Thank you very much for your detailed review and the very useful suggestions.

TITLE

The new title “The 1430s: A period of extraordinary internal climate variability during the early Spörer Minimum and its impacts in Northwestern and Central Europe” does not work gramatically. It would work, for example, if “and its” was replaced with “with”. Also, the “impacts” should be qualified in oder to reflect the special aspect of this paper. “Societal impacts” or “socioeconomic impacts” or “impacts on societies” or something like that. Could otherwise be anything, such as impacts on ecosystems, erosion, or endless other things readers of Climate of the Past might think of.

We changed the title into: “The 1430s: A cold period of extraordinary internal climate variability during the early Spörer Minimum with social and economic impacts in Northwestern and Central Europe”

ABSTRACT

The abstract is not well organised but jumping back an forth between different aspects of the paper, i.e. the climatic and the impacts analysis. Also, the Spörer minimum is first referred to, then later explained. And it falls short of making the main points of the paper. Please improve. This is particularly important if the article is proposed for highlighting, which might be an option, given the interesting climate-society connection.

After revision of the manuscript the abstract content will probably need to be adapted accordingly

We restructured the abstract and distinguished between aspects of climatic analysis and impact analysis. The term Spörer is deleted.

LANGUAGE

As mentioned by the reviewers, the language is often imprecise and a little awkward. A revised version that is acceptable needs to be improved in that aspect. I put some edits into the manuscript, partly to demonstrate the kind of issues meant. The entire manuscript should be combed through, please. I am sure there is enough capacity for that in the author team.

We thoroughly went through the whole manuscript and clarified/homogenized the language.

TEXT ORGANISATION

The text organisation should be improved, as also pointed out by a reviewer, but then mostly disregarded in the revision. The text deficiencies are also surprising given the prominent list of co-authors and cumulative publishing experience.

The text still reads as three separate parts of different character. I appreciate that it might be challenging to homogenise texts of researchers with different cultures, but am asking nevertheless for some further, moderate improvements:

- The introduction chapter lacks clarity what the purpose of the paper is. Moreover, from about page 3 line 29 a lot reads like preempting the results/discussion already. Please check to make a clear distinction between introduction/framing etc, and presentation of the results.
- Chapters 2 and 3 provide information that goes significantly beyond the key aspect of the paper (according to the new title), i.e. the 1430’s. We can accept that as background information, but I am asking for a summary paragraph at the end of the data and modelling chapters that highlight the most relevant conclusions for the key storyline.

We changed the text organisation of the abstract, the introduction and the conclusion. In particular the parts of the introduction which contained results were integrated into the respective chapters. Chapter two and three end now with a brief summary of the major results.

- Chapter 4 (as mentioned by a reviewer) is simply disproportionately long - too long to be read by CP readers in its current form. I suggest to cut where possible (some suggestion in my annotated text, but please check for further potential for condensing) AND to move climate information to chapter 2 even if from historical sources AND add sub-chapter structure to chapter 4. Sub-chapters could logically follow the scheme in figure 7.

All climate information from chapter 4 has been removed to chapter 2. Chapter 4 has been shortened considerably. Subtitles have been added to the chapter.

One referee also suggested to highlight adaptation measures and to separate out the more societal/political from the religious ones. I think this would also be a great way of presenting the adaptation topic better, given that we have major adaptation challenges in front of us today also.

The paper falls short of translating the results to what we can conclude for our modern society and current situation about things like vulnerability and adaptation responses. It would be great of the authors could expand a bit on that, if they dare. Could be in the conclusions or as a short (sub-)chapter before.

We added a paragraph to the conclusion in regard to vulnerability and adaptation.

Please check the use of the term weather. In several places, it seems to be used inappropriately when climate is actually meant.

Done

A major finding highlighted from the paleoclimate analysis is the attribution of the high-seasonality period to internal variability, not external forcing. It would be good to explain (probably mostly in chapter 3) why this is relevant for this paper, as opposed to just detecting the seasonality and then looking at the impacts on societies.

This finding might not be of particular importance for the impact part, but we think that it is also important to address the cause behind these particular climatic conditions (especially in the framework of such an interdisciplinary effort).

CONCLUSIONS
As asked by referees, the conclusions should be better substantiated (see also some annotations I made into the text).
We changed the structure and added information.

FIGURES
Fig. 2 has turned out very nicely. Other figures were criticised by referees to be less important, and I agree with them. On the other hand, as you seem to feel strongly to keep them, I am fine to keep them in the paper, even if they might illustrate non-central points.
Please note a few remarks in the annotated manuscript.

Done

The 1430s: A cold period of extraordinary internal climate variability during the early Spörer Minimum with social and itseconomic impacts in Northwestern and Central Europe

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Abstract. Throughout the last millennium, changesChanges in the climate mean state affected human societies. throughout the last millennium. While European cold periods like the Maunder Minimum in solar activity in the 17th and 18th century have been assessed in greater detail, earlier cold periods such as the 15th century received much less attention due to the sparse information available. Based on newNew evidence from different sources ranging from proxy archives to , historical documentary sources, and climate model simulations, it is now possible permit us to provide aan interdisciplinary, systematic assessment about the climate state duringof an exceptionally cold period in the 15th century,. Our assessment includes the role of internal, unforced climate variability and external forcing in shaping these extreme climatic conditions, and the impacts on and responses of the medieval society in Northwestern and Central Europe.

Climate reconstructions from a multitude of natural and anthropogenic archives indicate that the 1430s, a period coinciding with the early Spörer Minimum, was were the coldest decade in Northwestern and Central Europe in the 15th century. The particularlyThis decade is characterized by cold winters and normal but wetaverage to warm summers resultedresulting in a strong seasonal cycle in temperaturestemperature. Results from comprehensive climate models indicate consistently that challengedthese 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. As a consequenceSocieties were not prepared to cope with failing markets and interrupted trade routes. Only in response to the crisis, authorities implemented numerous measures of supply policy in order to cope with the crisis. Adaptation measuresand adaptation such as the installation of grain storage capacities were taken by town authorities to to be prepared for future events. The 15th century is characterised by a grand solar minimum and enhanced volcanic activity, which both imply a reduction of seasonality. Climate model simulations show that periods with cold winters and strong seasonality are associated with internal climate variability rather than external forcing. Accordingly, it is suggested that the reconstructed extreme climatic conditions during this decade occurred by chance and in relation to the partly chaotic, internal variability within the climate system.food production shortfalls.

1. Introduction

Several cold periods occurred in Europe during the last millennium and might have affected human socio-economic systems. The cold can be attributed to external climate forcing and internal (chaotic) climate variability. Forcing included cooling by sulphate aerosols from explosive volcanism and solar irradiance variations against the background of slow variations of Earth's orbit leading to a decrease in summer insolation over the past several millennia.

The past climate is reconstructed from information recorded in climate archives such as tree rings, sediments, speleothems, ice, and historical documents. Documented impacts of severe cold periods on socio-economic systems include reductions in the amount and quality of agricultural products. This in turn, together with other political, social, and cultural factors, sometimes resulted in impacts on food availability and prices, famines, reductions in birth rates, population growth, population size, and social distress, many of which provoked adaptation policies and measures. 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, 1976: 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), much less is known about an exceptionally cold period in Europe during the 15th century.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 sulphate 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 socio-economic change during a particular cold period in Europe from around 1430–1440 CE (Fig. 1). This is done by analysing multi-proxy 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, and by analysing multi-proxy evidence from various natural and anthropogenic archives to inferidentify the origin of the reconstructed climate variability in terms of temperature, and precipitation, and underlying mechanisms. 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 socio-economic conditions, impacts, resilience, and adaptionadaptation to change by using quantitative indicators such as corngrain prices, population and trade statistics, as well as descriptions. The potential impacts of climate on society are discussed in the context of other important socio-economic drivers.

Our study concentrates on Northwestern and Central Europe during the period of the Spörer Minimum (SPM) in solar activity in the wider context of the "Little Ice Age" (LIA; ~1300–1870). . Concerning the temporal extentA particular focus is on the decade 1430–1440, which coincides with the early SPM. We stress that this temporal concurrence does not imply causality, and that the particular climatic conditions during the 1430s are not necessarily the result of changes in solar irradiation. Concerning the temporal extend of the SPM, a number of differing definitions exist: 1400–1510 (Eddy 1976b; Eddy 1977; Jiang and Xu, 1986); 1420–1570 (Eddy, 1976b; Eddy, 1977; Kappas 2009); 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. Here, we use the years 1421–1550. The period of strongest reduction in incoming total solar irradiance (TSI) occurred during ~1460–1550 (Eddy, 1976a) and coincides with several large volcanic eruptions (Sigl et al., 2013; Bauch, 2016).Note that this temporal coherence between solar forcing and the particular climatic conditions during the 1430s does not necessarily imply causality.

Historic documents show that the 1430s were a period of enhanced seasonality with cold winters and normal summers (Luterbacher et al., 2016; Fig S1). Yet, such changes in seasonality have not been assessed in detail using climate proxy data nor climate model output (Wanner et al., 2008). It remains unclear how, if at all, this seasonality was linked to external forcing or resulted by chance from internal climate variability and whether the seasonality was extraordinary in the context of the last millennium.

Concerning the hemispheric-scale mean changes climateClimate model simulations and multi-proxy 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 study collecting hemispheric-scalesynthesis of climate reconstructions suggests a more 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 only the Maunder Minimum was avolcanic-solar down turns in the 16th and 17th century were associated with globally coherent cold phase during the last millennium.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 different regions during periods of strong external forcing (such as the SPM; PAGES2K-PMIP3 Community et al., 2015). Still, the simulations agree with the reconstructions for Europe in that a major cooling happens after 1450, so after the 1430s.

In Western Europe, the 1430s featured a series of extremely cold and extended winters (Buismann, 2011; Camenisch, 2015b; Fagan, 2002; Lamb, 1982; Le Roy Ladurie, 2004), which affected the productivity of terrestrial ecosystems in the subsequent growing seasons. The consequences were losses in agricultural production. Crop failures, famines, epidemic plagues, and high mortality rates haunted large parts of Europe at the end of this decade and in the 1440s (Jörg, 2008; Camenisch, 2012). Weather conditions during winter affected the food production and food prices in different 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 was substantially decreased (causes include cold injury, alterations of the energy and water balance, and advanced/retarded phenology; e.g., 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; Camenisch 2015b; van Schaïk, 2013).

Given the sparse knowledge of this time periodWilliams et al., 2015). For instance, very low temperatures could destroy the winter seed (mostly rye or wheat), which was sown in the fields in autumn. Usually, the winter temperatures do not have much influence on grain production, but in the case of the 1430s temperatures sank to such extremely low levels that – combined with no or almost no snow cover – the seedlings were damaged or destroyed (Camenisch 2015b; Pfister 1999). Late frosts, as occurred during the 1430s, usually had a devastating effect on grain production. Additionally, cattle as well as fruit and nut trees suffered from very low temperatures. Frozen rivers and lakes could cause disturbances in the transport of food and consequently the food trade. Frozen bodies of water and drifting ice were also responsible for broken bridges and mills. The first meant disrupted trade routes and the latter interferences with regard to the grinding of grain into flour (Camenisch, 2015b). Thus, this period is an historic example of how society reacted to extreme climatic conditions and other changes such as abruptly rising food prices, market failure, famine, epidemic diseases and wars and how adaptation strategies were implemented. Still, whether the famines associated with the documented crop failures were a mere result of climate change is questioned as prior to but also during the SPM international trade went through a period of deepening recession, hindering the people to sufficiently mitigate crop failure (Campbell, 2009; Jörg, 2008; Camenisch, 2015b).

Given this lack of understanding, 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 outlinestructure of the paper is as follows: section 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 section 4, socio-economic 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., in preparation; 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 ~~temperatures~~temperature in Europe ~~were~~was not colder during the SPM than ~~before or afterwards~~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 ~~deviations were~~deviation in average winter temperature was not unusual during the SPM~~ in light of the early LIA~~.

While the centennial-scale climate variability informs mainly about the influence of the prolonged ~~TSI~~total solar irradiance (TSI) minimum during the SPM, inter-annual to decadal-scale climate variability illustrates (cumulative) volcanic forcing or internal (unforced) variability. Fig. 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 ~~normal~~average or warm (for the years 1430–1439, Luterbacher et al., 2016, see supporting information, Fig S1). Striking is the very cold decade 1451–1460, which is a consistent feature across all summer temperature proxy series and coincides with two consecutive very large 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 ~~are reconstructed~~occurred during the 1430s. The slightly warm anomaly on record [8] 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 ~~was observed~~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 (~~Schurer et al., 2014;~~ Hernańdez-Almeida et al., 2015~~). Cold winters were also confirmed in these areas after 1590 (1594 Ruang)~~ although the expected mean response to a volcanic eruption is a winter warming over Europa (e.g., Robock and ~~1600 Huaynaputina eruptions; Arfeuille~~Mao 1995; Fischer et al. 2007, Ortega et al~~., 2014; Sigl et al., 2014~~. 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 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 characterized 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 ~~(i.e., cold winters and normal to warm summers)~~ is the comparison of summer and winter temperature reconstructions. Fig. 2 shows that such a period was only evident from 1431–1440 in the proxy records. ~~Additionally, the~~ In contrast, other decades with low winter temperatures do not feature an increase in temperature seasonality.

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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: 106)

Further, summer precipitation is ~~shown~~presented in Fig. 2 in order to assess whether during ~~this period~~ the 1430s also the hydrological cycle was ~~also~~ unusual, either ~~too~~particularly dry or ~~too~~ 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 two flood and five drought years occurred (Pichard and Roucaute 2014; Glaser and Stangl, 2003). South of the Alps, the years 1430 to 1433 were extraordinarily wet (Bauch 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). ~~no consistent behaviour is found, i.e., some records show normal condition whereas one record show a strong increase in summer precipitation.~~

It can be concluded that, on centennial scales, the climatic conditions in Europe during the SPM were not unusual in the context of the LIA. On inter-annual 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 ~~European~~ summers coincide with very cold winters ~~in Western Europe. Whether or not these changes in~~. To understand the underlying mechanisms which may have caused this extraordinary seasonality ~~are due to~~ , the influence of external forcing ~~or~~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 inter-annual changes are due to volcanic forcing, despite large differences between models. A 31-yr moving average filtered version of the total forcing is shown in Fig. 3b, illustrating the contribution of volcanic forcing at inter-annual to multi-decadal time scales.

There are ~~uncertainties~~differences in the climatic conditions simulated by the different models~~ due to~~. 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; Fernández-Donado et al., submitted). Miller 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 ~~North Atlantic~~ 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 northeastern 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 ~~radiocarborn~~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 supporting information) 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 ± 0.98 K averaged over Europe. The seasonality is increased to 14.27 ± 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 ~~seasonalities~~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, extremely cold decades are identified in all available simulations (see supporting information). 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 ~~winter~~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 multi-model ensemble. The superposed epoch analysis shows the mean anomaly of the 10 strongest volcanic eruptions with respect to the unperturbed mean of the five years before an eruption. As illustrated in Fig. 6 (for maps, see supporting information), after an eruption, the annual mean temperature is reduced over Central Europe whereas precipitation shows no signal. ~~The seasonality of temperature~~Temperature shows a reduction in seasonality, especially in the year of an eruption. A volcanic eruption tends to induce an NAO-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 ~~(Clausius-Clapeyron equation).~~. 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 ~~during the early Spörer Minimum~~

Human societies are strongly influenced by climate, climate variability and extreme weather conditions (Winiwarter, Knoll 2007). ~~These influences~~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 ~~divided into short-term impacts (such as subsistence crises), conjunctural (price movement developments) and long-term impacts (~~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). ~~decline of empires, big migration movements) (de Vries, 1980). Furthermore, in regard to a subsistence crisis as an example of a short-term climate impact, different levels of influence~~ Usually winter temperatures do not have much influence on grain production, but temperatures can ~~be determined as the~~ 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 ~~demonstrates (see Fig. 7). On the first level, primary production (food, feed, and fuelwood), water availability, and microorganisms are directly affected~~ presented in Fig. 7 illustrates how societies are affected on different levels by ~~weather conditions. Economic growth (through prices of biomass or energy) as well as epidemics and epizootics are in turn influenced by these first-order impacts. The third level comprises demographic and social implications such as malnutrition, demographic growth, and social conflicts while cultural responses and coping strategies (e.g., religious rituals, cultural memory, learning processes, adaptation) constitute fourth-order impacts (Krämer, 2015).~~

~~This simplified climate-society-interaction~~extreme climatic conditions. This model ~~(see Fig. 7)~~also gives the structure of how the climate impacts on society during the 1430s are presented ~~in this paper, starting~~

~~with a description and extreme weather conditions, followed by the description of the climate impacts on society, level by level. ~~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, ~~2016~~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~~. Due~~ 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~~ Europe experienced a dramatic decline of population during the 14th century. During the first decades of the 15th century the~~. The population stabilised ~~but remained ~~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 1995, Campbell, 2016). As a consequence of the lower population~~ pressure~~, 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~~, and a~~. A sharp contraction in ~~overseas~~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), todays 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 ~~by them through~~in several ways. Armies – confederates or enemies – marauded ~~on~~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 ~~explode the~~to exploding prices. In addition, wars ~~led to~~caused increasing taxes, unsecure trade routes and a lack of farmworker and draught cattle ~~when~~as workers and horses were recruited by the territorial lord ~~needed soldiers and horses ~~for his military campaigns (Schmitz, 1968; Contamine et al., 1993; Camenisch 2015b).

In France, the Hundred Years War came into its last phase. In 1435, the Duke of Burgundy, a former ally of the English party, changed sides and again joined the French side. In the following 18 years, the English party lost its entire territory on the continent with the exception of Calais. The recapture started during the second half of the 1430s and included the devastation of parts of Flanders and Hainault by French troops. The desertion of the Duke of Burgundy in 1435 had further consequences for the economy of the Low Countries. The textile manufactories there were highly dependent on the import of English wool that failed for political reasons (Blockmans, 1980; Curry, 2012; Contamine et al., 1993; Derville, 2002). Furthermore, the Low Countries had to pay high taxes for the maintenance of the Duke's armies involved in the recapture of the English territories in France. As a consequence, a number of cities in the Low Countries were in open rebellion against their Duke (Barron, 1998; van der Wee, 1978). Further to the East, the Czech Lands and the northern parts of the Hungarian kingdom in the early 1430s were still affected by the repercussions of the protracted Hussite wars (Brázdil and Kotyza, 1995). In the winter of 1431, the Hungarian army – greatly fearing a Turkish attack – had increased its operations at the southern borderline due to the deeply frozen Danube (Hungarian National Archives, DL 54734). In Bologna, Italy, military actions and social unrest had weakened the city and its hinterland. Furthermore, communities in the contado complained about ravaging floods and claimed a reduction of their taxes towards the municipal authorities. Additionally, a serious earthquake hit the city simultaneously with the incessant rain and worsened the situation (Bauch, 2015). The area of the Swiss confederation was also impacted by political troubles in the years preceding the Old Zürich War (1440–1446). This conflict about the possession of territories and hegemony in the area of today's Eastern Switzerland was fought out between the canton of Zurich and the cantons of Schwyz and Glarus together with the other cantons of the Old Swiss Confederacy. (Reinhardt, 2013; Maissen, 2010).

As the reconstructions in Sect. 2 (see Fig. 2) show, the weather conditions during the 1430s stood out due to harsh and chilly winters. In the historical sources many descriptions can be found. In the area of the Low countries the winters of 1431/32, 1432/33, 1434/35 and 1436/37 were extremely cold whereas the winters of 1433/34 and 1437/38 were very cold. In the same area spring temperatures were very low or extremely low in 1432, 1433 and 1435 (Camenisch 2015a). Bohemia, Austria, and the Hungarian Kingdom suffered from a number of cold winters during the 1430s, especially the winter of 1431/32, 1432/33, 1434/35 were outstanding cold in these areas (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 had to be melted with fire before it could be drunk.[2] Extremely cold winters during the 1430s were also reported in Ireland (Dawson, 2009). In South-eastern France the winter seasons from 1434 until 1437 were outstandingly cold. In addition, there were frost periods in April 1432 and 1434 mentioned in that area (Maughan, 2016). In North and Central Italy, the winter of 1431/1432 was extremely cold till April 1432 (Bauch, 2015). In addition, in the Low Countries the summer seasons of 1436 and 1438 were also very cold (Camenisch 2015a).

In South eastern France, in the Provence area, and in the Netherland the first half of the 15th century was characterised by high levels of hydro-climatic variability. From 1424 to 1433 two flood and five drought years occurred (Pichard and Roucaute 2014; Glaser and Stangl, 2003). South of the Alps, the time span from 1430 to 1433 was extraordinarily wet (Bauch 2015). Likewise, during the 1430s, Bohemia, Austria, and the Hungarian Kingdom suffered from one of the greatest known flood anomalies characterised, for example, by the 'millennial' July 1432 flood in Bohemia (Brázdil et al., 2006) or by the*First order impact: biophysical effects*

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 and their consequences 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). An analogical temperature and precipitation pattern is also indicated by CESM (see Fig. 5).

The main first-order climatic impact during these yearsthe 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

[2] "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: 106)

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 todays Bratislava) (Ortvay, 1900).

Second order impact: economic growth, human and animal health

As a consequence of the poor harvests in many European regions, food prices increased considerably ~~(second-order impact according to Krämer's model, see Fig. 7).~~. 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, ~~the situation seemed more complicated. A~~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 ~~proved~~, however, report moderate prices in 1435 and no price increases in England before 1438 (Munro, 2006).

~~In almost all historical sources which have been examined for this research epidemic diseases are mentioned~~Food shortages and crisis are mentioned in many places during the 1430s in Northwestern 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.[3]

Most historical sources examined here mention epidemic diseases simultaneously with cold and wet weather conditions, dearth and subsistence crisis. Yet, 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

[3] «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: 167)

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). The relationship between weather conditions and the plague is still part of an ongoing discussion (Audouin-Rouzeau, 2003; Saluzzo, 2004). 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).

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, and from 1450–1457, when summer temperatures were the most depressed and ecological stress was again acute (Biraben, 1975). (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 death peopledeaths 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, due to epidemiological and reproduction regimes that kept deaths in excess of births (McEvedy and Jones, 1978; Broadberry et al., 2015). .

It also appears that the The extreme weather ofclimatic conditions during the 1430s also had a strong impact on the health and fertility of sheep flocks in England. Thus, as severalSeveral manorial accounts from south English demesnes reveals,reveal that the years 1432, 1433, 1437 and 1438 saw excessive mortality rates in sheep flocks, with the (on average figures standing at 32 per cent (%, compared withto 4––5 per cent% in normal years). The weatherclimate also seems to have also affected the fertility rates of ewes (calculated as the ratio between newborn lambs and all mature female sheep). The figures stood at 83 in 1434 and fell to about 55 in 1437 and 1438 (East Sussex Record Office, S-G/44/85-94). It should be borne in mind that in the late-medieval period, about 90–95 lambs were expected to be born of 100 ewes in normal years. The decline in sheep health and fertility rates also implied a decline in the productivity rates of sheep. In the 1430s, the average fleece weight per mature sheep was 1.1 lbs, falling to 1 lb in the 1440s and the 1450s (compared with the average of 1.4 lbs for the period 1210–1455) fleece (Stephenson, 1988). The fall in wool productivity is reflected in the annual export levels of English wool, which fell from an

~~annual~~ 13,359 sacks/year (each sack = 364 lbs) in 1426–1430 to 9,385 ~~sacks~~ in 1431–1435 and 5,379 ~~sacks~~ in 1436–1440. The respective figures for 1437, 1438, and 1439 were 1,637; 1,548; and 1,576 sacks~~ a~~ /year (Carus-Wilson and Coleman, 1963).

~~The impact of the extreme weather on the health of other animals is less clear. In 1434–1435, 37% of all cows died at Alciston (Sussex), but this seems to have been a local, rather than national outbreak. Also, the fertility rates of cows declined from about 90 to 66 in that year, on the same demesne (East Sussex Record Office, S-G/44/85-94). More detailed research is needed, in order to determine to what extent the situation at Alciston is reflective of other parts of England.~~

~~As has been shown, food shortages and crisis are mentioned at many places during the 1430s in North-western and Central Europe. Most places were already affected during the first part of the 1430s as has been shown in regard to the rising prices. In the years from 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.[4] Almost everywhere people tried to cope with the dearth.~~

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~~ Stephen Brown~~ organised the successful import of rye from Prussia (Brie, 1906b).~~ Thus, the narrative sources written for the nobility and the merchant elite both living in London completely neglect the effects of the granaries erected during the 14th and 15th century (Grandsen, 1982; Keene, 2012).~~ 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 ~~poor weather~~harsh climatic conditions in the late 1420s and especially from 1437–1439, Yarmouth's trade pattern changed completely. Merchants from the Low Countries were purchasing large amounts of ~~and sometimes exclusively~~ grain to bring to the famished

4 ~~«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: 167)~~

cities on the southern side of the North Sea. Due to extremely high~~ grain~~ 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~~, thereby closing England as a supply source to the Low Countries. During the remaining crisis years, the official records show very little grain leaving Norfolk via Yarmouth, and this grain was mainly sent to a number of small harbours along the East Anglian coastline. Smuggling across the North Sea was likely, but naturally not mentioned, in the customs rolls~~ (Norfolk Record Office, Great Yarmouth Borough Archives, Court Rolls, Y/C 4/134-149; Calendar of the Close Rolls Henry VI). In (West-) Hungary, ~~the ~~food shortage was already ~~a problem~~problematic in 1433 due to ~~the ~~high ~~volume~~export volumes of cereal~~ exported~~ 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 – 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, ~~at~~in several places in the Holy Roman Empire ~~the ~~beer brewing was regulated during the years 1434 and 1437/38 (~~Jürg~~Jörg, 2008).

Mainly as a result of money devaluation (new silver coins: 1436) and taxation problems, ~~one of the most significant medieval~~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).

Fourth order impact: cultural responses

Also~~,~~ religious responses to the ~~bad weather~~harsh climatic conditions during the 1430s are known. In Bologna, the civic cult of the Madonna di San Luca ~~started~~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 one year later as bad weather returned; in the following decades, processions were organised when all ~~kind~~kinds of perils (~~like~~e.g., epidemics and war) threatened the civic community. With this approach ~~to~~of coping with ~~this crisis~~crises, Bologna~~ clearly~~ 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. ~~The perception and treatment of the Romani which were then called “gypsies” at the beginning of the 15^{th} century is directly connected to the worsening of the weather during the early SPM. In chronicles of the 15^{th} and 16^{th} centuries, this connection was described as purely negative (Gronemeyer, 1987).~~ For instance, the newly arrived Romani (then called ‘gypsies’) were blamed for the ~~worsening of the weather~~harsh conditions ~~during the years~~from 1430 to 1440 as well as the associated consequences, including rising food prices, famine, and plagues (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 ~~to misfortunes~~with disasters, could be seen as an attempt to solve underlying social tensions and problems. ~~Climate change, in particular, entailed a variety of social problems through the shortage of resources. Thus, the statement that the newly arrived ‘gypsies’ were the cause for the worsening of the weather is an expression of this coping strategy. Furthermore~~Further, Jews were blamed for usury during the 1430s~~. In~~ and were expelled from many towns ~~of~~in the Holy Roman Empire ~~the Jews were expelled.~~. The reasons ~~for that~~behind this were complex and ~~are~~ strongly linked to ~~political reasons in regard to the Holy Roman Empire~~politics and the Church Councils in the first half of the 15^{th} 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 which 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 15^{th}, 16^{th} and 17^{th} 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).

~~As a consequence of the crisis of~~Following the 1430s, communal granaries were built ~~during the subsequent years at~~in several places in Europe, for instance in Basel, Strassbourg, Cologne or London (Jörg, 2008; Dirlmeier, 1988; Campbell, 2009, Litzenburger, 2015). These building activities ~~of the towns~~ were an adaptation strategy ~~that should~~to prevent the local society ~~there~~ from further food shortages.

~~Another example of how the climate during the SPM affected human society concerns fishery. Historical evidence plausibly connects the output of medieval fisheries for herring (*Clupea harengus*) in the North Sea and the Baltic~~Prior to ~~decadal-scale fluctuations in regional weather conditions. Preserved herring were the most important and widely marketed fish product in Europe. In particular, they provided the cheapest protein-rich food permitted during the six weeks of Lent in late winter and early spring when Christian rules most harshly forbade consumption of animal products. Recent fisheries science has established a close relationship between the regional climate and the success of these herring stocks. Limits of herring ranges move northwards in warmer and southwards in colder decades. Furthermore, larval herring experience high mortality during cold late winters and springs in their primary habitat of the eastern North Sea, resulting in low adult populations and poor fishing 2–4 years later (Alheit and Hagen 1997, 2001, 2002; Archipelago~~

~~Research Institute, 2015; Bailey and Steele, 1992; Finney et al., 2010; Krovnin and Rodionov, 1992; Poulsen, 2008).~~

~~Between the 1360s and 1540s, three kinds of historical sources indicate fluctuations in herring catches and stocks: contemporaries report losses in specific fisheries; 25 price series from 11 locations document great local volatility but also periods of widespread price peaks; and a unique record of yearly landings, written between 1405/06–1491/92 at Dieppe, a modest port near the southern boundary of the fishery range for herring. Taken together, these records identify at least regional and temporary collapses of herring catches for a time after 1360 (in the southern North Sea), locally in the Øresund from the 1410s, and more generally during the 1440s–1460s, the 1480s, and 1520s–early 1530s (e.g. Allen-Unger Database, 2015; Gemmill and Mayhew, 1995; Gerhard and Engel, 2006; Hauschild, 1973; Hitzbleck, 1971; Rogers, 1866–1902; van der Wee, 1963; Hoffmann, forthcoming). While some herring fisheries may have diminished in~~ the 1430s~~, regional and general failures of catches and stocks were most likely greater during the cold spells of the 1360s, mid-1400s, and after 1520.~~

~~In the decades prior to the examined period,~~ societies were ~~less vulnerable~~comparably resilient to ~~such~~ large-scale famines~~. The reason for this lies in the described~~, 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~~,~~ ~~the~~ as well as higher wages and generally lower living costs (Campbell, 2009). ~~But~~So, why did Europe suffer ~~from this crisis if the society was less vulnerable? This question cannot yet be answered completely.~~to such an extent? The crisis during the 1430s was the most severe since ~~the beginning of the 14th century~~ more than 100 years (Bauernfeind, 1993; van der Wee, 1978~~). This was~~), 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 ~~an extent that happened during these years~~dimensions (Jörg, 2008). ~~Presumably, the high food prices during the first part of the 1430s had the effect that food stocks were already consumed and there was no possibility to accumulate supplies during this period of poor harvests.~~

~~However,~~ Europe was affected ~~by this crisis~~ from the Iberian Peninsula to the Baltic and the Russian Principalities as well as to the British Islands. Yet, 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 ~~the~~ 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, ~~the rising food prices did~~however, this was not ~~result into famine; then an aggregate~~the case. In Italy, Holland, and England, a decline of 13~~ per cent~~% in GDP per head ~~in Italy, Holland, and England between 1435 and 1442, initiated by disastrous grain, wine, and wool harvests,~~ 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). ~~Clearly, too, there~~

was little prospect of breaking out of the prevailing economic and demographic stagnation while the agricultural output remained depressed and harvests uncertain. Together, prevailing environmental and economic constraints were too strong (Campbell, 2012). It is not until the final quarter of the 15th century, once the early Spörer Solar Minimum was past its worst, that incipient signs of regrowth become apparent in Italy, Spain, and England and especially in commercially enterprising Portugal and Holland (Campbell, 2013). Nonetheless, in many parts of EuropeIn many parts of Europe, the next subsistence crisis did not occur before the 1480s (Morgenthaler, 1921; van Schaïk, 2013; Camenisch, in press).

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. Still, this is not yet sufficient in order to explain the magnitude of the crisis and the regional differences. Perhaps, institutionalInstitutional 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 1430s, a particularly cold period in Europe coinciding with the early Spörer Minimum in solar irradiation, characterised by devastating losses in agricultural production and the associated socio-economic consequences.

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 the 1430s were subjected to very, with its cold winters and normal to warm summers. This strong increase in the seasonality of temperature suggests that, despite normal climatic conditions in the growing seasons, terrestrial ecosystem productivity was substantially decreased during , this decade.

was outstanding in the context of the LIA. State-of-the-art climate models indicate that this strongerstrong seasonality was likely caused by internal, natural variability in the climate system rather than external forcing. In fact, the results suggest that strong volcanicVolcanic eruptions lead to a decrease the seasonality of 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 and thus cause the opposite effect. Taken together, these lines of evidence indicate that the increased occurrence of extremely cold winters during this decade can be attributed to unforced, internal variability and the resulting atmospheric conditionsseasonality.

In response to the prevailing weather conditions, harvest failures all over Europe were reported. These harvest failurescold 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 socio-economic factors, led to an increase in food prices. In particular, (e.g., wars in different parts of Europe and , market failures caused byfailure through export stops, and other interruptions of trade played a role.) these harvest failures led to an increase in food prices. Especially in the Low Countries, parts of France, and parts of the Holy Roman Empire, increasingrising food prices resulted in a subsistence crisis. Many, 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—implemented by civil or . 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, an example is the invention of a civic cult, were established by religious authorities as well as by the population itself —are documented during this crisis, including trade regulations and restrictions on the brewing of beer.. In the context of the crisis the Romaniminorities were blamed the first time for adverse weatherharsh 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. Until now little considered and analysed, this periodWith 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 society reacted to deteriorating climate conditions, i.e., a shortening of the growing season due to a series of cold winters and the associated increase in seasonality. This period demonstrates how different environmental and social factors and the interplay between them can generate strong impacts on the socio-economic 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 time scales, societies and authorities learned, forced by the large negative socio-economic impacts and high mortality rates of the 1430s, and prepared for the next crisis by developing and applying adaptation strategies.

The 1430s are an outstanding period due to the fact that before those crisis years no supra-regional famine occurred since the middle of the 14th century. Although the extent of the crisis was a new experience for the societies, town authorities all over Europe started to implement supply policies or other coping strategies as has been shown. It should last another 40 years before the next subsistence crisis hit larger parts of Europe.Are there lessons for the modern situation? Large-scale negative climatic and environmental impacts on natural and socio-economic 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 socio-economic factors in shaping human societies and thus highlights the need for holistic, interdisciplinary approaches for analysing them.

Appendix: Data base of reconstructions

A comprehensive set of paleoclimate records is considered in section 2 to provide a wide range of climate variables from different paleoclimate archives, which are representative for most of Northwestern 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 (Tab. 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 ~~(here: 1421–1550),~~, and ideally the period 1300–1700;
- continuous, with no major data gaps; and
- published in a peer-reviewed journal (except Hasenfratz et al., in preparation).

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

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Tables

Tab. 1: Comprehensive multiproxy, multisite reconstructions from Western and Central Europe representing summer and winter temperatures as well as summer precipitation.

N°	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 + 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-Luxemburg	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	www.tambora.org / C Europe	Riemann et al. (2015)
10	DJF indices	Historical documents	Low Countries	Camenisch (2015b)
11	NDJFM indices	Historical documents	Belgium-Netherlands-Luxemburg	van Engelen et al. (2001)
12	Mean AWS Temp	Speleothems	Switzerland / W-C Europe	Hasenfratz et al., in preparation
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)

Tab. 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)

Figures

Fig. 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, 25.05.1480.

Fig. 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-yr mean) summer temperature, winter temperature and summer precipitation for the 16 climate reconstructions, standardized with reference to the period 1300–1700 (data sets 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., in preparation, [13]Amann et al. (2015), [16]Wilson et al. (2013).

Fig. 3: (a) Estimations of total external forcings used by the models in Tab. 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) 31-year moving average filter outputs of (a).

Fig. 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 yrs).

Fig. 5: Maps of surface temperature (top; °C) and precipitation (below; mm/day). 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 + 1sigma) compared to all years. Seasonality is defined as the difference between the means June–August and December–January of the respective year.

Fig. 6: Superposed Epoch Analysis on the ten strongest volcanic eruptions in six PMIP3 models, by measure of the respective forcing data set 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 x 10 eruptions) is expressed as an anomaly to the mean of the five 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.

Fig. 7: ThisSimplified model developed by Daniel Krämer and Christian Pfister showsillustrating how climate interacts with society. Extreme weather causesclimatic 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).

Fig. 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 South England, the massive reduction in Durham tithe receipts and the marked inflation of grain prices for three consecutive years. In 1442, the harvests in South 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).