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# The 1430s: a cold period of extraordinary internal climate variability during the early Spörer Minimum with social and economic impacts in north-western and central Europe

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**Abstract.** Changes in climate affected human societies throughout the last millennium. While European cold periods in the 17th and 18th century have been assessed in detail, earlier cold periods received much less attention due to sparse information available. New evidence from proxy archives, historical documentary sources and climate model simulations permit us to provide an interdisciplinary, systematic assessment of an exceptionally cold period in the 15th century. Our assessment includes the role of internal, unforced climate variability and external forcing in shaping extreme climatic conditions and the impacts on and responses of the medieval society in north-western and central Europe.

Climate reconstructions from a multitude of natural and anthropogenic archives indicate that the 1430s were the coldest decade in north-western and central Europe in the 15th century. This decade is characterised by cold winters and average to warm summers resulting in a strong seasonal cycle in temperature. Results from comprehensive climate models indicate consistently that these conditions occurred by chance due to the partly chaotic internal variability within the climate system. External forcing like volcanic eruptions tends to reduce simulated temperature seasonality and cannot explain the reconstructions. The strong seasonal cycle in temperature reduced food production and led to increasing food prices, a subsistence crisis and a famine in parts of Europe. Societies were not prepared to cope with failing markets and interrupted trade routes. In response to the crisis, authorities implemented numerous measures of supply policy and adaptation such as the installation of grain storage capacities to be prepared for future food production shortfalls.

## 1 Introduction

Several cold periods occurred in Europe during the last millennium and might have affected human socioeconomic systems. While more recent cold events, such as the "Year Without Summer" after the 1815 eruption of Tambora (e.g. Luterbacher and Pfister, 2015) or the so-called Maunder Minimum in solar irradiation in the 17th century, are extensively discussed and documented in the literature (e.g. Eddy, 1976a; Luterbacher et al., 2000, 2001; Xoplaki et al., 2001; Shindell et al., 2001; Brázdil et al., 2005; Yoshimori et al., 2005; Raible et al., 2007; Ammann et al., 2007; Keller et al., 2015; Wanner et al., 2008), much less is known about a cold period in Europe during the 15th century. Cold events can be attributed to external climate forcing and/or internal (chaotic) climate variability. Forcing included cooling by sulfate aerosols from explosive volcanism and solar irradiance reductions against the background of slow variations of Earth's orbit – the latter leading to a decrease in northern hemispheric summer insolation during the last millennium (Schmidt et al., 2011, and references therein).

The aim of this study is to provide a systematic assessment of what is known about climate forcing, the role of internal, unforced climate variability and socioeconomic change during a particular cold period in Europe from around 1430 to 1440 CE (Fig. 1). This is done by analysing multiproxy evidence from various natural and anthropogenic archives and by exploring the output from last millennium simulations with comprehensive state-of-the-art climate models driven by solar and volcanic forcing to identify the origin of the reconstructed climate variability in terms of temperature and precipitation. Seasonality changes, which may have played an important role in generating impacts for medieval society, are discussed in detail. Historical documents are exploited to unravel socioeconomic conditions, impacts, resilience and adaptation to change by using quantitative indicators such as grain prices, population and trade statistics, as well as descriptions. The potential impacts of climate on society are discussed in the context of other important socioeconomic drivers.

Our study concentrates on north-western and central Europe during the period of the Spörer Minimum (SPM) in solar activity. Concerning the temporal extent of the SPM, a number of differing definitions exist: 1400–1510 (Eddy, 1976b, 1977; Jiang and Xu, 1986), 1420–1570 (Eddy, 1976b, 1977; Kappas, 2009) and 1460–1550 (Eddy, 1976a). According to more recent reconstructions (see e.g. Schmidt et al., 2011, and references therein), we use the years 1421–1550. A particular focus is on the decade 1430–1440, which coincides with the early SPM. Note that this temporal coherence between solar forcing and the particular climatic conditions during the 1430s does not necessarily imply causality.

Climate model simulations and multiproxy climate reconstructions agree in that the SPM was a period of rather cold conditions on hemispheric average (e.g. Fernández-Donado et al., 2013; Lehner et al., 2015). A recent synthesis of climate reconstructions suggests a diverse picture of regional temperature changes with different regions having opposed trends during the SPM (Neukom et al., 2014). Europe seems to have been only slightly cooler than average during the SPM (PAGES 2k consortium, 2013; Luterbacher et al., 2016). The authors state that the volcanic–solar downturns in the 16th and 17th century were associated with globally coherent cold phases (except Antarctica). Recently, these continental-scale reconstructions are compared to the latest simulations of the Paleoclimate Modelling Intercomparison Project III (PMIP3; Schmidt et al., 2011), showing that models tend to overemphasise the coherence between the differ-

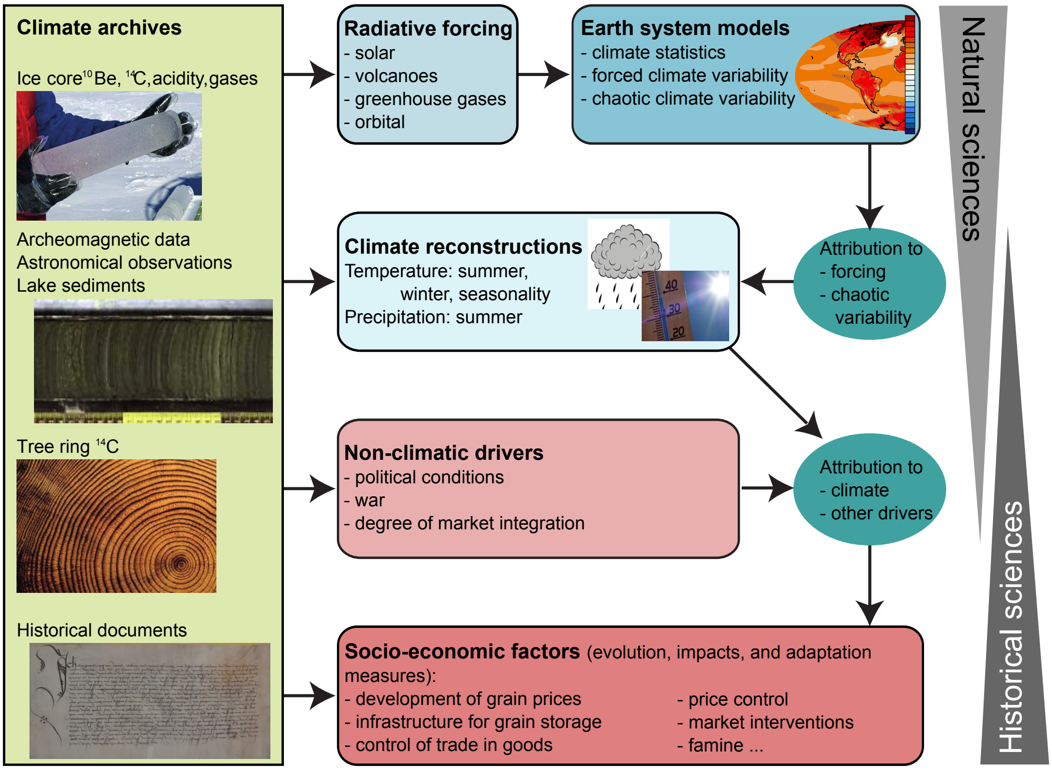


**Figure 1.** Illustration of the research disciplines and methods brought together in this systematic assessment. Picture of the historical document: Staatsarchiv des Kantons Bern, Fach Urfehden, 25 May 1480.

**Table 1.** Comprehensive multiproxy, multisite reconstructions from western and central Europe representing summer and winter temperatures as well as summer precipitation.

| No. | Variable | Archive | Area | References |
|---|---|---|---|---|
| Summer temperature | | | | |
| 1 | $JJA_{anomaly}$ | Lake sediments | Switzerland W–C Europe | Trachsel et al. (2010) |
| 2 | $JJAS_{anomaly}$ | Tree rings | Greater Alps | Büntgen et al. (2006) |
| 3 | $JJA_{anomaly}$ | Tree rings and lake sediments | Switzerland–Austria/W–C Europe | Trachsel et al. (2012) |
| 4 | $JJA_{anomaly}$ | Tree rings | W–C Europa | Büntgen et al. (2011) |
| 5 | JJA indices | Historical documents | C Europe | www.tambora.org/Riemann et al. (2015) |
| 6 | JJA indices | Historical documents | Low Countries | Camenisch (2015b) |
| 7 | MJJAS indices | Historical documents | Belgium–Netherlands–Luxembourg | van Engelen et al. (2001) |
| Winter temperature | | | | |
| 8 | ONDJFMAM | Lake sediments | Switzerland/W–C Europe | de Jong et al. (2013) |
| 9 | DJF indices | Historical documents | C Europe | www.tambora.org/Riemann et al. (2015) |
| 10 | DJF indices | Historical documents | Low Countries | Camenisch (2015b) |
| 11 | NDJFM indices | Historical documents | Belgium–Netherlands–Luxembourg | van Engelen et al. (2001) |
| 12 | Mean AWS Temp | Speleothems | Switzerland/W–C Europe | Hasenfratz et al. (2016) |
| Summer precipitation | | | | |
| 13 | MJJA | Lake sediments | Swiss Alps/W Europe | Amann et al. (2015) |
| 14 | AMJ | Tree rings | W–C Europe | Büntgen et al. (2011) |
| 15 | JJA | Historical documents | Low Countries | Camenisch (2015b) |
| 16 | MAMJJ | Tree rings | S–C England/W Europe | Wilson et al. (2013) |

ent regions during periods of strong external forcing (such as the SPM; PAGES2K-PMIP3 Community et al., 2015).

The remarkable climatic conditions during the 1430s as described in historical documents are marginally mentioned in the literature (Buismann, 2011; Camenisch, 2015b; Fagan, 2002; Lamb, 1982; Le Roy Ladurie, 2004) but have never been assessed in depth. Also the climatic impacts on society and economy have only been examined for isolated areas (Jörg, 2008; Camenisch, 2012, 2015b; van Schaïk, 2013).

Given the sparse knowledge of this time period, it is timely to combine available evidence in a systematic study, from external forcing to climate change and implications to adaptation in an historical perspective. The structure of the paper is as follows: Sect. 2 focuses on the physical system during the SPM and presents climate reconstructions from different proxy archives. Section 3 presents climate model results and explores the role of external forcing versus internal variability. In Sect. 4, socioeconomic implications are analysed using historical evidence. Furthermore, this section illustrates how society reacted and which strategies were pursued in order to adapt. A discussion and conclusions are provided in the last section, which aims at stimulating a future focus on this period of dramatic impacts in Europe.

## 2 Reconstructions of climate during the Spörer Minimum

Sixteen comprehensive multiproxy multisite datasets covering western and central Europe are analysed to characterise the mean climate and seasonality during the SPM (Appendix, Fig. 2). The data include annual or near-annual, well-calibrated, continuous series from tree rings, lake sediments, speleothems and anthropogenic archives (see Table 1) covering the period 1300 to 1700. Summer temperature is represented by seven data series (Büntgen et al., 2006, 2011; Camenisch, 2015a; Riemann et al., 2015; Trachsel et al., 2010, 2012; van Engelen et al., 2001) and winter temperature by five data series (Camenisch, 2015a; de Jong et al., 2013; Glaser and Riemann, 2009; Hasenfratz et al., 2016; van Engelen et al., 2001). Four data series provide information about summer precipitation (Amann et al., 2015; Büntgen et al., 2011; Camenisch, 2015a; Wilson et al., 2013).

In a first analysis, the centennial-scale variability is investigated by comparing the temperature mean of the SPM (1421–1550) with the preceding century (1300–1420) and the century afterwards (1550–1700). It appears that time-averaged summer temperature in Europe was not colder during the SPM than in the previous and following period (not shown). On the contrary, the proxy series from western Europe and the Swiss Alps that include lake sediment data and temperature reconstructions from chironomid transfer functions (Trachsel et al., 2010, 2012) reveal that, overall, the SPM was significantly ($p < 0.01$) warmer than the periods before and afterwards. For winter temperatures, a similar conclusion can be drawn from the reconstructions; i.e. the deviation in average winter temperature was not unusual during the SPM.

While the centennial-scale climate variability informs mainly about the influence of the prolonged total solar irradiance (TSI) minimum during the SPM, interannual to decadal-scale climate variability illustrates (cumulative) volcanic forcing or internal (unforced) variability. Figure 2 shows the decadal means of the standardised proxy series. Decadal-scale variability shows pronounced temporal and spatial heterogeneity across Europe. Summers from 1421 to 1450 were consistently average or warm (for the years 1430–1439; Luterbacher et al., 2016; see Fig. S1 in the Supplement). Striking is the very cold decade 1451–1460, which is a consistent feature across all summer temperature proxy series and coincides with two very large consecutive volcanic eruptions in 1453 (unknown) and 1458 (Kuwae; Sigl et al., 2013; Bauch, 2016). These cold summers across Europe persisted for one or two decades and were followed by rather warm summers until the 1530s, particularly in the Alps. Similar decadal-long cold summer spells were observed between 1590 and 1610, which also coincided with two very large volcanic eruptions (Ruiz in 1594 and Huaynaputina in 1600; Sigl et al., 2013).

Winter temperature variability behaved differently. In western Europe, the coldest conditions occurred during the 1430s. The slightly warm anomaly on record no. 8 (de Jong et al., 2013) can be explained by its location in the Alps. Situated at 1791 m a.s.l., during the winter the site is often decoupled from the boundary layer and, as such, is of limited representativeness for the lowlands. From 1450 to 1500, very strong winter cooling is reconstructed in both the Alps and Poland. At least for these areas, consecutive strong volcanic forcing seemed to result in very cold and long winters (Hernańdez-Almeida et al., 2015) although the expected mean response to a volcanic eruption is a winter warming over Europa (e.g. Robock and Mao, 1995; Fischer et al., 2007, Ortega et al., 2015).

There is also evidence in historical sources. In the Low Countries (the area of modern Belgium, the Netherlands, Luxembourg and parts of northern France) the winters of 1431/32, 1432/33, 1434/35 and 1436/37 (1433/34 and 1437/38) were extremely (very) cold, and also spring temperatures were very or extremely low in 1432, 1433 and 1435 (Camenisch, 2015a). In Bohemia, Austria and the Hungarian Kingdom, the winters of 1431/32, 1432/33 and 1434/35 were outstandingly cold (Brázdil et al., 2006). These remarkably cold winters caused the freezing of rivers and lakes in central Europe, England and the Netherlands and were accompanied by recurrent frost periods in April and May (Fejér, 1843; Marx, 2003; Brunner, 2004; Camenisch, 2015b). In Scotland during the winter 1432/33, for instance, the wine in bottles

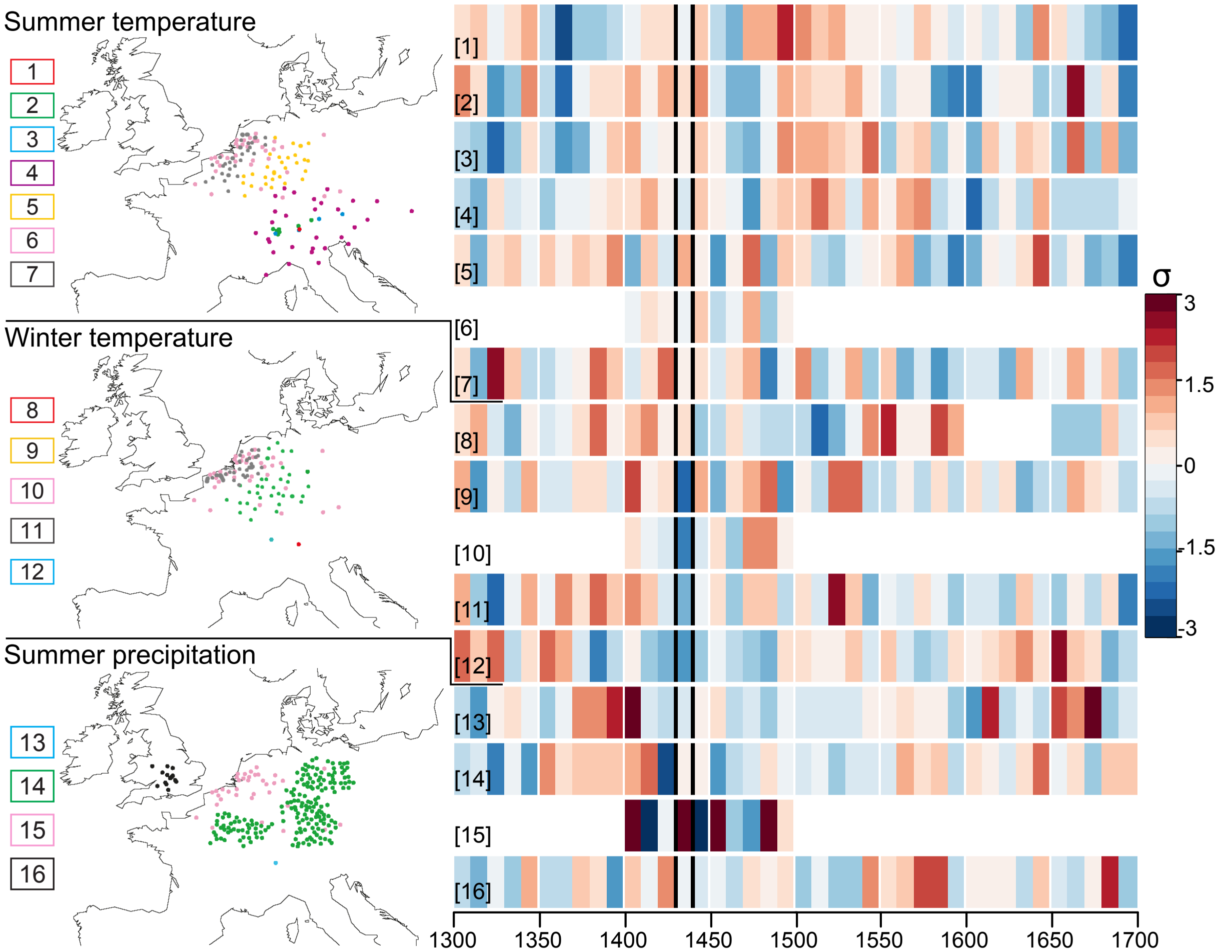


**Figure 2.** Individual paleoclimate reconstructions for summer temperature, winter temperature and summer precipitation. Left: dots are specific sites considered by the different authors (listed from 1 to 16; Table 1). Right: decadal-scale (10-year mean) summer temperature, winter temperature and summer precipitation for the 16 climate reconstructions, standardised with reference to the period 1300–1700 (datasets 6, 11 and 16: 1400–1500). The black lines enclose the decade 1430–1440. References: [1] Trachsel et al. (2010); [2] Büntgen et al. (2006); [3] Trachsel et al. (2012); [4,14] Büntgen et al. (2011); [5,9] Riemann et al. (2015); [6,10,15] Camenisch (2015b); [7,11] van Engelen et al. (2001); [8] de Jong et al. (2013); [12] Hasenfratz et al. (2016); [13] Amann et al. (2015); [16] Wilson et al. (2013).

had to be melted with fire before it could be drunk.[1] Extremely cold winters during the 1430s were also reported in Ireland (Dawson, 2009). In south-eastern France the winter seasons from 1434 to 1437 were outstandingly cold. In addition, there were frost periods in April 1432 and 1434 mentioned in that area (Maughan, 2016). In northern and central Italy, the extremely cold winter of 1431/1432 lasted until April (Bauch, 2015).

Reconstructions and historical sources reveal that the 1430s were characterised by particularly cold winter and normal to warm summer temperatures, which translates into a distinct seasonal cycle. A way to identify such years with high seasonality is the comparison of summer and winter temperature reconstructions. Figure 2 shows that such a period was only evident from 1431 to 1440 in the proxy records. In contrast, other decades with low winter temperatures do not feature an increase in temperature seasonality.

Further, summer precipitation is presented in Fig. 2 in order to assess whether during the 1430s also the hydrological cycle was unusual, either particularly dry or wet, which may have enforced potential impacts due to a short growing season. Given the rather sparse information of only four records, no consistent behaviour is found. Some records show normal condition whereas one record shows a strong increase in summer precipitation. Historical sources also provide insights into hydro-climatic variability. In south-eastern France, the Provence area and in the Netherlands, from 1424 to 1433 2 flood and 5 drought years occurred (Pichard and Roucaute, 2014; Glaser and Stangl, 2003). South of the Alps, the years 1430 to 1433 were extraordinarily wet (Bauch,

[1] "In the time of King James the First [. . . ] a vehement frost was in the winter afore, that wine and ail was sauld be pound wechtis and meltit agane be the fire." (Dawson, 2009)

**Table 2.** Overview of the climate models used in this study. Details of the respectively applied forcing can be found in Bothe et al. (2013), Lehner et al. (2015), PAGES2k-PMIP3 group (2015) and references therein.

| Model (abbreviation) | Institute | Reference |
|---|---|---|
| CCSM4 | National Center for Atmospheric Research | Landrum et al. (2012) |
| CESM1 | National Center for Atmospheric Research | Lehner et al. (2015), Keller et al. (2015) |
| FGOALS-gl | State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences | Dong et al. (2014) |
| FGOALS-s2 | | Bao et al. (2013) |
| GISS-E2-R | National Aeronautic and Space Administration, Goddard Institute for Space Studies | Schmidt et al. (2014) |
| IPSL-CM5A-LR | Institut Pierre Simon Laplace des sciences de l'environnement | Dufresne et al. (2013) |
| MPI-ESM-P | Max Planck Institute for Meteorology | Jungclaus et al. (2014) |

2015). Likewise, during the 1430s, Bohemia, Austria and the Hungarian Kingdom suffered from a cluster of flood events, including the "millennial" July 1432 flood in Bohemia (Brázdil et al., 2006) and significant floods of the Danube reported in 1432, 1433, 1436, 1437, 1439 and 1440 (see e.g. Brázdil and Kotyza, 1995; Rohr, 2007; Kiss, 2012). Major flood events were also documented in the second half of the decade (e.g. in 1435, 1437, 1438 and 1440) in the eastern part of the Carpathian Basin, in Transylvania and in the Tisza catchment (Brázdil and Kotyza, 1995; Rohr, 2007; Kiss, 2011). In the Low Countries the summer seasons of 1432 and 1438 were very wet (Camenisch, 2015a).

It can be concluded that, on centennial scales, the climatic conditions in Europe during the SPM were not unusual in the context of the Little Ice Age (LIA). On interannual to decadal scales, however, the decade 1430 stands out. Its high seasonality with cold winters and normal to warm summers is unique in the proxy records investigated here.

## 3 Modelling the climate state during the Spörer Minimum

For the 1430s, the reconstructions show an increase in seasonality in western and central Europe: consistently normal or warm summers coincide with very cold winters. To understand the underlying mechanisms which may have caused this extraordinary seasonality, the influence of external forcing versus internal variability of the climate system needs to be assessed. However, this cannot be answered by the reconstructions alone. Therefore, simulations with comprehensive climate models for the last millennium are analysed to identify underlying mechanisms and to discuss the relationship between reconstructed variability and external forcing factors (Schurer et al., 2014). Our ensemble of opportunity (see Table 2) includes simulations from the PMIP3 archive (Schmidt et al., 2011) as well as two newly provided transiently forced (HIST) and control (CNTRL; 600 years with perpetual 850 CE forcing) simulations using the Community Earth System model (CESM; Lehner et al., 2015; Keller et al., 2015).

The dominant forcing factors during the last millennium prior to 1850 were changes in solar activity and volcanic aerosols, with additional small contributions from changes in the Earth's orbit, in land use and in greenhouse gas concentrations (Stocker et al., 2013). The total forcing applied to the different models, including solar, volcanic greenhouse gases and anthropogenic aerosol contributions, is shown in Fig. 3a. The largest interannual changes are due to volcanic forcing, despite large differences between models. A 31-year moving average filtered version of the total forcing is shown in Fig. 3b, illustrating the contribution of volcanic forcing at interannual to multidecadal timescales.

There are differences in the climatic conditions simulated by the different models. Reasons are the use of different solar and volcanic forcing reconstructions in various models, how these forcings are implemented in a given model, as well as model-specific responses, and internal variability. The SPM features reduced solar irradiance and coincides with two dominant volcanic eruptions in 1453 and 1458 (Sigl et al., 2013; Bauch, 2016). The latter eruption, Kuwae, was previously dated to 1452/53 and appears at this date in the standard model forcings. As to the change in solar activity, most models include changes in TSI. However, the magnitude of the changes of TSI remain unknown and might be anywhere between 1 and several $W\,m^{-2}$ (e.g. Steinhilber et al., 2010; Shapiro et al., 2011). In addition, potential feedback mechanisms exist involving, e.g. stratospheric dynamics (e.g. Timmreck, 2012; Muthers et al., 2015).

The models analysed here simulate an average decrease in the temperature of the Northern Hemisphere from 1050–1079 to 1450–1479 of about 0.4 °C, consistent with earlier studies (Fernández-Donado et al., 2013, 2016). Miller

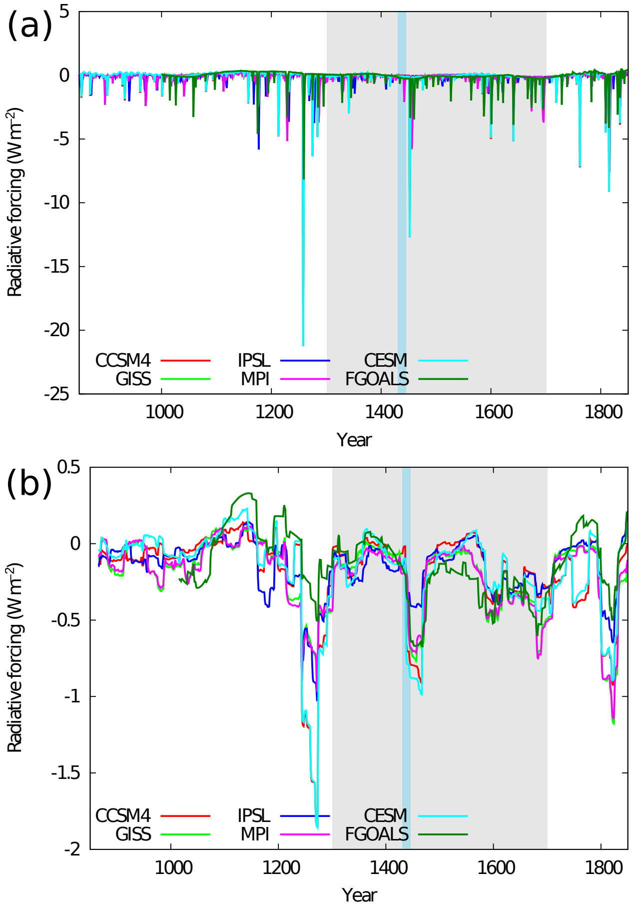


**Figure 3.** **(a)** Estimations of total external forcings used by the models in Table 2 according to Fernández-Donado et al. (2013). The panel includes anomalies with respect to the period 1500–1850 including the contributions of anthropogenic (greenhouse gases and aerosols) and natural (solar variability and volcanic aerosols). **(b)** The 31-year moving average filter outputs of **(a)**.

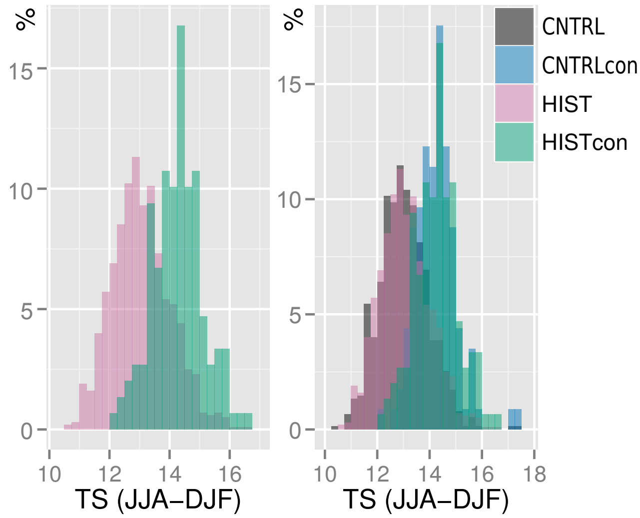


**Figure 4.** Probability density functions of seasonality in surface temperature (TS; °C) averaged over Europe (8° W–22° E, 41–55° N) for all years and years with a very cold winter (conditional). The latter are defined by winter temperatures cooler than mean-1sigma. Left: for the years 850–1849 of the transient CESM simulation (HIST). Right: also for the unforced control simulation (CNTRL; 600 years).

et al. (2012) were able to simulate the LIA cooling due to volcanic eruptions alone, without invoking changes in solar activity. In their model, amplifying feedbacks involving a change in the ocean circulation of the North Atlantic cause a long-term cooling of the climate in response to the eruptions in the 13th and 15th century. Similarly, Lehner et al. (2013) found that a negative solar or volcanic forcing leads to an amplifying feedback also involving sea ice changes in the Nordic Seas.

While oceanic feedbacks following an initial volcanic or solar trigger mechanism might not be separable, the initial response of the European climate to volcanic and solar forcing is expected to be different in terms of its seasonality. Both forcings are expected to cool during summer, but while low solar forcing is expected to weaken the westerlies and lead to low temperatures in eastern Europe (e.g. Brugnara et al., 2013), volcanically perturbed winters tend to have a stronger westerly flow and higher temperatures in north-eastern Europe (Robock, 2000). Note, however, that the mechanism of how changes in solar activity affect weather conditions and climate is still not well understood and thus these mechanisms may not be implemented in all climate models. The climate influence may proceed through changes in TSI, solar UV (Gray et al., 2010) or energetic particles (Andersson et al., 2014), which may have varying temporal developments. Further, reconstructions of the variations in solar radiation rely on proxy information such as sunspot counts or the abundance of radiocarbon and beryllium isotopes in tree rings or ice cores and are thus affected by uncertainties.

The modelled seasonality ($T_{JJA}$–$T_{DJF}$; for time series of both variables, see Supplement) of temperature in Europe is stronger in years with cold winters. This is illustrated by results from CESM (Fig. 4). The temperature difference between summer and winter is $13.06 \pm 0.98$ K averaged over Europe. The seasonality is increased to $14.27 \pm 0.84$ K when considering only years with very cold winters; here a winter is considered very cold if its temperature is within the lowest 17 % of all winters. No such dependence can be found for precipitation. Overall, 56.8 % of the years with a very large (above 1 standard deviation) seasonality coincide with a very cold winter. There is no difference between the control and the transient simulation concerning the occurrence of cold winters (HIST: 15.0 %; CNTRL: 15.2 % of all years) as well as seasonality, thus implying that, on average, external forcing does not affect modelled seasonality in Europe.

External forcing could also affect the seasonality during specific time periods. Based on winter temperatures, ex-

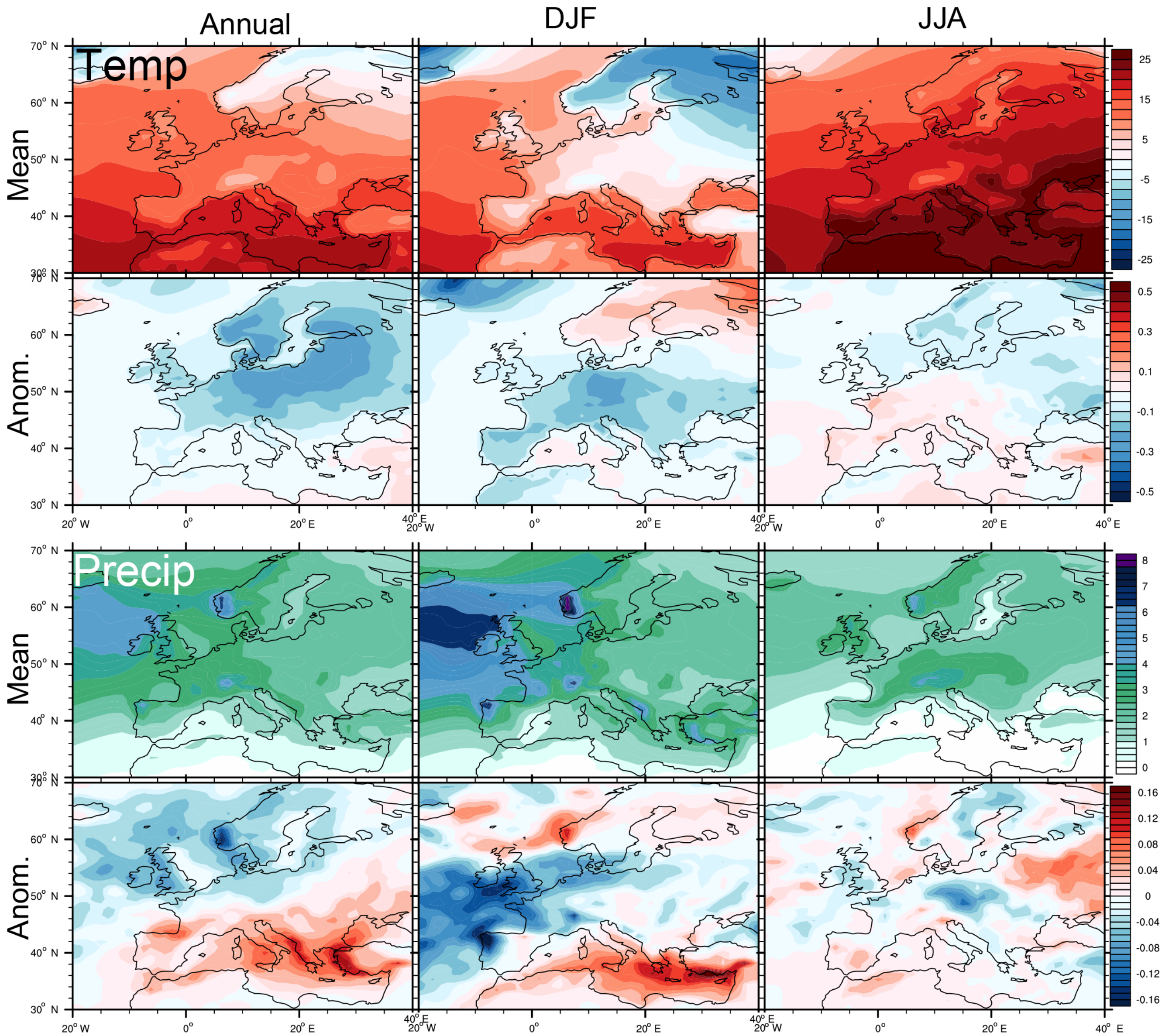


**Figure 5.** Maps of surface temperature (top; °C) and precipitation (below; mm day$^{-1}$). Shown are annual (left), DJF (middle) and JJA (right) averages based on the transient simulation (years 850–1849) with CESM. First row: mean for all years. Second row: anomalies for years with strong seasonality in TS (> mean $+1\sigma$) compared to all years. Seasonality is defined as the difference between the means June–August and December–January of the respective year.

tremely cold decades are identified in all available simulations (see Supplement). However, the lack of consistency between models indicates that there is no clear link between external forcing and an increase in the occurrence of cold winter decades.

Maps of temperature and precipitation for the years with strong seasonality in temperature are given in Fig. 5, based on the transient simulation with CESM. In agreement with the reconstructions, years with strong seasonality show anomalously cold winters in Europe. The effect on the annual mean temperatures, however, is limited to certain regions; the reason is the partial cancellation of cold winters and warmer-than-average summers. Anomalies in precipitation also show large spatial differences. During cold winters, it is wetter than usual in southern Europe and drier than usual in western and central Europe.

Volcanic eruptions are an important forcing factor, and since one of the strongest eruptions of the last millennium occurred within the SPM, a superposed epoch analysis is applied to the seasonality of temperature and precipitation in the multimodel ensemble. The superposed epoch analysis shows the mean anomaly of the 10 strongest volcanic erup-

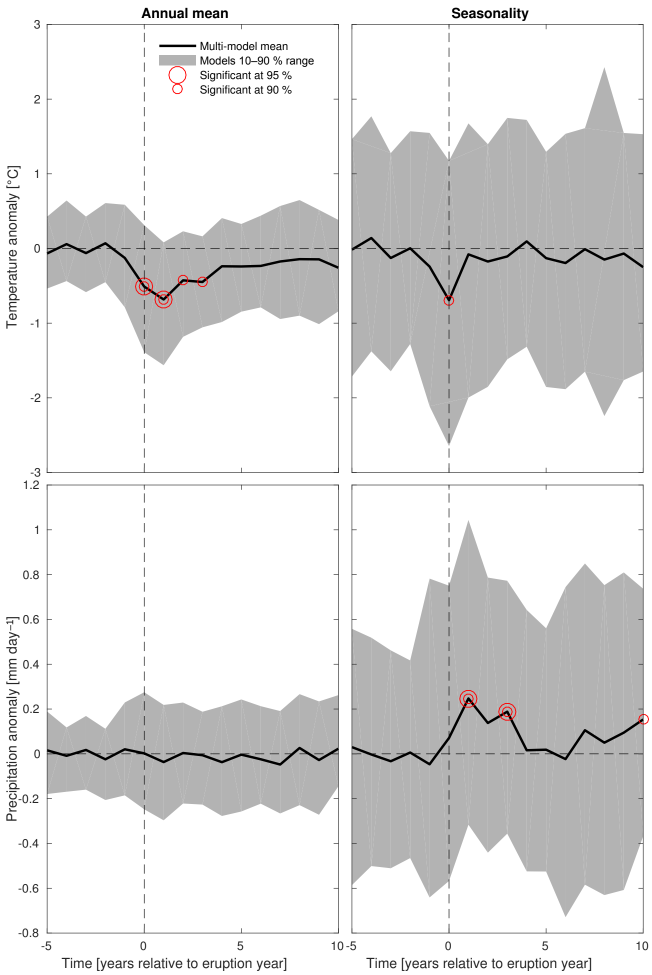


**Figure 6.** Superposed epoch analysis on the 10 strongest volcanic eruptions in six PMIP3 models, by measure of the respective forcing dataset unit (aerosol optical depth or injection amount), over the period 850–1849. (Left) Annual mean temperature (top) and precipitation (bottom) and (right) seasonality defined as the difference between the means June–August and December–January of the respective year. Each of the 60 time series (6 models × 10 eruptions) is expressed as an anomaly to the mean of the 5 years preceding the eruption year (year 0). The shading indicates the 10–90 % confidence interval, while the black solid line is the mean across all 60 time series. The red circles indicate significantly different means at 95 and 90 % confidence according to a $t$ test comparing each year to the 5-year mean preceding the eruption year.

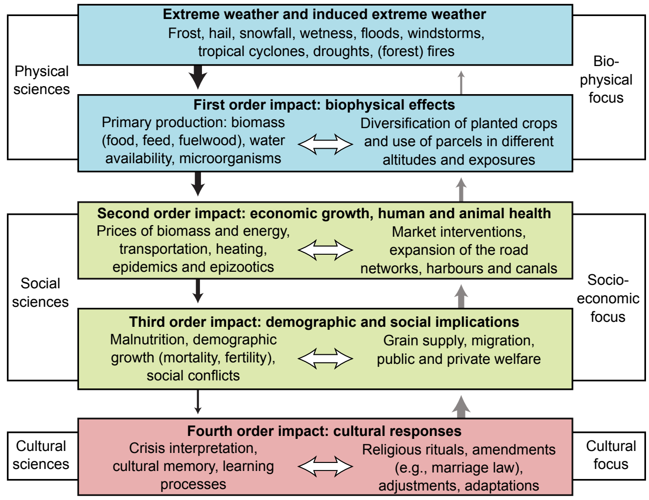


**Figure 7.** Simplified model illustrating how climate interacts with society. Extreme climatic conditions cause biophysical effects on the first level, which can be followed by second-order impacts that concern economic growth as well as human and animal health. On a third level are demographic and social implications situated, whereas cultural responses act as fourth level impacts (Krämer, 2015; Luterbacher and Pfister, 2015).

tions with respect to the unperturbed mean of the 5 years before an eruption. As illustrated in Fig. 6 (for maps, see Supplement), after an eruption the annual mean temperature is reduced over central Europe, whereas precipitation shows no signal. Temperature shows a reduction in seasonality, especially in the year of an eruption. A volcanic eruption tends to induce a North Atlantic Oscillation positive phase-like pattern that eventually leads to a warming of central Europe in winter while, during summer, the radiative cooling of the volcanic aerosols dominates. Precipitation seems to reflect the temperature behaviour; i.e. it mainly follows thermodynamics. Thus, the simulations suggest that in periods of frequent volcanic eruptions seasonality is reduced, in contrast to the increased seasonality in the 1430s decade. This also suggests that the exceptionally cold winters in this decade are not the result of volcanic forcing.

To conclude, there is no evidence from models that external forcing causes an increase in the occurrence of decades with both high temperature seasonality and very cold winters such as the 1430s. This points towards a dominant influence of natural, unforced variability in shaping the climate anomalies of the 1430s.

## 4 Climate and weather impacts on the economy and society

Human societies are strongly influenced by climate, climate variability and extreme weather conditions (Winiwarter and Knoll, 2007). Cold and wet conditions in spring, summer and autumn have a negative influence on both quantity and quality of the production of grain, vine, diary and forage (Pfister and Brázdil, 2006). Also the weather conditions during winter affect food production and food prices in multiple ways (Walter, 2014; Camenisch, 2015b). An exceptionally cold and/or long winter can be the reason that, despite good growing conditions in the subsequent summer, terrestrial ecosystem productivity is substantially decreased (causes include cold injury, alterations of the energy and water balance and advanced/retarded phenology; e.g. Williams et al., 2015). Usually winter temperatures do not have much influence on grain production, but temperatures can sink to such extremely low levels that – combined with no or almost no snow cover – the winter seed (mostly rye or wheat) is damaged or destroyed (Camenisch, 2015b; Pfister, 1999). Also late frosts often have a devastating effect on grain production. Frozen rivers and lakes can cause disturbances in the transport and processing of food (Camenisch, 2015b). The simplified climate–society interaction model presented in Fig. 7 illustrates how societies are affected on different levels by extreme climatic conditions. This model also gives the structure of how the climate impacts on society during the 1430s are presented here.

The respective information is available in a variety of historical documents such as narrative or administrative sources of different origins (Brázdil et al., 2005; Camenisch, 2015a; Bauch, 2015). Here, mainly contemporary English, German, Hungarian, Czech, Austrian, Italian and Dutch charters, letters, manorial, town and toll accounts, as well as narratives, are analysed.

The demographic, economic and political situation of Europe before and during the 1430s needs to be considered since it provides the context for the vulnerability and resilience of societies to climate extremes and their impacts. Europe experienced a dramatic decline of population during the 14th century due to famine, the Black Death and repeated episodes of plague and other diseases. The population stabilised at very low levels during the first decades of the 15th century. This did not change before the 1460s when European population began to grow again (Herlihy, 1987; Livi Bacci, 1992; Campbell, 2016). As a consequence of the lower population, wages were rather high and living costs rather low in comparison to other periods. Furthermore, settlements were withdrawn from environmentally and politically marginal locations (Allen, 2001). Thus, the adverse effects of climate deterioration were offset by the dwindling numbers of mouths to be fed and the shrinking proportion of households with incomes below the poverty line (Broadberry et al., 2015).

During the first half of the 15th century Europe suffered of the bullion famine, price deflation, major territorial and commercial losses to the Ottomans. A sharp contraction in oversea trade were generating serious economic difficulties of their own (Day, 1987; Spufford, 1989; Hatcher, 1996). Several wars in France, the Low Countries (Blockmans, 1980; Curry, 2012; Contamine et al., 1993; Derville, 2002; Barron, 1998; van der Wee, 1978), today's Switzerland (Reinhardt, 2013; Maissen, 2010), the Czech Lands, the northern parts of the Hungarian kingdom (Brázdil and Kotyza, 1995; Hungarian National Archives, DL 54734) and the area of Bologna in Italy (Bauch, 2015) aggravated the already tense situation. The food supply situation and the grain markets were influenced in several ways. Armies – confederates or enemies – marauded in the countryside in order to supply themselves. Furthermore, it belonged to the techniques of warfare of the time to weaken adversaries through destroying fields as well as seed and killing peasants and cattle. As a consequence, the rural populations sought refuge behind the walls of nearby towns, where the increasing demand for food led to exploding prices. In addition, wars caused increasing taxes, unsecured trade routes and a lack of farm worker and draught cattle as workers and horses were recruited by the territorial lord for his military campaigns (Schmitz, 1968; Contamine et al., 1993; Camenisch, 2015b).

### 4.1 First-order impact: biophysical effects

The main first-order climatic impact during the 1430s was a decline in food production. In England, Germany, France, the Netherlands, Bohemia and other places, crop failures were reported in 1432, 1433, 1434, 1436, 1437 and 1438 (Jörg, 2008; Tits-Dieuaide, 1975; Camenisch, 2012; Brázdil et al., 2006). In late April 1434, vineyards were damaged by frost in Hungary, Austria and Bohemia. In Italy, the years 1431–1435 were characterised by harvest failures and dearth (Bauch, 2015). During the harsh winters of 1434/35 and 1436/37, in the London area special references were made to herbs such as laurel, sage and thyme, which were destroyed by the frost. Moreover, the lack of fire wood and coal is mentioned (Brie, 1906a). In the area of the Low Countries and the Holy Roman Empire, several authors describe frozen vineyards, devastated winter grain and damages to livestock during the winter of 1436/37. Vegetables, vine and grain in the fields were destroyed by two frost periods at the end of March 1437 and in the second half of May (Camenisch, 2015b). Harvest failures and grain shortages were also mentioned in the area of Berne in the same year (Morgenthaler, 1921). In 1440, serious losses in wine production and a bad hay harvest were reported for Pozsony/Pressburg (which is today's Bratislava; Ortvay, 1900).

### 4.2 Second-order impact: economic growth, human and animal health

As a consequence of the poor harvests in many European regions, food prices increased considerably. Early reports on rising food and firewood prices in Paris, Cologne, Augsburg and Magdeburg date back to the years 1432 and 1433 (Beaune, 1990; Cardauns et al., 1876). In 1433, high food prices prevailed in Austria, the Czech Lands and the Hungarian kingdom (Höfler, 1865). Even in Scotland and Ireland, high prices and shortages were mentioned in the same year (Dawson, 2009). Special attention was paid to the price development of eatables in 1437–38 and 1438–39 in London (Brie, 1906a). In many other places in the Holy Roman Empire and the Low Countries, very high food prices were mentioned in the second half of the 1430s (Jörg, 2008; Camenisch, 2015b). In England, a chronicle reported increasing wheat prices in 1435 and the consumption of substitute food such as bread made from fern roots was reported in the north

(Marx, 2003). In London, rising prices for different grains were noted as well as for wine, sweet wine, meat and fish. The consequences that were described for the wider population were inferior bread and malnutrition (Brie, 1906a). Other sources, however, report moderate prices in 1435 and no price increases in England before 1438 (Munro, 2006).

Food shortages and crises are mentioned in many places during the 1430s in north-western and central Europe. Most places were already affected by rising prices during the first half of the 1430s. In the years 1432–1434 Bohemia was confronted with famine. During the second part of the decade especially the Low Countries and the Holy Roman Empire suffered a veritable famine. The author of the *Tielse kroniek* described the year 1438 with the following words: "In 1438 there was such a dearness and famine in the entire Netherlands so that one did not know how to complain about poverty and moan on misery."[2]

Most historical sources examined here mention epidemic diseases simultaneously with cold and wet weather conditions, dearth and subsistence crises. However, often it is not possible to identify the type of disease since an exact description is lacking and most diseases were just called "pestis". Several links between weather conditions and diseases are known. Cold and humid weather favour the spread of certain diseases of the respiratory system (Litzenburger, 2015). Also, ergotism – then called "Saint Anthony's fire" and perceived as an epidemic disease and not as a dangerous and potentially lethal intoxication through the ergot fungus as it actually is – is linked to cold and humid weather. The fungus prospers best in a humid and rather cold environment (Billen, 2010). Furthermore, undernourished people were prone to diseases of the digestive and respiratory system and infections (Galloway, 1988; Landsteiner, 2005; Campbell, 2009). The relationship between weather conditions and the plague, however, is still under discussion (Audouin-Rouzeau, 2003; Saluzzo, 2004).

### 4.3 Third-order impact: demographic and social implications

Diseases resurged in these years and deaths from the plague were widely reported during the serious famine of 1438–1439, when predisposing environmental and economic conditions favoured host–vector–human interactions (Biraben, 1975). Epidemics and high death rates were mentioned in the north of England (Brie, 1906a). Furthermore, "pestilentia" was reported as far east as the Hungarian kingdom (e.g. ca. 1430: Iványi, 1910; 1440: Hungarian National Archives DL 55213). During the second half of the 1430s, Italy saw a row of country-wide epidemics (Bauch, 2015). In Bruges, 24000 deaths due to epidemics and famine were mentioned (Camenisch, 2015b). Around Easter of 1439, the epidemic disease also reached Berne where a considerable part of the town's inhabitants was carried off (Morgenthaler, 1921). During the 1440s and 1450s, Europe's population sank to its lowest levels during the Late Middle Ages.

The extreme climatic conditions during the 1430s also had a strong impact on the health and fertility of sheep flocks in England. Several manorial accounts from southern English demesnes reveal that the years 1432, 1433, 1437 and 1438 saw excessive mortality rates in sheep flocks (on average 32 %, compared to 4–5 % in normal years). The climate also seems to have affected the fertility rates of ewes (East Sussex Record Office, S-G/44/85-94). The decline in sheep health and fertility rates also implied a decline in the productivity rates of sheep fleece (Stephenson, 1988). The fall in wool productivity is reflected in the annual export levels of English wool, which fell from 13 359 sacks/year (each sack = 364 lbs) in 1426–1430 to 9385 in 1431–1435 and 5379 in 1436–1440. The respective figures for 1437, 1438 and 1439 were 1637, 1548 and 1576 sacks $yr^{-1}$ (Carus-Wilson and Coleman, 1963).

Usually, grain was traded whenever the price difference between two places was high enough to yield a profit despite the high transport costs; this was rather often the case. During the 15th century grain trade occurred regularly in many European regions (Achilles, 1959; Camenisch, 2015b). Grain was bought from distant places in order to increase the food offerings and consequently stabilise food prices and supply people with victuals. In London, the Mayor organised the successful import of rye from Prussia (Brie, 1906b). In Great Yarmouth, a seaport in Norfolk with a focus on herring fishery and trade, grain was usually used to fill up the ships to maximise profits on the return journey. However, when harvests failed in northern and central Europe due to harsh climatic conditions in the late 1420s and especially from 1437 to 1439, Yarmouth's trade pattern changed completely. Merchants from the Low Countries were purchasing large amounts of grain to bring to the famished cities on the southern side of the North Sea. Due to extremely high prices, the long-distance grain trade became so profitable that intermediary traders from the Thames estuary region organised large-scale shipments into the usually exporting Norfolk area, most likely to Norwich. To stop the flow of grain to the Low Countries, the English crown issued an export ban in September 1438 (Norfolk Record Office, Great Yarmouth Borough Archives, Court Rolls, Y/C 4/134-149; Calendar of the Close Rolls Henry VI, 1937). In (western) Hungary, food shortage was already problematic in 1433 due to high export volumes of cereal to the neighbouring countries. Thus, in October 1434, a royal charter prohibited cereal export in order to avoid a great famine (Fejér, 1843). Such export bans were also established in the Low Countries and in the territory of the Teutonic Order in the Baltic area (Tits-Dieuaide, 1975). In 1437 in the area of modern Switzerland, after a poor harvest, the town of Zurich excluded Schwyz and Glarus –

[2] "In 1438 heerste er zo'n duurte en zulk een hondersnood in geheel Neder-Duitsland dat men van armoede en ellende niet meer wist hoe te jammeren en te klagen." (Kuys et al., 1983)

which were in political trouble with Zurich at that time – from the grain markets in its territory (Schnyder, 1937). This exclusion was a catastrophe since the cattle-breeding cantons of Schwyz and Glarus were dependent on these markets even in times of plenty; in times of dearth it was a deadly threat. After this embargo, Schwyz, Glarus and their allies took up arms and began a war – the Old Zurich War – that lasted several years (Reinhardt, 2013; Maissen, 2010). Furthermore, in several places in the Holy Roman Empire beer brewing was regulated during the years 1434 and 1437–38 (Jörg, 2008).

Mainly as a result of money devaluation (new silver coins: 1436) and taxation problems, a peasant uprisings occurred in 1437/38 in Transylvania; similar problems and a power controversy between German and Hungarian citizens motivated the turbulence of the Buda inhabitants in 1439. In 1440, serious problems in wine production, bad hay and poor cereal harvest formed the basis for a (royal) tax reduction in Pozsony/Pressburg (see e.g. Engel, 2001).

## 4.4 Fourth-order impact: cultural responses

In addition, religious responses to the harsh climatic conditions during the 1430s are known. In Bologna, the civic cult of the Madonna di San Luca was founded in 1433 as a reaction to the continuous rainfall from April to June of that year. The veneration of a miraculous icon was repeated 1 year later as bad weather returned; in the following decades, processions were organised when all kinds of perils (e.g. epidemics and war) threatened the civic community. With this approach of coping with crises, Bologna followed the model of neighbouring Florence, where the Madonna dell'Impruneta was famous for helping the city in all kinds of (natural) disasters since 1333 (Bauch, 2015).

In several parts of the Holy Roman Empire, people blamed minorities for their misery. For instance, the newly arrived Romani (then called "gypsies") were blamed for the harsh conditions from 1430 to 1440 as well as the associated consequences, including rising food prices, famine and plagues (Gronemeyer, 1987; Winstedt, 1932). The ability to change or create weather was attributed to the "gypsies" magical powers. The discrimination and persecution of the "gypsies", especially in connection with disasters, could be seen as an attempt to solve underlying social tensions and problems. Further, Jews were blamed for usury during the 1430s and were expelled from many towns in the Holy Roman Empire. The reasons behind this were complex and strongly linked to politics and the Church Councils in the first half of the 15th century. The tensions through the subsistence crisis only aggravated the situation (Jörg, 2013). During the following centuries the accusations of Jews squeezing profit from the misery of people who suffered from the consequences of subsistence crises by committing usury, hoarding of staple food for later profit and debasing of money did not vanish (Bell, 2008). However, in the course of the 15th, 16th and 17th century "witches" were suspected of "weather-making". They had the function of scapegoats in many cases of extreme weather events (Behringer, 1999; Pfister, 2007; Litzenburger, 2015).

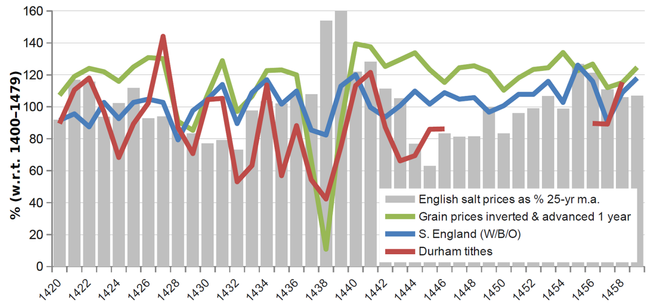


**Figure 8.** Crop yields from southern England (wheat, barley, oats), Durham tithes, English grain prices and English salt prices for the years 1420–1460 (values are given as anomalies with reference to (w.r.t.) the period 1400–1479). Shown are the years 1437 and 1438 in the back-to-back grain harvest failure in southern England, the massive reduction in Durham tithe receipts and the marked inflation of grain prices for 3 consecutive years. In 1442, the harvests in southern England are again poor. As far as the agricultural impacts of the Spörer Minimum are concerned in England, 1432–1442 stands out as the worst period, especially 1436–1438 (adapted from Campbell, 2012).

Following the 1430s, communal granaries were built in several places in Europe, for instance in Basel, Strasbourg, Cologne or London (Jörg, 2008; Dirlmeier, 1988; Campbell, 2009, Litzenburger, 2015). These building activities were an adaptation strategy to prevent the local society from further food shortages.

## 4.5 Social vulnerability and resilience to subsistence crisis during the 1430s

Prior to the 1430s societies were comparably resilient to large-scale famines, the reasons being the lower demographic pressure after the Great Famine and the Black Death at the beginning and in the middle of the 14th century as well as higher wages and generally lower living costs (Campbell, 2009). So, why did Europe suffer to such an extent? The crisis during the 1430s was the most severe since more than 100 years (Bauernfeind, 1993; van der Wee, 1978), which is probably the reason why societies (and especially the authorities) were not prepared to cope with failing markets and interrupted trade routes in such dimensions (Jörg, 2008).

Europe was affected from the Iberian Peninsula to the Baltic and the Russian Principalities as well as to the British Islands. However, there were big differences in the magnitude and sequence of the crisis (Jörg, 2008; Contamine et al., 1993). In northern France, for instance, the famine formed the nadir of agrarian production and demographic development of the 15th century (Neveux, 1975). In the Low Countries and the Holy Roman Empire, the crisis developed into a veritable famine. In other parts of Europe, however, this was not the case. In Italy, Holland and England, a decline of 13 % in GDP per head did not escalate into a demographic repeat of the Great European Famine of 1315–1321 (see Fig. 8; Malanima, 2011; van Zanden and van Leeuwen, 2012; Broadberry et al., 2015; Campbell, 2009). In many parts of Europe, the next subsistence crisis did not occur before the 1480s (Morgenthaler, 1921; van Schaïk, 2013; Camenisch, 2016).

The reason why some regions were hit more than others is difficult to detect. It can be assumed that wars and riots played an important role. Furthermore, the different levels of market integration, the unequal dependence on the markets in order to feed the population and the demographic structure of the different regions are certainly of importance. Institutional factors such as poorly conceived famine relief, lower tax base due to the declined population or higher transport costs as a consequence of the high wages need to be examined in future research in order to better understand this crisis of the 1430s.

## 5 Conclusions

Here we have presented the first systematic assessment of the particular climatic conditions during the 1430s and their impacts on society and economy. Natural (tree rings, lake sediments and speleothems) and anthropogenic archives agree that, with its cold winters and normal to warm summers, this decade was outstanding in the context of the LIA. State-of-the-art climate models indicate that this strong seasonality was likely caused by internal, natural variability in the climate system rather than external forcing. Volcanic eruptions lead to a decrease in temperature seasonality and cannot explain the reconstructed climate during the 1430s. There is also no indication that a reduction in solar forcing causes an increase in temperature seasonality.

In response to the prevailing cold and long-lasting winters, the growing season was considerably shortened which, together with rainfalls during harvesting, resulted in crop failures in many European regions. Together with other socioeconomic factors (e.g. wars, market failure through export stops, other interruptions of trade) these harvest failures led to an increase in food prices. Especially in the Low Countries, parts of France and the Holy Roman Empire, rising food prices resulted in subsistence crisis, even famine. In combination with epidemic diseases, this led to an increase of mortality rates in England, Italy, Hungary, parts of the Holy Roman Empire and the Low Countries. The European population size sank to its lowest level during the 15th century.

As a consequence of the subsistence crisis societies developed and implemented various coping strategies. Civil authorities bought grain supplies from distant places in order to stabilise the prices and to nourish their own population. Elsewhere, export bans were established in order to avoid price increases due to a drain of food from the local markets. Further coping strategies, such as the invention of a civic cult, were established by religious authorities. In the context of the crisis minorities were blamed for harsh climatic conditions, rising food prices, famine and plague. Furthermore, the subsistence crisis was the reason for the subsequent construction of municipal granaries in different towns in Europe. With that adaptation strategy the authorities intended to diminish the societies' vulnerability against future crises.

The example of the 1430s provides a rich source of knowledge on how different environmental and social factors and the interplay between them can generate strong impacts on the socioeconomic system with consequences such as famine. Societies and authorities were not prepared in the 1430s to cope with the failing markets and the interrupted trade routes. In immediate response to the crisis, societies and authorities tried to avoid the worst by implementing short-term coping strategies. This short-term reaction likely reduced but did not avoid negative impacts. On longer timescales, societies and authorities learned, forced by the large negative socioeconomic impacts and high mortality rates of the 1430s, and prepared for the next crisis by developing and applying adaptation strategies.

Are there lessons for the modern situation? Large-scale negative climatic and environmental impacts on natural and socioeconomic systems are linked with anthropogenic greenhouse gas emission causing global warming, an increase in the frequency of extreme events, sea level rise and ocean acidification (IPCC, Synthesis Report). In view of this development, governments decided to implement effective greenhouse gas emission mitigation and climate change adaption measures in a timely way (UNFCCC, Paris Agreement, entered in force October 5, 2016; http://unfccc.int/paris_agreement/items/9485.php). Our analysis of the subsistence crisis of the 1430s shows that societies that are not prepared for adverse climatic and environmental conditions are vulnerable and may pay a high toll. This illustrates the need of measures towards avoiding dangerous anthropogenic climate interference (UNCFCCC, 1994 http://unfccc.int/key_documents/the_convention/items/2853.php) if the wish is to avoid similar or even larger crises. Further, this study illustrates the complex nature of the interplay of climatic conditions and socioeconomic factors in shaping human societies and thus highlights the need for holistic, interdisciplinary approaches for analysing them.

## 6 Data availability

PMIP3 model simulations are available from https://pmip3.lsce.ipsl.fr/; model results with CESM presented in this study are available from the corresponding author upon request (keller@climate.unibe.ch). For access to the proxy data, the respective authors should be contacted personally.

## Appendix A: Data base of reconstructions

A comprehensive set of paleoclimate records is considered in Sect. 2 to provide a wide range of climate variables from different paleoclimate archives, which are representative for most of north-western and central Europe (Fig. 2). Information about summer and winter temperatures as well as summer precipitation are obtained from historical sources, tree rings, speleothems, and varved lake sediments in order to characterise the climate during the SPM (Table 1).

The datasets are selected according to the following criteria:

- calibrated and validated proxy-climate relationship (demonstrated plausible mechanistic relation to climate);
- annual to near-annual resolution, covering the SPM and ideally the period 1300–1700;
- continuous, with no major data gaps; and
- published in a peer-reviewed journal (except Hasenfratz et al., 2016).

All datasets are analysed at decadal-scale resolution. For comparability, all annual data are standardised with reference to the period 1300–1700 (datasets 6, 11 and 16: 1400–1500). Finally, decadal means (10-year mean windows) are calculated for each dataset.

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