum of a few days. […] Governments have typically, however, implemented emergency fuel storages to keep most critical facilities alive for several weeks up to a month. After one month with no electrical power, water, transportation, emergency services, critical manufacturing, and chemical sectors can face widespread outages within the affected region.[175]

Water may still be available for drinking and a minimum of personal hygiene, albeit hardly for the full use of water systems. In combination with power blackouts, extreme water shortages would lead

> to many cascading effects. Hospitals, schools, nursing homes, restaurants, and office buildings all rely on water to operate. Water is used for drinking, sanitation, and heating and cooling systems in those facilities. Many

173 Patt, Anthony, Stefan Pfenninger, and Johan Lilliestam, "Vulnerability of Solar Energy Infrastructure and Output to Climate Change," *Climatic Change* 121.1 (2010): 93-102. doi:10.1007/s10584-013-0887-0.

174 Bundesanstalt für Gewässerkunde, *Niedrigwasserperiode*, 188.

175 Bruch, Michael et al., *Power Blackout Risks: Risk Management Options*, CRO Forum Position Paper, published 2011, accessed August 26, 2014. <https://www.allianz.com/v_1220677760000/media/responsibility/documents/position_paper_power_blackout_risks.

> manufacturing operations either use water as an ingredient in their processes or rely on wastewater systems to remove and process their manufacturing waste. Access to safe water is necessary for providing mass care services and preventing the spread of disease.[176]

Under conditions of water shortages and power blackouts, excess mortality might take on staggering dimensions.

The cost of energy blackouts could be enormous. Researchers at the Hamburg Institute of Global Economics concluded that a one-hour blackout in mid-afternoon Berlin would cost the city €23 million. In the unlikely event of a one-hour blackout across Germany at peak time the cost would be €593 million.[177] For Switzerland, an analysis of the electricity industry estimates a minimum daily 2.4 billion Swiss francs' GDP loss and a 1.3 billion loss of daily earnings. In addition, longer term physical, financial, physiological, and psychological consequences also have to be considered. [178] In 2015 the Swiss Federal Office of Civil Protection estimated the cost of a longer term thirty percent power deficit due to an extended winter drought at one hundred billion CHF without, however, considering the 2014 study about the outstanding summer drought in 1540.[179] All in all, the vulnerability of modern societies in the face of a 1540-like megadrought is many times higher than that of pre-modern societies.

5 Conclusions

Nobody is able to imagine the magnitude and severity of low probability, high-impact events that are expected more frequently in the future as the result of continuing Global Warming, is the expert's tenor in an influential study edited

176 Ibid.

177 Peter Terium, head of energy provider RWE, warns of blackouts in Europe: "Energy Boss Warns of Blackouts in Europe," published by The Local, accessed November 7, 2013. <http://www.thelocal.de/20131029/energy-boss-warns-of-blackouts-in-europe>.

178 Verband Schweizerischer Elektrizitätsunternehmen, "Elektrischer Blackout: Basiswissen Stand November 2015," accessed April 11, 2017. <https://www.strom.ch/fileadmin/user_upload/Dokumente_Bilder_neu/010_Downloads/Basiswissen-Dokumente/29__Blackout.pdf>.

179 Bundesamt für Bevölkerungsschutz, "Katastrophen und Notlagen Schweiz: Technischer Risikobericht 2015," accessed April 11, 2017. <https://www.newsd.admin.ch/newsd/mes

by the World Bank.[180] This is the first paper to provide coherent evidence on what Europe might expect in the case of a worst-case high impact event. Nature has made an appropriate experiment in 1540 which hundreds of chroniclers across the continent recorded in words as a memory for future generations. However, because the individual texts were so far not properly interpreted and integrated into a coherent picture, their message went unheard.

The drought in 2003 was not extreme according to the lowest twentieth century values measured in France, Germany and Switzerland, in contrast to 1540. Seasonal precipitation for this year was estimated from the number of precipitation days obtained from Swiss and Alsatian chronicles as well as for a weather diary from Cracow (Poland). Rain-days in spring, summer and autumn were considerably below those of the 20th century average—in Alsace and Switzerland even below the absolute minima of the instrumental period. The amount of precipitation estimated from the observed rain-days remained significantly below one hundered-year minimum levels in 1540 throughout spring, summer and autumn. No event comprising a persistent extreme drought is documented within the instrumental period.

Likewise, the year 2003 does not rank among the smallest annual values in many very long German discharge series. Discharge deficits of more than fivty percent were not registered for large rivers. Those of the river Rhine were −37 percent, while in 1540 they were about ninety percent both in Basel and Cologne. The levels of other large rivers—Seine, Elbe, Thames—were also below their 2003 minima, as can be estimated from coherent qualitative descriptions. In conclusion, Western and Central Europe suffered from a dust-dry spring in 1540, which was then followed by a torrid summer and an almost rainless autumn making 1540 the worst drought year of the last five centuries. In the discussion about the significance of soil-dessication feedbacks for extreme heat waves there is consensus that spring droughts are an important precondition for the triggering of such events.

We demonstrated that the study on grape harvest dates in Burgundy[181] overestimated spring-summer temperatures in 2003 in comparison with 1540. Likewise, it was shown that the tree-ring study on Lötschental (Switzerland) showing average summer temperatures in 1540[182] in contrast to the maximum value in 2003 is inconsistent with later research.

180 Field, Christopher B. et al., ed. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press, 2012).

181 Chuine et al., "Historical Phenology."

Premodern societies were remarkably resilient to heat and drought, even in the face of the Megadrought. They mainly suffered from water scarcity, which affected cattle breeding, milling and transportation. Forest and settlement fires together with widespread cattle mortality were probably the worst consequences. The winter grain harvest was satisfactory, because the yields and water needs of the crop were much below present-day values.

The vulnerability of present-day societies to a 1540-like drought was assessed by looking at the known impacts of the hot 2003 summer. Agriculture, transportation and energy were the main sectors of the economy impacted by the heat wave. Energy production turned out to be particularly sensitive due to the enormous need of cooling water for thermal (fossil and nuclear) power stations. The major impacts of a 1540-like worst-case event on present-day societies would be related to water scarcity and its multiple ripple effects across other interlinked systems. In any case, the drought would heavily affect cattle breeding and milk production. Whether thermal power stations, consuming the lion's share of the average available surface water for cooling purposes, might maintain their production capacity is open to debate. The power cuts in Baden-Württemberg experienced in August 2003 suggest that large-scale, long-lasting, disruptive power blackouts might not be excluded, involving cascading effects on critical infrastructure such as wastewater systems, gasoline availability and medical support, not including the staggering cost from lost production. Resource conflicts for water both between economic branches within and between countries could hardly be avoided.

From these considerations, it becomes obvious that "Europe's largest nature-induced disaster"[183] is far from being merely a topic of academic discussion about the remote past. Rather, it meets the criteria of the implausible black swan being a low-probability, high-impact event of an appalling magnitude. In the present, it would likely jeopardise critical national infrastructures and human security in Europe. The reasons why climatologists and risk analyists so far have not given due consideration to this hazard is rooted in several interrelated factors:

1. The quality of the raw data and the methodology were not checked in the case of the aforementioned *Nature* paper about the Dijon grape harvest dates. Perhaps this is because the review of man-made evidence in the

183 Bojanowski, Axel, "Hitze-Jahr 1540: Wetterdaten enthüllen Europas größte Naturkatastrophe," published by Spiegel Online Wissenschaft, July 2, 2014, accessed October 14, 2014. <http://www.spiegel.de/wissenschaft/natur/hitze-und-duerre-1540-katastrophe-in-

archives and their interpretation "should be seen as a delicate task requiring a lot of endurance and accurateness" as historians Thomas Labbé and Damien Gaveau, who were critically looking at the Dijon series, have emphasised.[184]

2. In the face of the record-breaking heat and drought, the grapes' response was outside the normal range of biological and probability laws. Considering the comparative study of documentary and tree-ring data, trees responded to the 1540 megadrought with very small rings in 1541.[185] On the other hand, the record breaking tree-ring for 2003 in the series from Lötschental (Switzerland)[186] may well be related to both extremely high temperatures and a substantial availability of moisture,[187] whereas earlier hot summers in Switzerland were dry.[188]
3. With regard to the pre-instrumental low probability of high impact events such as 1540, models still leave decision makers with little practicable information on the scales over which they have jurisdiction[189] and they are rarely included in risk analyses. Yet "the characterization of such events and the related climate system functioning is particularly relevant in the context of global warming and the corresponding increase of extreme heat wave magnitude and occurrence frequency."[190]
4. Climate change studies have so far put a focus on temperature reconstruction at the expense of precipitation, although infrequent but catastrophic droughts—often connected with heat waves—may lead to far more devastating impacts than from heat waves alone.[191] Precipitation is the most important source of uncertainty derived from the Global Circulation Model predictions, and this uncertainty is further magnified by runoff-related issues.[192]
5. The great potential of documentary evidence for detailed studies on extreme events and their human impacts is not yet known, simply overlooked or not fully recognised. This epistemological blind spot has deep roots in the culture of the sciences, in which solely quantitative evidence and statistical methods lead to valid conclusions.

184 Labbé, and Gaveau, "Les Dates de Bans de Vendange à Dijon."
185 Büntgen Ulf et al., "Combined Dendro-Documentary Evidence," 3947-3959.
186 Büntgen et al, "Summer Temperature."
187 Wiliam Jolly and coauthors found a divergent vegetation growth response during the 2003 event in the Swiss Alps characterized by high elevation growth enhancement and low elevation growth suppression in response to the extreme summer temperatures and low-altitude drought conditions. Jolly, William M.et al. "Divergent Vegetation Growth Responses to the 2003 Heat Wave in the Swiss Alps," *Geophysical Research Letters* 32 (2005): L18409, doi:10.1029/2005GL023252.
188 Bundesamt für Umwelt, *Hitzesommer*.
189 Oreskes, Naomi, David A. Stainforth, and Leonard A. Smith, "Adaptation to Global Warming: Do Climate Models Tell Us What We Need to Know?," *Philosophy of Science* 77.5 (2010): 1023.
190 Orth et al., "European Temperatures in 1540"
191 Ibid., 1014.

What occurred five hundred years ago may happen again in the near future. Last but not least, we have already witnessed record-breaking seasons in the new millennium, of a kind which shaped the eleven-month long heat and drought in 1540, albeit in different years and in a somewhat less extreme form. Spring 2011 was warm and extremely dry,[193] while summer 2003 and autumn 2006 were by far the hottest within the period of instrumental measurement.[194] In order to put such estimates on a broader empirical basis, further black swans need to be investigated in the period prior to 1540.

192 Mukheibir, Pierre, "Potential Consequences of Projected Climate Change Impacts on Hydroelectricity Generation," *Climatic Change* 121.1 (2013): 67-78. doi: 10.1007/s10584-013-0890-5.
193 Quesada, Benjamin, Robert Vautard, Pascal Yiou, Martin Hirschi, and Sonia I. Seneviratne, "Asymmetric European Summer Heat Predictability from Wet and Dry Southern Winters and Springs," *Nature Climatic Change* 2 (2012): 736-741. doi:10.1038/nclimate1536.
194 Luterbacher et al, "European Warmth."