The early Spörer Minimum – a period of extraordinary climate and socio-economic changes in Western and Central Europe

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Abstract. Throughout the last millennium, mankind was affected by prolonged deviations from the climate mean state. While periods like the Maunder Minimum in the 17th 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 new evidence from different sources ranging from proxy archives to model simulations, it is now possible to provide an end-to-end assessment about the climate state during an exceptionally cold period in the 15th century, 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 Central Europe. Climate reconstructions from a multitude of natural and human archives indicate that, during winter, the period of the early Spörer Minimum (1431–1440 CE) was the coldest decade in Central Europe in the 15th century. The particularly cold winters and normal but wet summers resulted in a strong seasonal cycle that challenged food production and led to increasing food prices, a subsistence crisis, and a famine in parts of Europe. As a consequence,

5   authorities implemented adaptation measures, such as the installation of grain storage capacities, in order 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 hypothesised that the reconstructed extreme climatic conditions during this decade occurred by chance and in relation to the partly chaotic, internal variability

10   within the climate system.

1. Introduction

Several cold periods occurred in Europe during the last millennium and affected the socio-economic systems. The cold resulted from external climate forcing and internal (chaotic) climate variability. Forcing included cooling by sulphate aerosols from explosive volcanism and solar irradiance variations in the background of slow variations of Earth's orbit

15   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 inter alia reductions in the amount and quality of agricultural products. This in turn, pending on antecedent and political, social, and cultural factors, sometimes resulted in negative impacts on food availability and prices, famines, reductions in birth rates, population growth, population

20   size, and social distress, all 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 the 17th century, are extensively discussed and documented in the literature (e.g., Eddy, 1976: 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.

25   The aim of this study is to provide an end-to-end 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 to 1445 CE (Fig. 1). This is done by exploring the output from simulations with comprehensive state-of-the-art climate models driven by solar and volcanic forcing, and by analysing multi-proxy evidence from various climatic and documentary archives to infer climate variability in terms of temperature, precipitation, and underlying mechanisms. Seasonality changes,

30   which may have played an important role in generating devastating impacts for medieval society, are discussed in detail. Historical documents are exploited to unravel socio-economic conditions, impacts, resilience, and adaption to change by

using quantitative indicators such as corn prices, population and trade statistics, as well as more descriptive information. The potential impacts of climate on society are discussed in the context of other important socio-economic drivers.

The focus is on Western and Central Europe and the periods from 1430 to 1445, here termed the early Spörer Minimum, and the period of the Spörer Minimum in solar activity in the wider context of the "Little Ice Age" (LIA; ~1300 to 1870). The Spörer Minimum (SPM) lasted from about 1420 to 1550 with the strongest reduction in incoming total solar irradiance (TSI) during ~1460–1550 (Eddy, 1976) and was punctuated with several large volcanic eruptions (e.g. Bauch, 2016).

In Western Europe, the early SPM featured a series of extremely cold and extended winters (Buismann, 2011; Camenisch, 2015b; Fagan, 2002; Lamb, 1982; Le Roy Ladurie, 2004), which substantially affected the productivity of terrestrial ecosystems in the subsequent growing seasons. The consequences were devastating 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). 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. Late frosts, as occurred during this decade, 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 in regard to the grinding of grain into flour (Camenisch, 2015b). Thus, this period is an historic example of how society reacted to climate and other changes 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 Spörer Minimum international trade went through a period of deepening recession, hindering the people to sufficiently replace crop failure (Campbell, 2009; Jörg, 2008; Camenisch, 2015b).

Historic documents show that the early SPM was a period of enhanced seasonality with cold winters and normal summers. 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 climate model simulations and multi-proxy climate reconstructions agree in that the SPM was a period of rather cold conditions (e.g., Fernández-Donado et al., 2013; Lehner et al., 2015). A recent study collecting hemispheric-scale reconstructions suggests a more diverse picture of temperature changes with different continents 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). The authors state that only the Maunder Minimum was a coherent cold phase during the last millennium. 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 early SPM. Taken at face value, these findings, in particular the offset in timing, seem to contradict the historical evidence mentioned above.

5   Given this lack of understanding, it is timely to combine available evidence in an end-to-end study, from external forcing to climate change and implications to adaptation in an historical perspective. The outline 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

10   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 changes in Europe – the early Spörer Minimum.

2. Reconstruction of the Spörer Minimum

Sixteen comprehensive multiproxy multisite datasets covering Western and Central Europe are analysed to characterise the mean climate and seasonality during the Spörer Minimum (Appendix A, Fig. 2). The data include annual or near annual,

15   well-calibrated, continuous series from tree rings, lake sediments, speleothems, and documentary 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; Glaser and Riemann, 2009; 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.,

20   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 summer temperatures in Europe were not colder during the SPM than before or afterwards (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

25   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 not unusual during the SPM in light of the early LIA. Concerning summer precipitation, the SPM appears to be consistently and significantly ($p < 0.01$) drier than the very moist early LIA (1300–1420, not shown), but still considerably wet in the context of the entire millennium (Büntgen et al., 2011; Amann et al., 2015).

30   While the centennial-scale climate variability informs mainly about the influence of the prolonged TSI minimum during the SPM, inter-annual to decadal-scale climate variability is rather diagnostic for (cumulative) volcanic forcing or internal (unforced) variability. Figure 3 shows the decadal means of the standardised proxy series. Decadal-scale variability shows

pronounced temporal and spatial heterogeneity across Europe. Summers in the early SPM (1421–1450) were consistently normal or warm (for the years 1430–1439, see supporting information). 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., 2014). These cold summers across Europe persisted for one or

5   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 (Ruang in 1594 and Huaynaputina in 1600; Sigl et al., 2014).

Winter temperature variability behaved differently. In Western Europe, the coldest conditions are reconstructed 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

10   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 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 and 1600 Huaynaputina eruptions; Arfeuille et al., 2014; Sigl et al., 2014).

15   An exceptionally cold and/or long winter could 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., Williams et al., 2015). 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. Figure 3 shows that such a period was only evident from 1431–1440 in the proxy records. Additionally, the

20   summer precipitation is shown in Fig. 3 in order to assess whether during this period the hydrological cycle was also unusual, either too 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, i.e., some records show normal condition whereas one record show a strong increase in summer precipitation.

3. Modelling the climate state of the Spörer Minimum

25   For the 1430s, the reconstructions show an increase in seasonality: consistently normal or warm European summers coincide with very cold winters in Western Europe. Whether or not these changes in seasonality are due to external forcing or internal variability of the climate system 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

30   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; 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. 4a. The largest interannual changes are due to volcanic forcing, despite

5 large differences between models. A 31-yr moving average filtered version of the total forcing is shown in Fig. 4b, illustrating the contribution of volcanic forcing at interannual to multi-decadal time scales.

There are large uncertainties due to the use of different solar and volcanic forcing reconstructions in various models, as well as to how they are implemented in a given model. The Spörer Minimum features reduced solar irradiance and two dominant volcanic eruptions in 1453 and 1458 (Sigl et al., 2013; Bauch, 2016). The latter eruption, Kuwae, was previously dated to

10 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 simulate an average decrease in the temperature of the Northern Hemisphere from 1050–1079 to 1450–1479 of

15 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 cause a long-term cooling of the climate 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.

20 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

25 solar activity affect weather and climate is still not well understood and thus these mechanisms may not be implemented in 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 and beryllium isotopes in tree rings or ice cores and are thus affected by uncertainties.

30 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. 5). 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, 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. 6, 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, 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 Spörer Minimum, 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. 7 (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 shows the expected result, i.e., a reduction in seasonality after 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.

4. Climate and weather impacts on the economy and society during the early Spörer Minimum

Human societies strongly depend on climate. These influences can be divided into short-term impacts (such as subsistence crises), conjunctural (price movement developments) and long-term impacts (e.g., collapses 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 can be determined as the simplified climate-society-interaction model demonstrates (see Fig. 8). On the first level, primary production (food, feed, and fuelwood), water availability, and microorganisms are directly affected 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).

Numerous climate impacts on society documented during the 1430s can be attributed to this simplified climate-society-interaction model (see Fig. 8). 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). Here, mainly contemporary English, German, Hungarian, Czech, Austrian, Italian and Dutch charters, letters, manorial, town and toll accounts, as well as narratives are analysed. Monocausal explanations are never sufficient in order to explain economic and societal developments. Therefore, other reasons for these climate impacts are subsequently discussed.

As the reconstruction in Sect. 2 (see Fig. 3) shows, the weather conditions during the 1430s stood out due to harsh and chilly winters. 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). Heavy snow falls followed by outstanding frost were reported in March 1438 in Berne (Morgenthaler, 1921). In Scotland, for instance, the wine in bottles had to be melted with fire before it could be drunk. Extremely cold winters during the 1430s were also reported in Ireland (Dawson, 2009). 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, while the winter seasons from 1434 until 1437 were outstandingly cold (Pichard and Roucaute 2014; Maughan, 2016; Glaser and Stangl, 2003). South of the Alps, the time span from 1430 to 1433 was extraordinarily wet, with the winter of 1431/1432 extremely cold till April 1432 (Bauch, 2015). Likewise, during the 1430s, Bohemia, Austria, and the Hungarian Kingdom suffered from a number of cold winters and 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 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). Problems due to 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). This temperature and precipitation pattern is also indicated by the models (see Fig. 6).

The main first-order impact during these years was a decline in food production. In England, Germany, France, the Netherlands, Bohemia, and other places, crop failures were reported during several years of the 1430s (Jörg, 2008; Tits-Dieuaide, 1975; Camenisch, 2012). In late April 1434, frost damaged vineyards 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 described frozen vineyards, devastated winter grain, and damages to livestock during the winter of 1436/37. Two frost periods at the end of March 1437 and in the second half of May destroyed vegetables, vine, and grain in the fields (Camenisch, 2015b). Harvest failures and grain shortages were also mentioned in the area of Berne (Morgenthaler, 1921). In 1440, serious problems in wine production and a bad hay harvest were reported for Pozsony/Pressburg (which is todays Bratislava) (Ortvay, 1900).

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

5   attention was paid to the price development of eatables in 1437/38 and 1438/39 (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 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

10 that were described for the wider population were inferior bread, malnutrition, epidemics, and high death rates; one of the centres of misery was the North of England (Brie, 1906a). Other sources proved moderate prices in 1435 and no price increases in England before 1438 (Munro, 2006).

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,

15 when summer temperatures were the most depressed and ecological stress was again acute (Biraben, 1975). 'Pestilentia' was also reported as far east as the Hungarian kingdom (e.g. ca. 1430: Iványi, 1910; 1440: HNA DL 55213). During the second half of the 1430s, Italy saw a row of country-wide epidemics (Bauch, 2015). Around Easter of 1439, the epidemic disease also reached Berne where a considerable part of the town's inhabitants were carried off (Morgenthaler, 1921). During the 1440s and 1450s, Europe's population sank to its lowest levels, due to epidemiological and reproduction regimes that kept

20 deaths in excess of births (McEvedy and Jones, 1978; Broadberry et al., 2015). In fact, the negative human consequences of this conjuncture of adverse climatic, biological, and societal circumstances would have been of an even larger order of magnitude except that the long post-Black Death decline in population raised the returns to labour as a factor of production, facilitated the withdrawal of settlements from environmentally and politically marginal locations, and created conditions of relative resource abundance (Allen, 2001). Thus, the adverse effects of climate deterioration were offset by the dwindling

25 numbers of mouths to be fed and the shrinking proportion of households with incomes below the poverty line (Broadberry et al., 2015).

It also appears that the extreme weather of the 1430s had a strong impact on the health and fertility of sheep flocks in England. Thus, as several manorial accounts from south English demesnes reveals, the years 1432, 1433, 1437 and 1438 saw excessive mortality rates in sheep flocks, with the average figures standing at 32 per cent (compared with 4–5 per cent in

30 normal years). The weather 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) (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 (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).

5 The impact of the extreme weather on the health of other animals is less clear. Thus, 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.

Grain was bought from distant places in order to increase the food offerings and consequently stabilise food prices and
10 supply people with victuals. In London, 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 in the late 1420s and
15 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 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,
20 thereby closing England as a supply source to the Low Countries. During the remaining famine 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 (Pribyl). In (West-) Hungary, the food shortage was already a problem in 1433 due to the high volume of cereal exported to the neighbouring countries. Thus, in October 1434, a royal charter prohibited cereal export in order to avoid a great famine
25 (Fejér, 1843).

In addition to dearth, the area of the Swiss confederation was also impacted by political troubles in the years preceding the Old Zürich War. 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. In 1437, after a poor harvest, the town of Zurich excluded Schwyz and Glarus from the grain
30 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. As a consequence of this embargo, Schwyz, Glarus, and their allies took up arms and began a war that lasted several years (Reinhardt, 2013; Maissen, 2010).

Mainly as a result of money devaluation (new silver coins: 1436) and taxation problems, one of the most significant medieval peasant uprisings occurred in 1437–1438 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).

Also, religious responses to the bad weather conditions during the 1430s were known. In Bologna, the civic cult of the Madonna di San Luca started 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 of perils (like epidemics and war) threatened the civic community. With this approach to coping with this crisis, 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 gypsies at the beginning of the 15th century is directly connected to the worsening of the weather during the Spörer Minimum. In chronicles of the 15th and 16th centuries, this connection was described as purely negative (Gronemeyer, 1987). For instance, the newly arrived gypsies were blamed for the worsening of the weather conditions during the years 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, 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.

The weather conditions were not the only concern of the people during the 1430s. At the same time, the bullion famine, price deflation, major territorial and commercial losses to the Ottomans, and a sharp contraction in overseas trade were generating serious economic difficulties of their own (Day, 1987; Spufford, 1989; Hatcher, 1996). Several wars aggravated the already tense situation. 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, which

enhanced the impacts of weather extremes (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 (HNA, DL 54734).

The Bolognese food crisis of 1433/34 can only be explained by taking the years since 1430 into account, when 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).

In the decades prior to the examined period, societies were less vulnerable to such large-scale famines. The reason for this lies in the lower demographic pressure after the Great Famine and the Black Death at the beginning and in the middle of the 14th century (Campbell, 2009). At the beginning of the 15th century, this changed at least in some parts of Europe, and the famine during the 1430s was the most severe since the beginning of the 14th century (Bauernfeind, 1993; van der Wee, 1978). Europe was affected by this crisis 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 the demographic development of the 15th century (Neveux, 1975). In other parts of Europe, the rising food prices did not develop into a famine; then an aggregate 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 1316–1322 (see Fig. 9; 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).

Another example of how the climate during the Spörer Minimum affected human society concerns fishery. Mutually reinforcing historical evidence plausibly connects the output of medieval fisheries for herring (*Clupea harengus*) in the North Sea and the Baltic 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.

5. Conclusions

Here we have presented the first end-to-end assessment of the early Spörer Minimum (1430–1445), a particularly cold period in Europe characterised by devastating losses in agricultural production and the associated socio-economic consequences. Natural (tree rings, lake sediments, and speleothems) and documentary archives agree that the 1430s were subjected to very 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.

State-of-the-art climate models indicate that this stronger seasonality was likely caused by internal natural variability in the climate system rather than external forcing. In fact, the results suggest that strong volcanic eruptions decrease the seasonality of 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 conditions.

In response to the prevailing weather conditions, harvest failures all over Europe were reported. These harvest failures, together with other socio-economic factors, led to an increase in food prices. In particular, wars in different parts of Europe and market failures caused by export stops and other interruptions of trade played a role. In parts of Europe, especially in the Low Countries, parts of France, and parts of the Holy Roman Empire, increasing food prices resulted in a subsistence crisis. A number of coping strategies during this crisis are documented, including trade regulations and restrictions on the brewing of beer. The subsequent construction of granaries in different towns in Europe could be understood as an example of adaptation strategies.

Until now little considered and analysed, this period 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 that a multitude of environmental and social factors and the interplay

between them are needed to generate strong impacts on the socio-economic system with threatening consequences such as famines.

Appendix A: Data base of reconstructions

5 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 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 (Tab. 1).

The datasets are selected according to the following criteria:

10 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).

Welch two sample t-tests are applied to the proxy-based climate reconstructions for comparing means (temperature and
15 precipitation from tree rings and varved lake sediments), using

$$T1 = \frac{\acute{x} - \acute{y}}{sxy.\sqrt{\frac{1}{nx} + \frac{1}{ny}}} \quad \text{and} \quad T2 = \frac{\acute{y} - \acute{z}}{syz.\sqrt{\frac{1}{ny} + \frac{1}{nz}}} \, .$$

x is the period 1300–1420 (nx = 21; $\acute{x}$ the data mean), y the period 1421–1550 (ny = 130; $\acute{y}$ the data mean), and z the period 1551–1700 (nz = 150; $\acute{z}$ the data mean). sxy denotes the covariance between x and y, syz the covariance between y and z.

Then, all datasets are analysed at the decadal-scale resolution. Therefore, annual data are standardised to the reference period
20 1300–1700 to make a comparison possible between each variable and the different seasons reconstructed (e.g. JJA vs. JJAS temperature):

$$Zscores = \frac{x - \acute{x}}{\sigma}$$

with x as the annual climate value, $\acute{x}$ the data mean, and σ the standard deviation over the reference period 1300–1700.

Finally, decadal means (10-year mean windows) are calculated for each dataset (40 mean windows/record). Data are presented according to the different variables reconstructed (Fig. 3).

25 ### Acknowledgements

This study is an outcome of the workshop "The Coldest Decade of the Millennium? The Spörer Minimum, the Climate during the 1430s, and its Economic, Social and Cultural Impact", organized by the three lead authors, which took place from 4 to 5 December 2014 at the University of Bern in Bern, Switzerland. The workshop was supported by the Oeschger Centre

of Climate Change Research (OCCR), the Intermediate Staff Association of the University of Bern (MVUB) and the Faculty of Humanities of the University of Bern. K.M.K., S. Blumer, F.J. and C.C.R. acknowledge support from the Swiss National Science Foundation through project 200020_159563. Simulations with NCAR CESM1 were carried out at the Swiss National Supercomputing Centre in Lugano, Switzerland.

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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	HISKLID database / C Europe	Glaser and Riemann (2009)
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	HISKLID database / C Europe	Glaser and Riemann (2009)
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
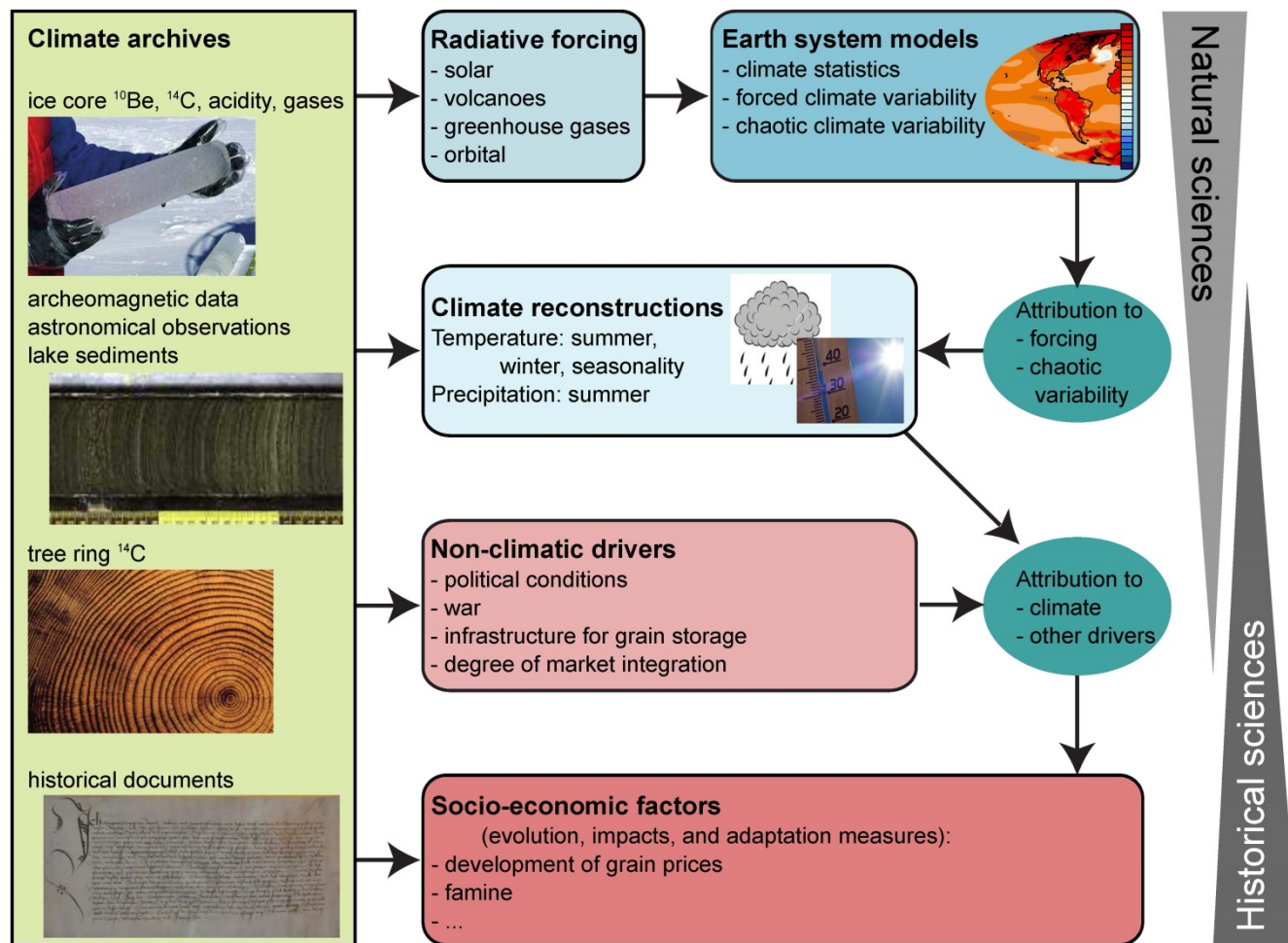
Fig. 1: Illustration of the research disciplines and methods brought together in this end-to-end assessment.
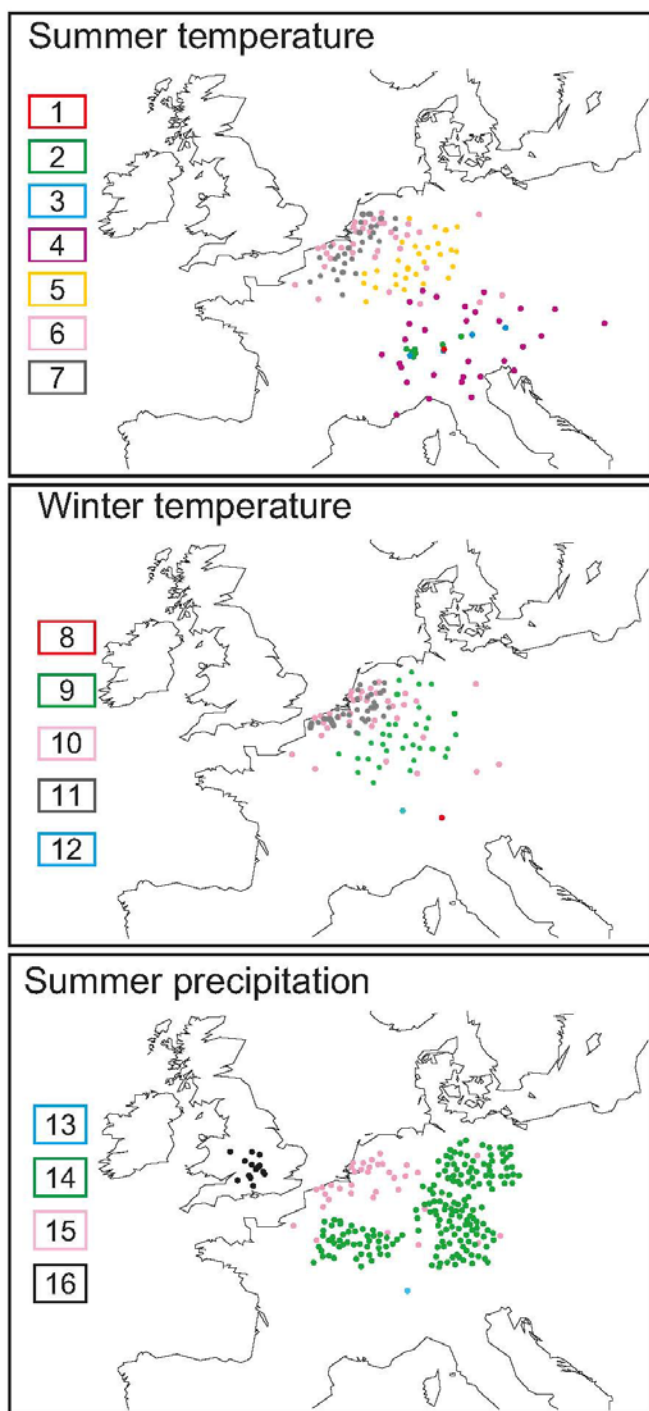
Fig. 2: Individual paleoclimate reconstructions for summer temperature, winter temperature and summer precipitation. Dots are specific sites considered by the different authors (listed from 1 to 16; Table 1)
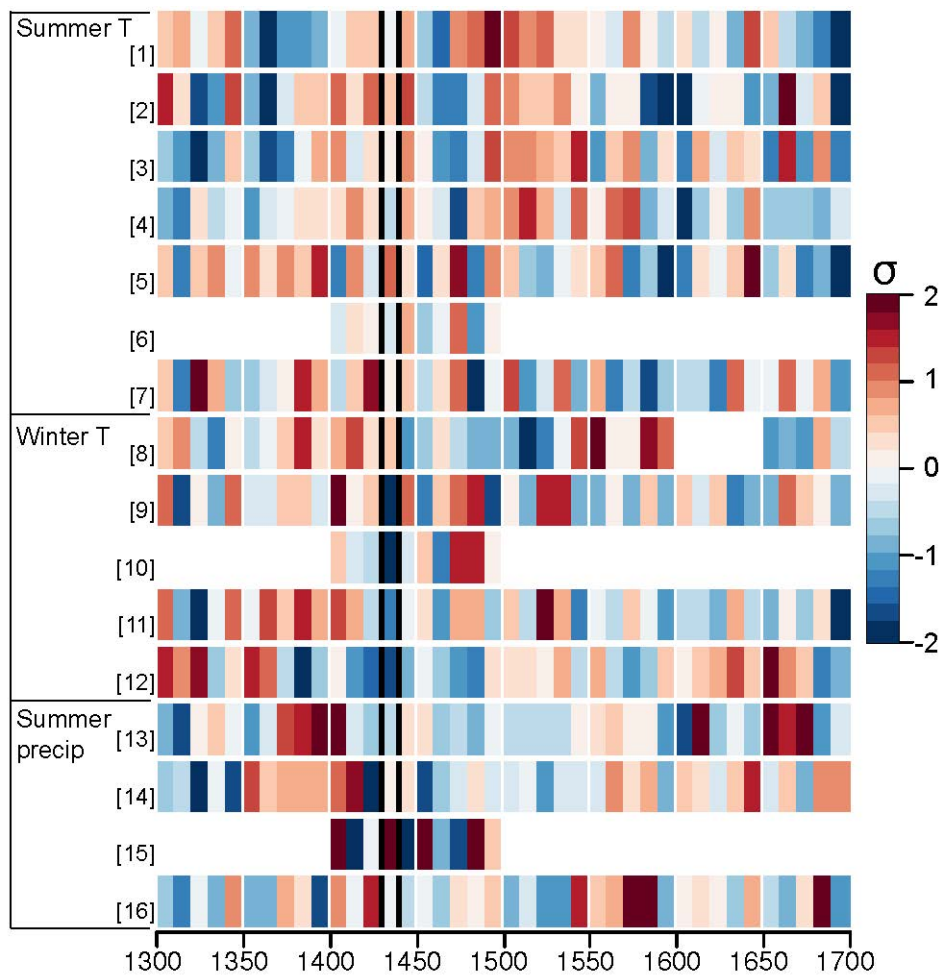
Fig. 3: Decadal-scale (10-yr mean) summer temperature, winter temperature and summer precipitation for the 16 climate reconstructions, standardized w.r.t. the period 1300–1700 (data sets 6, 11 and 16: 1400–1500). The black lines enclose the decade 1430–1440.
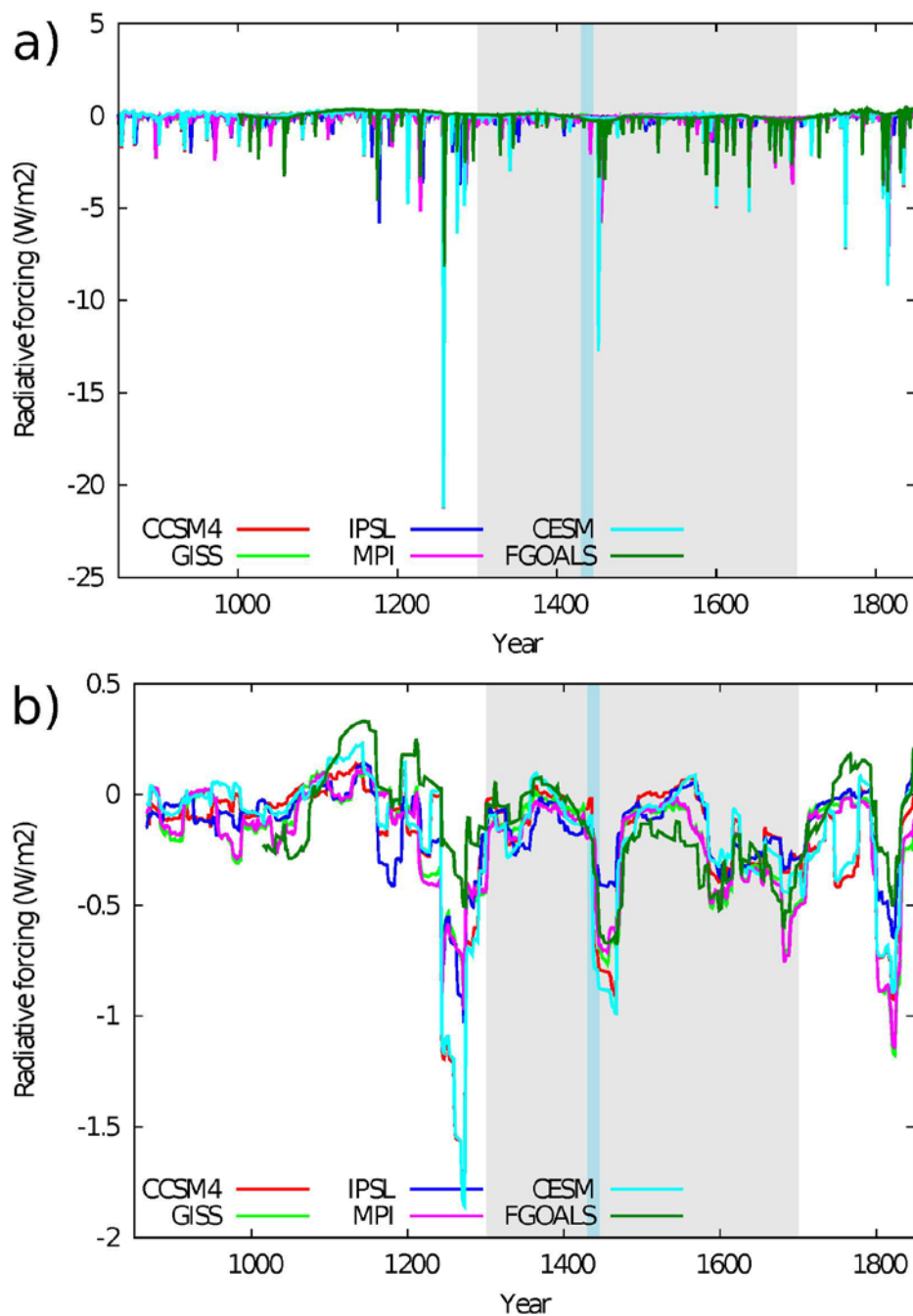
Fig. 4: (a) Estimations of total external forcings used by the models in Tab. 2 according to Fernández-Donado et al. (2013). The panel includes anomalies with respect to the period 1500–1850 including the contributions of anthropogenic (greenhouse gases and aerosols) and natural (solar variability and volcanic aerosols). (b) 31-year moving average filter outputs of (a).
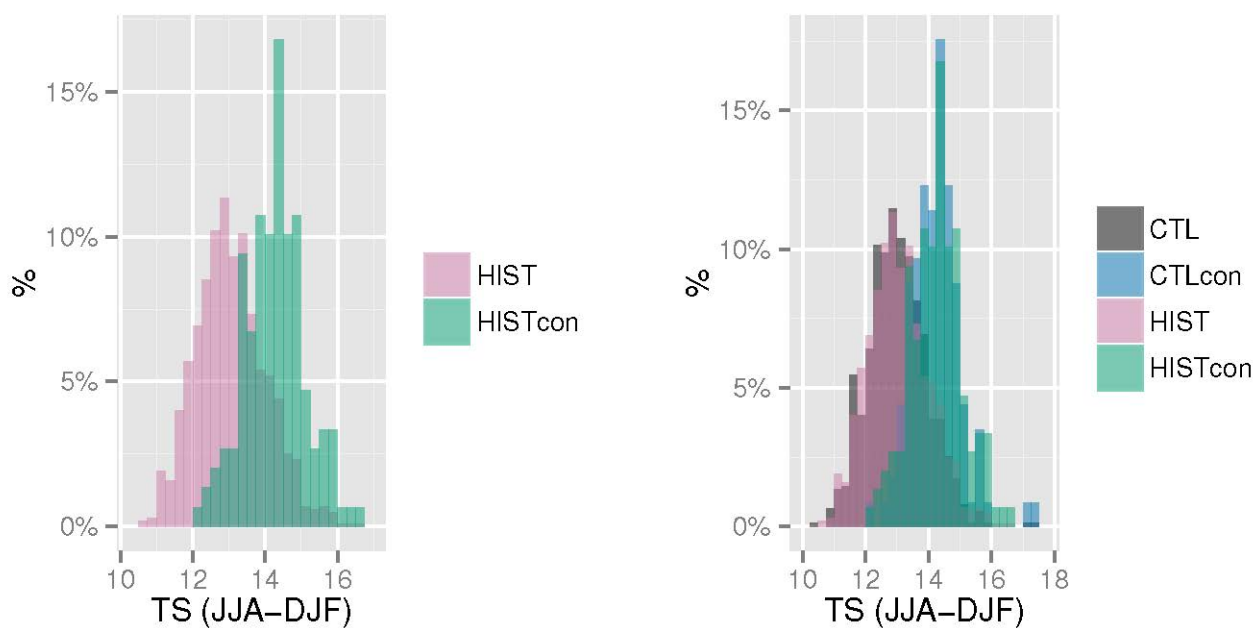
Fig. 5: PDFs of seasonality in surface temperature (TS; °C) averaged over Europe (8°W–22°E, 41–55°N) for all years and years with winter temperatures cooler than mean-1sigma (conditional). Left: for the years 850–1849 of the transient CESM simulation (HIST), right: also for the unforced control simulation (CTL; 600 yrs).
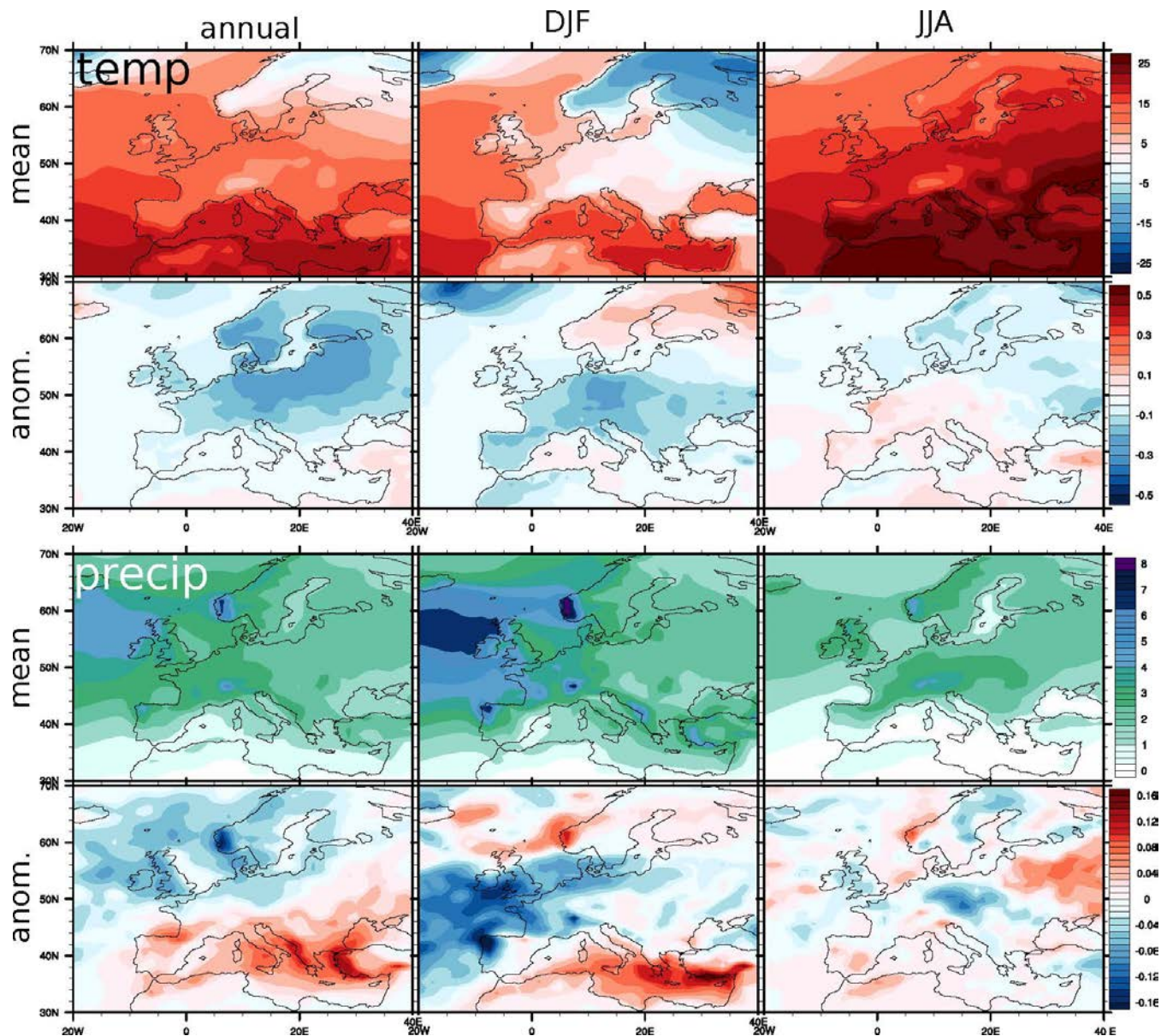
Fig. 6: Maps of surface temperature (top; °C) and precipitation (below; mm/day). Shown are annual (left), DJF (middle) and JJA (right) averages based on the transient simulation (years 850–1849) with CESM. First row: mean for all years. Second row: anomalies for years with strong seasonality in TS (> mean + 1sigma) compared to all years.
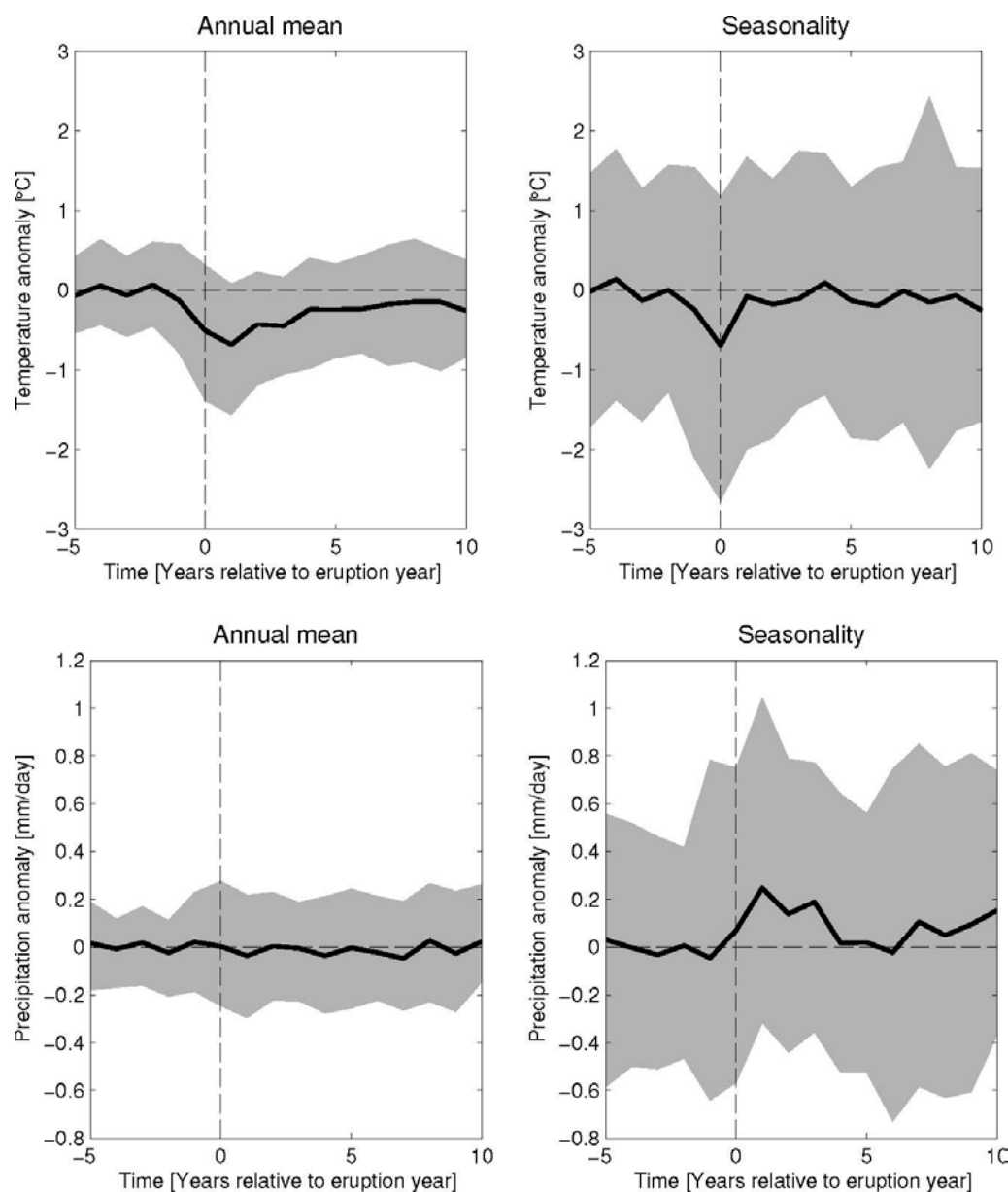
Fig. 7: Superposed Epoch Analysis on the ten strongest volcanic eruptions in six PMIP3 models, by measure of the respective forcing data set unit (aerosol optical depth or injection amount), over the period 850–1849. (Left) Annual mean temperature (top) and precipitation (bottom) and (right) seasonality 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.
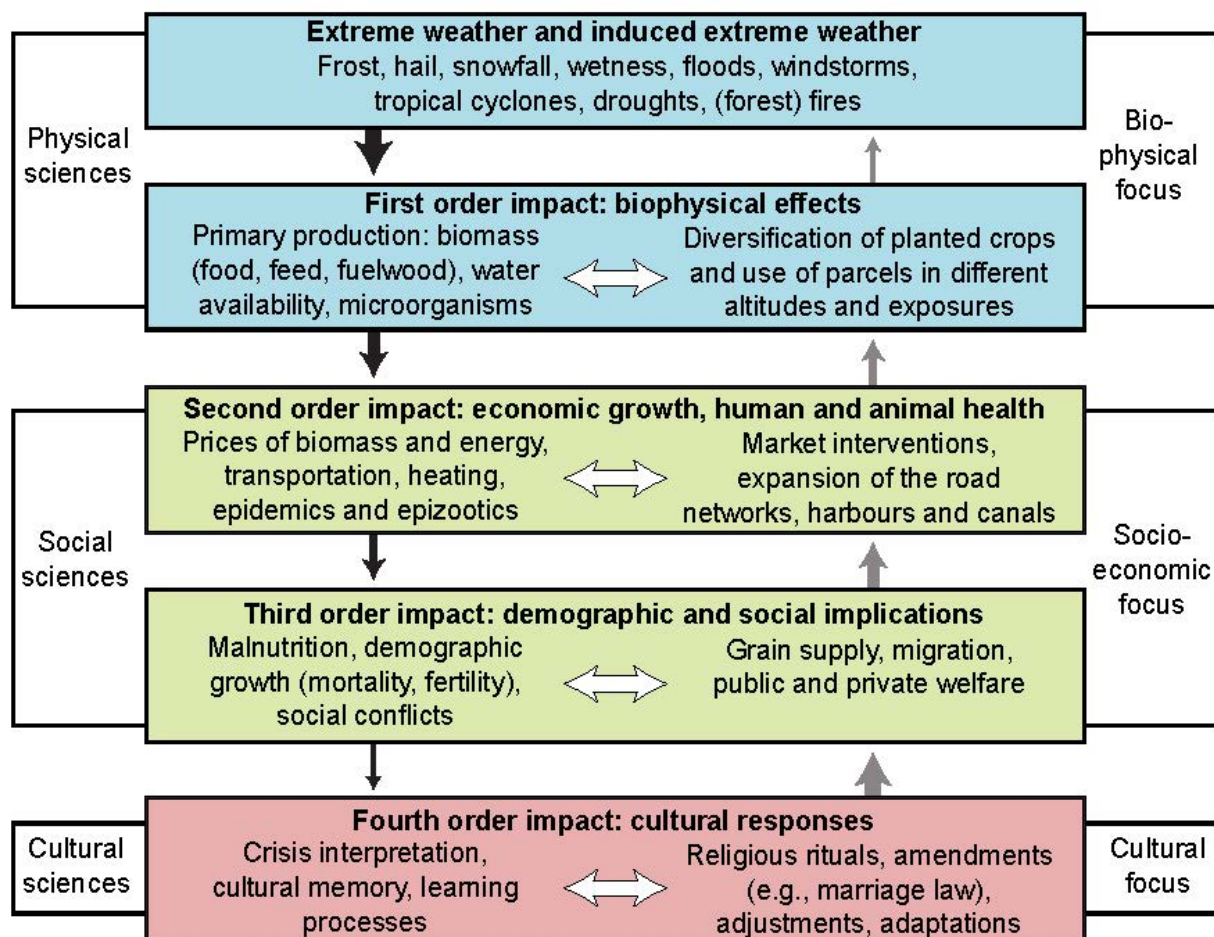
Fig. 8: This model developed by Daniel Krämer and Christian Pfister shows how climate interacts with society. Extreme weather causes biophysical effects on the first level, which can be followed by second order impacts that concern economic growth as well as human and animal health. On a third level are demographic and social implications situated whereas cultural responses act as fourth level impacts (Krämer, 2015; Luterbacher and Pfister, 2015).
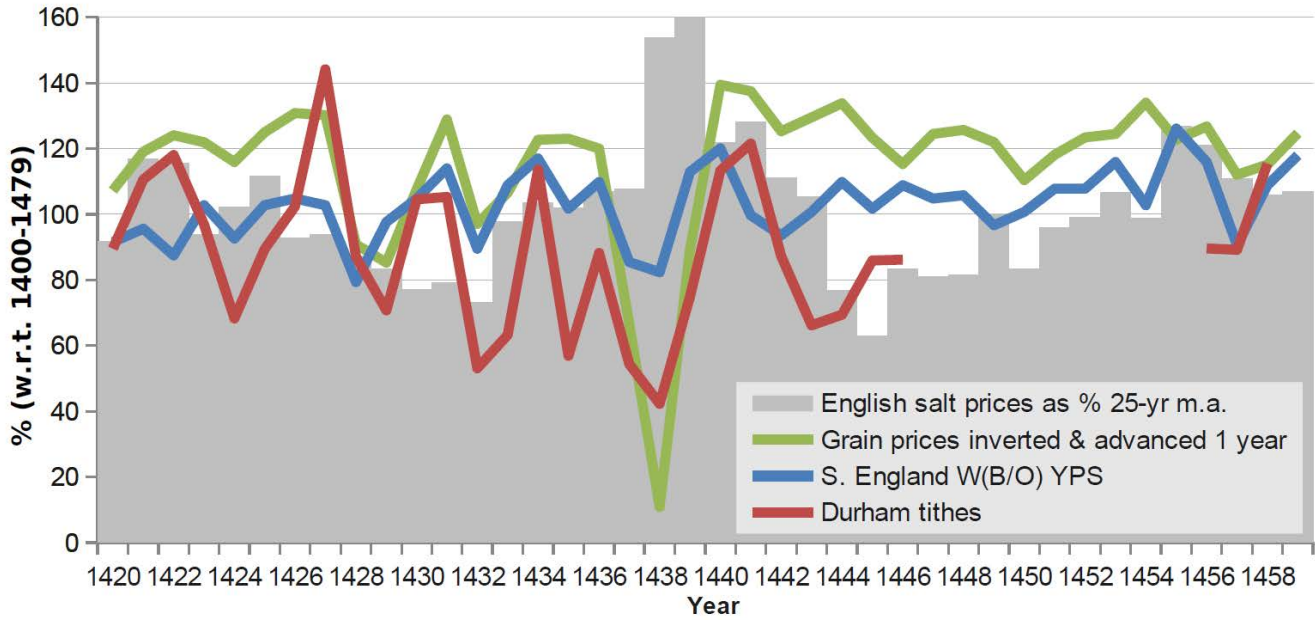
Fig. 9: Crop yields from Southern England, Durham tithes, English grain prices and English salt prices 1420–1460. Shown are the years 1437 and 1438 in the back-to-back grain harvest failure in South England, the massive reduction in Durham tithe receipts and the marked inflation of grain prices for three 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).