Endless cold: A seasonal reconstruction of temperature and precipitation in the Burgundian Low Countries during the fifteenth century based on documentary evidence

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Abstract

This paper applies the methods of historical climatology to present a climate reconstruction for the area of the Burgundian Low Countries during the fifteenth century. The results are based on documentary evidence that has been handled very carefully, especially with regard to the distinction between contemporary and non-contemporary sources. Approximately 3000 written records deriving from about 100 different sources were examined and converted into seasonal seven-degree indices for temperature and precipitation. For the Late Middle Ages only a few climate reconstructions exist. There are even fewer reconstructions which include winter and autumn temperature or precipitation at all. This paper therefore constitutes a useful contribution to the understanding of climate and weather conditions in the less well researched but highly interesting fifteenth century. The extremely cold winter temperatures during the 1430s and an extremely cold winter in 1407/08 are striking. Moreover, no other year in this century was as hot and dry as 1473. At the beginning and the end of the 1480s and at the beginning of the 1490s summers were considerably wetter than average.

1 Introduction

Emmanuel Le Roy Ladurie, one of the pioneers of historical climatology, stated the necessity for a quantitative, continuous and homogeneous series in order to reconstruct climate on the basis of historical documents for the time prior to instrumental records (Le Roy Ladurie, 1972). A true treasure of rich narrative texts, including a variety of weather-related information, can be found in documentary sources produced in the late Middle Ages (1300–1500 AD). This information consists of direct data (descriptions of temperatures and precipitation), and indirect data (climate proxies – phenomena which are related to climate such as freezing of water bodies or plant phenology). Nonetheless, they are far from being continuous or homogeneous. Moreover, they are not quantitative (Pfister et al., 2009).

As this paper demonstrates, there are methods that facilitate the transformation of this varied information into a reliable climate reconstruction on the basis of quantitative series. The presented paper aims to give an overview of weather conditions during the fifteenth century in the Burgundian Low Countries and surrounding areas in a seasonal resolution with separately reconstructed temperature and precipitation. Leading questions are as follows: what were the characteristics of these weather conditions? what are the advantages of using documentary data and what are the limits of these sources? Selected examples give a deeper insight into the characteristics of the sources and the applied methods in order to analyse them and convert them into homogeneous temperature and precipitation index series. The climate reconstruction not only provides an overview of the prevailing weather conditions of the whole century but presents detailed results. Since the source density in most cases is high enough, it is possible to detect not only anomalies but also less spectacular weather conditions. This is unusual because most reconstructions based on this type of data focus on extreme weather events. Moreover, many climate reconstructions are limited to temperature. As the inclusion of precipitation in reconstructions is crucial in order to obtain a more complete picture of past climates, this is a substantial gain in knowledge (Pfister, 2014). The inclusion of normal weather conditions apart from extreme events and of precipitation are preconditions for a comparison of climate and weather conditions with human society. Such a comparison is a further aim of historical climatology and will be realised in a future step.

The use of documentary evidence for examining past climate has a long tradition. Many catalogues with compilations of weather-related records exist (e.g. Hennig, 1904; Weikinn, 1958; Britton, 1937). These catalogues do not contain any critical source assessment and contain mistakes in dating. Reconstructions on the basis of such compilations repeat the dating errors. Some such catalogues cover the area of the Low Countries during the late Middle Ages (e.g. Easton, 1928; Vanderlinden, 1924).

In 1987 Pierre Alexandre established a benchmark for the reconstruction of medieval climate using documentary sources. Apart from analysing sources all over continental Europe he defined the necessity of a critical source assessment in order to improve the quality of such examinations. Jan Buisman collected an enormous number of documentary sources concerning the climate of the Low Countries. By 2015 six volumes with Dutch translations of weather-relevant records had appeared, covering the period from 1000 to 1800, and another three volumes are in preparation (Buisman, 1995; Buisman, 1996; Buisman, 1998; Buisman, 2000; Buisman, 2006; Buisman, 2015).

For the present analysis, documentary information was transformed into climate indices. Early examples of the method were published by Hubert Horace Lamb (Lamb, 1977; Lamb, 1982). The climate indices were developed and improved by Christian Pfister and Rudolf Brázdil (Pfister, 1984; Pfister 1999; Brázdil and Kotyza, 1995) and are an approved way to analyse sources (e.g. Alexandre, 1987; Schwarz-Zanetti, 1998; Dobrovolný et al., 2010; Brázdil et al., 2013; Dobrovolny et al., 2014).

Aryan van Engelen used Jan Buisman's compilation as a basis for climate indices (Shabalova and van Engelen, 2003; van Engelen et al., 2001). The ambitious goal of this Dutch reconstruction was to provide long series with (almost) no gaps. Aryan van Engelen fulfilled this promise by choosing a nine-degree scale for the temperature indices and a five-degree scale for the precipitation indices. The temperature reconstruction comprises a winter index (NDJFM) and a summer index (MJJAS).

The aim of the present paper is different. First of all, indices with a higher resolution were necessary because a comparison with economic development is intended and for that purpose at least seasonal reconstruction is indispensable (Camenisch, 2015; Pfister, 2014). Furthermore, it was mandatory to read the original texts since it is not possible to produce a reliable reconstruction with summarised and translated excerpts of totally diverse sources. The high-quality source compilations of Pierre Alexandre and Jan Buisman were consulted as well. Further important contributions related to medieval climate in the Low Countries were published by Elisabeth Gottschalk and Adriaan de Kraker (e.g. Gottschalk, 1975; de Kraker, 2005; de Kraker, 2013). In addition there are useful climate reconstructions focusing on regions in the neighbourhood of the Low Countries such as Germany (Glaser, 2013), Switzerland (Schwarz-Zanetti, 1998) France (Le Roy Ladurie, 2004), Lorraine (Litzenburger,

2015) and the British Isles (Kington, 2010) that are based either on similar source types or on similar methods.

Section 2 of this paper gives a short overview of the geographical scope of the research. In the subsequent Section 3 the data which form the basis of this reconstruction are presented and discussed. Some source examples complete this section. Section 4 is dedicated to the methods. Section 5 covers reconstructions and Section 6 provides a summary before Section 7 concludes.

2 Scope

The fifteenth century is part of the Little Ice Age and contains a number of highly interesting weather patterns and phenomena that warrant closer examination (Aberth, 2013; Brooke, 2014; Hoffmann, 2014). Moreover, this period is not as well researched as it deserves because Pierre Alexandre's reconstruction ends in 1425 (Alexandre, 1987) and other reconstructions begin only after 1500 (e.g. Pfister, 1999).

The methods used in this paper require a sufficient number of data. For this reason the Burgundian Low Countries have been chosen as a geographical frame. During the end of the fourteenth and in the course of the fifteenth century several parts of today's Belgium, the Netherlands, Luxembourg and Northern France fell under the rule or at least into the sphere of influence of a cadet branch of the French royal dynasty (see Fig. 1). This house of Burgundy reigned for almost hundred years over the Burgundian Low Countries before the male line became extinct (Calmette, 1996; Schnerb, 1999). In 1477 when the last of the dukes of Burgundy, Charles the Bold, died, his territory extended from the English Channel in the West to the Ardennes in the East and in the North from the West Friesian Islands to the Duchy of Luxembourg in the South (Blockmans and Prevenier, 1999; Prevenier and Blockmans, 1986).

The topography of the inshore area is particularly flat and the land largely lies below sea level. Only in the East do the hills of the Ardennes form a contrast to the otherwise flat topography. Weathering processes triggered by storm surges, ocean waves and currents have formed the shoreline until today (de Voogd, 2003; Reuss, 2006; Buisman, 2011). Large rivers such as the Rhine, Scheldt, Meuse and Ijssel cut through the plains before flowing into the North Sea. The area belongs to the most fertile agricultural landscapes of Europe thanks to the soil conditions, cultivation of land and soil improvement. In consequence, a remarkable level of agricultural productivity and the proximity to waterways – the fastest and most efficient transportation routes of the time – created an extraordinarily dense population (Erbe, 1993; Allen, 2000; Prevenier and Blockmans, 1986). The urbanisation level of the Burgundian Low Countries was outstanding. Extraordinarily populous cities were situated in Flanders, Artois, Brabant and Holland (van Bavel, 2010). This prosperous area was famous for its artistic production. Furthermore, a rich historiography and an accurate and elaborate account existed, which form the basis of this research.

3 Sources

3.1 Classification

In order to reconstruct temperature and precipitation several methods based on a variety of data are required. Besides the rich archives of nature consisting of organic proxies such as tree rings or non-organic proxies including ice cores, varves or terrestrial sediments man-made archives exist. Those archives contain documentary data and are the basis of climate reconstructions derived from historical climatology (Brázdil et al., 2005; Pfister, 1999; Pfister et al., 1999). Documentary evidence allows precise dating with a very high resolution. Depending on the type of information, annual, seasonal, monthly or even daily observations exist. Early instrumental measurement did not begin until the seventeenth century and is therefore not available for the Late Middle Ages (Behringer, 2010). Instead, other direct and indirect data provide information on climate. Direct data are descriptive records on weather spells, climatic anomalies or weather-induced disasters. Indirect data or proxy data comprise accounts of both organic and non-organic evidence that allow inferences regarding temperature and precipitation such as plant phenology (e.g. date of blooming or ripening of vines) or ice phenology (e.g. date of freezing or opening of water bodies) (Pfister, 1999; Pfister et al., 1999). The following example contains both direct and indirect data:

"*Item, en chi temporaile [...] fist si fort yviert et grant galée que la riviere de Mouze tresserat, et que de Jemeppe à Liege ons cherioit sus à charois bien chargiés de bleis ou d'aultres denrées; et durat celle galée plus de X semaines. [...] et chu fut l'an XIIIIc et VIII, le XXVIIIme jour de jenvier*." (Borgnet, 1861)

This short text is part of a chronicle written by the Benedictine monk Jean de Stavelot, a contemporary eye witness from Liège. He gives not only an account of heavy frost in the winter of 1407/08 but describes in addition how the Meuse was so firmly frozen between Jemeppe and Liège that chariots loaded with grain and other foods were driven on the ice. This frost lasted for 10 weeks before the ice started to melt on 28 January 1408 (the date is given in the Julian calendar style and in the Gregorian calendar equates to 7 February 1408).

Another distinction is made between institutional and individual sources on the one hand and between narrative and administrative sources on the other hand (see Table 1). The first classification takes note of the origination process of the text and the second focuses on the text type and its use (Pfister et al., 2009; Camenisch, 2015). Both have a direct impact on the quality of the sources, as discussed subsequently. Concerning the Late Middle Ages especially, chronicles, memoirs, and journals constitute the individual narrative sources, whereas annals belong also to the group of narrative sources but have an institutional origin. The lines between the two groups are blurred since many texts show characteristics of both types (Geary, 2013). Amongst the administrative sources accounts (written records on bookkeeping) and charters (documents for legal purpose) of different origin need to be mentioned. In this paper the first group was mainly used and charters did not play a major role. Also, administrative sources were generated either in an institutional context such as a monastery, town, and toll station or in a private individual context (Camenisch, 2015).

The fifteenth century is rich in narrative texts, mainly chronicles, annals, memoirs and journals. In the Burgundian Low Countries and the neighbouring regions a treasury of such manuscripts has been preserved until today and many of them have been published as edited books. The tradition of writing chronicles originates from antiquity and has survived for centuries in mostly a monastic or at least a clerical context (Rohr, 2007). The language of these texts is normally Medieval Latin (e. g. Balau, 1913; Dussart, 1892). Additionally, in the Late Middle Ages interested laypersons wrote chronicles, some of them on behalf of town authorities or nobles, others for a more private purpose (Schmid, 2009; Schmid, 2012). Those narrative texts were often written in a vernacular language. In the Burgundian Low Countries and the close neighbourhood these languages were Middle Low German (e. g. Lamprecht et al., 1895; Cardauns et al. 1877) , Middle Dutch (e. g. Kuys et al., 1983; De Jonghe, 1840; Fris 1904) or Middle French (e. g. Borgnet, 1861; Tutey, 1903) – each with local variations.

Usually, chronicles consist of a compilation of older texts followed by a second part composed by the chronicler and covering his life span. This second – contemporary – part is usually richer in information, more detailed and clearly more reliable. Some chroniclers summarise the crucial events year by year, others write their text many years after the events (Lambert, 1993; van Caenegem, 1997). In narrative texts, the authors often describe weather conditions, and especially extreme weather events because they could be a threat to the food supply or they were given a religious meaning (Ingram et al., 1981).

The reasons why weather conditions or proxy data are mentioned in administrative sources differ from those in narrative sources. The important source type of accounts is characterised by standardised records of cost and revenue. Either the climate proxies lead to costs or revenues and were listed for that purpose in the accounts or short descriptions of weather conditions appear as justification for extraordinary costs (Wetter and Pfister, 2011; Pribyl et al., 2012). In this paper narrative sources clearly form the main body of the data set and have been primarily analysed. In addition, a number of edited town accounts (such as the stadsrekeningen van Arnhem for the first decades of the fifteenth century, Jappe Alberts, 1967; Jappe Alberts, 1969; Jappe Alberts, 1971; Jappe Alberts, 1978; Jappe Alberts, 1985) and further unedited town accounts relying on Jan Buisman's compilations have been included in the data set (Buisman, 1996; Buisman, 1998).

3.2 Critical source assessment

A critical assessment not only for every source but for each record is crucial for the quality of the entire reconstruction because the characteristics and quality of the sources vary and they contain different types of information. Critical source assessment includes information on the author, especially dates of birth and death, the place where he lived and the context of his oeuvre (Alexandre, 1987). This information allows a distinction to be drawn between original text and copies of older manuscripts and is extremely important because of the significantly greater reliability of the records in the original (contemporary) part of the source. The closer the events occurred in relation to the time when the authors wrote their texts on paper or parchment the more reliable they are. The best quality is given in the case of year by year reports. Accounts and journals are usually produced in this way as well as the last part of annals and chronicles. If an event is convincingly proved by contemporary records, additional non-contemporary reports can be taken into account insofar as they confirm the main statement of the contemporary evidence. Since each source has its own dynamics that become clear by reading the text as a whole, it would be a fatal error just to pick the records from older or newer compilations without the critical source assessment and its context.

For this paper approximately 3000 records from about 100 sources were evaluated. Two-thirds of them are related to weather conditions whereas the last third focuses on economic impacts caused by these weather conditions. Many of the records contain long descriptions.

3.3 Source density

The density of the sources is not equal throughout the entire century as Fig. 2 shows. Because of the different time span of the sources not all decades have the same source density. In addition there is obviously more evidence in years with outstanding events whereas years with average weather conditions were less documented, if they were described at all. All depends on the quality of the sources covering the year in question and it is consequently the reason why years without enough evidence cannot just be interpreted as average (see Section 4).

Within the calendar year the distribution of the records is almost equal in terms of winter (27%), spring (25.5%), and summer (29.5%). In 18% of the records only autumn is less documented (Camenisch, 2015).

The distribution of the sources also differs with regard to their place of origin, as Fig. 3 shows. Most of the used sources have their origin in the Burgundian Low Countries but a number of texts derive from neighbouring areas and were included in the data set because of their excellent quality.

3.4 Dating

Confusion in dating is one of the most serious problems that can arise in a reconstruction. The reasons are closely linked to the fact that different calendar styles were in use during the particular epoch.

Before 1582 the Julian calendar style was in use in most European Christian countries. Since it is some minutes longer than the astronomical year, the calendrical beginning of the seasons diverged from the astronomic year. For many centuries the difference was barely observable. During the fifteenth century the deviation of the then nine days was not only perceptible to experts in astronomy but also to every attentive person (Schwarz-Zanetti, 1998; Borst, 2004; Grotefend, 1991). This means that in all the texts date indications deviate from the modern calendar style and need to be converted.

Another problem derives from the fact that during the Middle Ages six possible days for the beginning of the calendar year exist: 1 January, 1 March, 25 March, Easter, 1 September, 25 December (Grotefend, 1991). The first of September is used rather seldom so one has to take care, especially concerning events occurring between Christmas and Easter. If one chronicle uses the Easter style and another one uses the Christmas style the same events can be written down as two different years. This could result in the misinterpretation that two similar events happened in two subsequent years. A clear analysis of the correct dating of events is indispensable, keeping in mind that the non-contemporary part of a narrative text is a copy of an older text probably with another calendar style. The authors of older weather compilations did not pay enough attention to these problems and even if they were aware of them, they usually did not give sufficient information on how they converted the dates. In this paper much effort was made to avoid such dating errors.

A very useful way to cross-check the reliability of the dating of a certain narrative text is to search for records describing solar and lunar eclipses or comet observations. Many authors mention such observations because in medieval times they were seen as precursors to calamities (Rohr, 2013). The descriptions which appear in the narrative sources can be compared with catalogues of celestial events of the past (e.g. Kronk, 1999; Schroeter, 1923).

Most of the medieval authors used ecclesiastical feast days in order to give precise dates within a year. Usually, this does not lead to problems. More challenging are descriptions that refer to seasons without more detail. In the past the meaning of the seasons was ambiguous (and still is to a certain degree). Medieval authors meant either astronomical seasons that changed at equinoxes and solstices or they used the name of the season to refer to the duration of typical weather patterns, agricultural work or phenological phenomena prevalent in that season (Pfister, 1988; Ogilvie and Farmer, 1997; Grotefend, 1991).

4 Methodology

As argued above, continuous, homogeneous, and quantitative series are required for climate reconstructions. Since several source types with different features and varying quality form the basis of this paper, an adequate method that can cope with these inhomogeneous data is required. Climate indices (so-called Pfister indices, Mauelshagen, 2010) offer a solution that enables the integration of all the source types in one reconstruction. Christian Pfister chose a scale of seven degrees because fewer degrees would not be detailed enough, whereas a more extended scale would in most cases lead to numerous gaps. There are separate indices for temperature and precipitation. Because of the remarkable source density in the late-medieval Burgundian Low Countries a seasonal resolution is adequate. This means the entire climate reconstruction comprises eight different indices. The meteorological year forms the basis of the seasonal subdivision of the indices. Therefore the winter season covers the period from 1 December until 28 February, spring the period from 1 March until 31 May, summer from 1 June until 31 August and autumn from 1 September until 30 November.

Table 2 shows the scale of all the indices. The reconstruction is realised in several steps. At the beginning of the process the sources are sorted into groups related to the seasons to which they refer. Preliminary analysis of the sources shows which kind of descriptions recur and how they can be matched to a seven-degree scale. Fundamental knowledge about the perception and interpretation of natural phenomena is indispensable in order to avoid misinterpretations (Rohr, 2007; Wegmann, 2005).

4.1 Index criteria

Specific criteria for each season and degree are defined and as many years are attributed to the scale as possible by a comparative interpretation of all data (Mauelshagen, 2010; Pfister, 1999). Since initial analysis probably causes a rather unequal distribution of the seasons, the criteria need to be refined and the process of source analysis started again. The refined criteria form the basis of the final reconstruction. However, the author’s preference for describing extreme events in the sources leads to a certain overrepresentation of those index points in the reconstruction.

Table 3 shows as an example the basic structure of the indices in the first row and the refined criteria for the reconstruction of the winter temperatures in the second row. The criteria include measurable or at least comparable physical and biological proxies (Pfister, 1999). Concerning the winter temperatures this means for instance that in order to set a -3 in the reconstruction, records on the freezing of large water bodies such as the Rhine, Scheldt, and Meuse or even the shores of the North Sea are required. This information does not indicate absolute temperatures since those water bodies freeze after the temperature sinks below a certain threshold and it is not possible to determine the temperatures beneath that threshold (Pfister, 1999; Glaser, 2013). Similar are descriptions of frost damage to trees and winter crops. Only temperatures lower than -30 °C lead to bursting banks or freezing winter rye in the fields (Schubert, 2006).

More difficulties arise in reconstructing average or mild winter temperatures. For instance, the appearance of drifting ice is not comparable to today's conditions because of extensive changes in the river beds, the increasing inflow of wastewater or the construction of canals. For milder temperatures the ice phenology cannot be taken into consideration. To a certain extent plant phenology can offer valuables clues, but since there is no regular source of information on the same plants this method also has its limitations.

The analysis of winter precipitation before instrumental measurement records is challenging. The reason for this is that in the winter season precipitation often occurs as snowfall. It is extremely difficult to deduce the water content of snowfall only from descriptions. A further peculiarity of the contemporary descriptions is that in many cases the chroniclers do not clearly distinguish between the duration of snowfall and the timespan during which the snow cover did not melt, resulting in misinterpretations. In addition, floods are no clear indicator of the amount of precipitation because several causes exist and some of them, like ice jam and sudden snow melting, are linked to temperature (Wetter et al., 2011; Kiss, 2009). The chroniclers pay less attention to dryness and drought in winter. These problems are the reason why the winter precipitation index is less dense than the winter temperature index.

Concerning the climatic conditions during spring time, anomalies and extreme events are again overrepresented in the sources when compared with records of average conditions (see Fig. 5). In order to attribute a season to the index point of -3, it is necessary to have contemporary records of long frost periods or even frozen water bodies that last until springtime. Considerable deviations of plant phenology are also required. Some authors of narrative texts provide recurrent information on the beginning of the growing season, which is very useful for the reconstruction of all the degrees of the index scale.

Within the dataset no spring season can be assumed to be extremely wet (index point -3). This is because in many cases only part of the spring season is described. For several years there is information on one wet month but no information on the other two months so these years cannot definitely be allotted an extreme index value.

The refined criteria of the summer temperature reconstruction refer mostly to plant phenology. In particular, information on the growing of vines, grains or vegetables appears repeatedly in the texts and is very useful. Considerable deviations in the average phenology of those plants are necessary to obtain an index point of +3, +2, -2 or -3. In order to allocate a summer season to the index points of -1, 0 or +1 descriptions without phenological deviations were sufficient.

For the reconstruction of summer precipitation the refined criteria are mostly linked to descriptions of damages that were caused by either dry or wet anomalies. Since a sufficient but not excessive amount of precipitation during summer is crucial for the harvest in the Low Countries, the medieval chroniclers paid much attention to it. This is also the reason why this index is the best documented in terms of the precipitation reconstruction. A certain problem derives from the fact that medieval authors often do not clearly distinguish between heat and drought, and the terms are used synonymously.

The autumn reconstruction contains the most extended gaps (see Fig. 7). The sources are silent, especially on the time after the vine harvest and the sowing of winter crops in September and October. This is the reason why information on this season often remains fragmentary and why it is very difficult to determine seasons that can be allocated to the index points +3 and -3. In the autumn reconstruction the precipitation index is denser than the temperature index because the sowing of winter crops was more vulnerable to precipitation than to temperature.

Generally, gaps originating from a lack of sources cannot be filled with an average evaluation for several reasons. Usually more than one record indicating the same tendency in the weather conditions is necessary in order to give an index point. If there is contradictory information, the contemporary records are decisive. There are few cases when no contemporary records are available at all or some are plausible individually but contradictory as a whole. In such cases an index point was not set. This procedure leads to a more reliable reconstruction.

Since the data are inhomogeneous and no proxy would appear continuously for the whole century, there is no possibility of calibrating them with temperature or precipitation measurement of later times. After 1500, approaches to calibrate and verify indices with temperature and precipitation measurements exist (Dobrovolný et al., 2010; Dobrovolný et al., 2014).

5 Reconstruction

The climate reconstruction comprises four indices for each season concerning temperature and four indices concerning precipitation. The number of gaps in the indices varies and depends as well on the source density as on the clear classification of the criteria defined for every index.

5.1 Winter

The temperature index for the winter season is the most complete of the reconstruction (see Fig. 4). Extremely cold (index point -3) and very cold (index point -2) temperatures are very well documented. The descriptions of many of those winters are rich and numerous. The winter of 1407/08 for instance was one of the coldest in the century and the best documented season in the whole dataset. Many chroniclers emphasise that nobody could remember a winter like this. Jean Brandon, a monk at Ten Duinen Abbey on the Flemish coast, described this winter as dry and cold. Such low temperatures and chilly frost did not occur for a hundred years, as the Flemish monk affirms in his text (Kervyn de Lettenhove, 1870):

"*1407 […] Hoc anno […] hyemps sicca et frigida, ita ut gelu asperum esset a principio decembris usque in finem januarii, ut a C annis tantum frigus et tantum gelu non fuerit.*"

Thanks to the excellent source density, different phases of cold can be identified in the weather conditions of these months. Around the feast of Saint Martin on 11 November 1407 (20 November converted into Gregorian calendar style) temperatures sank in widespread areas, as is reported in texts from Liège, Paris, Cologne, Lübeck, Magdeburg and Dortmund (Camenisch, 2015). Another cold front reached the Burgundian Low Countries some days after the beginning of December (Gregorian calendar style – all following data are converted into this style). Several water bodies froze after Christmas, such as the Seine, the Rhine and the Meuse with its tributary stream, the Sambre. The ice cover was thick enough for people to ride horses on it or drive loaded chariots from one river bank to the other (Camenisch, 2015). Further away, Lake Zurich and Lake Constance were also frozen (Brunner, 2004).

At the end of January a few days with milder temperatures led to the breakup of the ice covers on the rivers (around 6 January in Paris, for example). The drifting ice jammed the rivers in Paris and Liège, flooding the river banks. According to most chroniclers the frost ended around the beginning of February. The winter crops perished in Flanders because of the frost (and the lack of protective snow cover). In Paris, vineyards and fruit trees were damaged by the same frost. Moreover, people, cattle and birds fell victim to the extremely low temperatures.

For more average winters (index points of -1, 0 or +1) fewer sources exist. During the fifteenth century three clusters of very cold and extremely cold winters can be detected. The clusters during the 1420s and during the 1460s are remarkable but that during the 1430s is outstanding. This decade is one of the coldest of the whole millennium if not the coldest (Lamb, 1982). In contrast are the extremely or very mild winters of the first half of the 1470s and the beginning of the 1480s. Less is known about the winter seasons of the middle of the century, especially the 1440s and 1450s because of the lack of contemporary sources.

Concerning precipitation the medieval authors remain rather silent in the first years of the century. As a consequence there is a remarkable gap in the reconstruction from 1410 to 1417. In addition, the second half of the 1430s, the last years of the 1440s and the 1450s in general are difficult to assess for the same reasons.

Only one extremely dry (1447/48) and a few very dry winter seasons could be identified during the fifteenth century. Three years with extremely wet seasons are known (1414/15, 1484/85, 1496/97). Accumulations of very wet and wet winter seasons can be observed in the first decade of the century, at the beginning of the 1420s and 1430s and in the middle of the 1480s.

5.2 Spring

A cluster of cold anomalies (index points of -3 and -2) can be detected during the second half of the 1420s, the 1430s and the last two decades of the century, similarly to the winter reconstruction. Warm anomalies prevailed during the 1460s and 1470s. The years 1432, 1443, 1446, 1481 and 1492 are reported to be years with extremely low temperatures (index point -3) whereas the spring season of the years 1420 and 1473 stood out for its extremely warm temperatures (index point +3).

No spring season has been proved to be extremely wet (index point -3). Also, at the other end of the scale, only the year 1424 was detected as an extremely dry spring season during the fifteenth century. Very wet, wet, average, dry and very dry seasons are spread across the century. Only the 1440s included two very dry spring seasons and in 1427 and 1428 very wet spring seasons occurred.

5.3 Summer

The prevailing weather conditions of the summer seasons are better documented than those of the spring seasons (see Fig. 6). This is owed to the preference of the medieval authors for describing weather conditions during periods when a lot of agricultural work had to be done. As a consequence fewer gaps exist in the two summer indices. Nonetheless, there is a lack of information at the beginning of the century and during the 1450s. Apart from that, shorter gaps are spread across the whole century. In 1406, 1428 and 1468 the weather conditions were extremely cold whereas extremely warm summer seasons (index point -3) are reported in the years 1466, 1471, 1473 and 1491. The year 1473 stands out by virtue of extremely high temperatures, possibly topped only by the year 1540 (Wetter et al., 2014). A cluster of warm anomalies at the beginning of the 1470s and clusters of cold anomalies during the 1480s and at the beginning of the subsequent decade are also remarkable.

Extremely dry years (index point -3) were 1422, 1424, 1442, 1473 and 1492. Extremely wet seasons (index point +3) were the summers in 1406, 1423, 1428, 1455, 1480 and 1491. Obviously there were extremes on both sides of the scale during the 1420s. A cluster of dry anomalies is documented during the 1450s, this rather unknown decade.

5.4 Autumn

The indices for autumn temperatures and precipitation are the least dense in the climate reconstruction. Fewer seasons are allocated to both ends of the scale because in many cases there is only information on part of the season. Consequently, 1468 is the only autumn season with index point -3 in the temperature reconstruction whereas at the other end of the scale the year 1487 fulfilled the criteria for the index point +3. During the 1480s there was an accumulation of cold and very cold autumn seasons.

Extremely dry (index point -3) autumn seasons occurred in the years 1442 and 1473. The years 1405, 1423, 1468, 1483 and 1491 can be awarded index point +3. Towards the end of the century wet and very wet autumn seasons prevailed. However, in both indices there are many gaps during the 1430s, 1450s and 1460s.

6 Prevailing weather conditions of the fifteenth century

The first decade of the fifteenth century was characterised by rather average temperatures with the exception of the extremely cold winter seasons in 1399/1400 and 1407/08 and the extremely cold summer of 1406. Also, with regard to precipitation, most years are within the average, apart from autumn 1405 and summer 1406, which were extremely wet, the very wet spring in 1404, summer in 1408 and winter in 1408/09 and the very dry seasons in winter 1403/04, autumn 1404 and spring 1409. There is not much information available for the subsequent decade concerning temperatures and most known seasons were average. However, in 1412 and 1413 there were very warm temperatures in the summer season and in 1416/17 the winter temperatures were reported as very cold. Regarding precipitation, the period from autumn 1414 to spring 1415 needs to be mentioned for its above-average wet seasons. The winter season of 1414/15 was also extremely wet.

A considerable number of very cold and one extremely cold (1422/23) winter seasons can be identified in the 1420s. Very cold spring temperatures are reported for 1421 and 1427, as well as a very cold summer in 1428. In 1420 there was an extremely warm summer whereas very warm and mild temperatures occurred in winter 1420/21 and summer 1422 and 1424.

The 1430s were an outstanding decade during the fifteenth century. The major part of the winter seasons was extremely cold or at least very cold and a considerable number of spring seasons had the same characteristics. This remarkable temperature cluster together with other cold periods in the fifteenth century is responsible for the chosen title ‘endless cold’. Horace Hubert Lamb suggested with regard to the winter temperatures that the 1430s and the 1690s constitute the coldest episodes of the last millennium (Lamb, 1982). The most recent research even associates this decade with an early phase of the Spörer Minimum (Camenisch et al., 2014). There is less information about summer temperatures because they were not as remarkable as the winter and spring temperatures. However, in 1432 there was a very warm summer and in 1436 and 1438 the summer temperatures were very cold. In the same decade a number of above-average wet seasons occurred such as winter 1430/31, winter 1434/35, summer 1432 and summer 1438.

During the 1440s, there were three extremely cold seasons in winter 1442/43, in the subsequent spring 1443, in spring 1446 and in addition one very cold season in autumn 1444. Only in summer 1442 were temperatures very warm. The decade was characterised by rather dry weather conditions in the Burgundian Low Countries, especially in 1442, 1447 and 1448. There are fewer sources available which describe the 1450s. However, there is a remarkable cluster of above-average wet summer seasons from 1453 until 1456. There is more information on the subsequent decade. Winter 1461/62 was extremely cold and very dry; in 1465 there was a second extremely cold winter. In the following year temperatures in summer were extremely warm and it was very dry until autumn. Moreover, in 1468 occurred an extremely cold and wet summer followed by an autumn with the same weather conditions.

The 1470s are a decade with warm anomalies in the summer season. Weather conditions were predominantly dry and warm in the years from 1471 to 1473 and again in 1479. At the very beginning of the decade there was an extremely cold winter followed by a very cold spring. Also from winter 1476/77 to spring 1477 and in winter 1477/78 below-average temperatures prevailed. During the last two years of the decade, there was again a tendency to warm spells.

At the beginning and at the end of the 1480s remarkable cold and wet weather conditions need to be mentioned. In particular the period from summer 1480 to summer 1481 was outstanding because of an above-average amount of precipitation and considerably low temperatures. In contrast, the winter of 1483 experienced extremely mild temperatures. The below-average temperatures of 1488 returned again in 1491 when almost the whole year was characterised by extremely cold weather conditions. With regard to precipitation the wet anomalies in summer 1491 and winter 1496/97 need to be mentioned as well as the drought in summer 1492.

7 Discussion

Comparison of the indices presented herein with a number of other reconstructions was made. The winter (NDJFM) and summer (MJJAS) temperature indices by Aryan van Engelen and Jan Buisman (Shabalova and van Engelen, 2003; van Engelen et al., 2001) for the Netherlands are based on documentary evidence and are the closest reconstruction regarding methods (nine-degree indices) and geographical coverage. Nonetheless, there are differences because the winter (DJF) and summer (JJA) temperature indices presented in this paper and the van Engelen indices do not cover exactly the same months and the van Engelen indices have considerably fewer gaps, especially in summer. However, the Pearson correlation coefficients are remarkably high. In relation to the winter temperatures a coefficient of -0.893 (N=81; Sig. < 0.01, the van Engelen indices equate to the winter indices presented here) and as regards the summer temperatures a coefficient of 0.783 (N=50; Sig. < 0.01) shows the close relation between the two reconstructions. The relation between the van Engelen summer temperature index and the presented summer precipitation index (Corr. 0.792; N=60; Sig. < 0.01), spring temperature index (Corr. 0.465; N=46; Sig. < 0.01), and spring precipitation index (Corr. 0.585; N=31; Sig. < 0.01) is also remarkably close.

Laurent Litzenburger (2015) has recently presented a further climate reconstruction from Metz (Lorraine, France) based on documentary data and containing seasonal temperature and precipitation indices. A comparison of the two reconstructions shows remarkable similarities. The summer temperatures (Corr. 0.844; N=40; Sig. < 0.01) and autumn precipitation (Corr. 0.708; N=31; Sig. < 0.01) are very close. Also rather similar are winter temperatures (Corr.

0.658; N=70; Sig. < 0.01), spring temperatures (Corr. 0.671; N=41; Sig. < 0.01) and precipitation (Corr. 0.609; N=27; Sig. < 0.01) as well as summer precipitation (Corr. 0.641; N=48; Sig. < 0.01), though N is rather low in some parts of the analyses. The comparison of the annual temperature (obtained by summing the seasonal indices as Christian Pfister and Rudolf Brázdil (1999) suggest) and precipitation series show even higher correlations (see Figure 8). The most obvious difference occurs during the 1450s when the indices presented here are much closer to the average than Litzenburger's. This is because the former indices have many gaps in this decade, producing a rather average and misleading result regarding the summed indices for the whole year.

Comparison with the indices presented by Rüdiger Glaser and Dirk Riemann (2009) shows weaker correlations. The closest relations exist between the summer temperature indices (Corr. 0.494; N=50; Sig. < 0.01), the spring temperature indices (Corr. 0.415; N=47; Sig. < 0.01) and the winter temperature indices (Corr. 0.393; N=82; Sig. < 0.01). The reason for this is probably the greater distance between the two researched areas and the different scales of the indices because Glaser applies a three-degree scale for the fifteenth century.

Furthermore, the indices presented here were compared with the grape harvest dates and spring-summer reconstruction for Burgundy presented by Chuine and colleagues (2004). Also, in this case the results show a strong relation between Chuine et al.'s data and the indices presented here. The grape harvest dates are sensitive to spring and summer temperatures. The highest Pearson correlation coefficients were obtained in comparison with these indices (spring temperatures: Corr. 0.521; N=47; Sig. < 0.01 and summer temperatures: Corr. 0.637; N=50; Sig. < 0.01). Obviously, the summer precipitation index is also rather similar (Corr. 0.548; N=60; Sig. < 0.01). In addition, a certain relation, albeit with a weaker level of significance, is established between the grape harvest dates and the spring precipitation (Corr. 0.435; N=32; Sig. < 0.05) and the autumn precipitation (Corr. 0.348; N=39; Sig. < 0.05). The results of the comparison with Chuine et al.'s data are very important as these data were obtained from completely independent methods and sources. The Litzenburger, van Engelen and Glaser indices were also produced independently but the applied method and a number of sources are very similar to the indices presented here.

Comparison between the indices and the reconstruction by Büntgen et al. (2011) shows only weak similarities. The considerable distance between the two researched areas and the completely different methods are probably the reason for this.

8 Conclusion

This paper gives an overview of seasonal temperature and precipitation during the fifteenth century. The reconstruction contains eight climate indices (separate indices on temperature and precipitation for every season) based on documentary evidence. The main body of the data set consists of narrative sources such as chronicles, annals, memoirs or journals and administrative sources such as accounts. These sources have an individual or institutional background. The sources contain either direct data or indirect data (proxy data that can be converted into climate indices). The basis of the indices is a seven-degree scale starting with -3 for extremely cold or extremely dry conditions and going up to +3 for extremely warm or extremely wet conditions. A catalogue of criteria was defined for every index point in order to evaluate as many seasons as possible. The indices for winter temperatures, summer temperatures and summer precipitation are the most complete. During the fifteenth century a number of outstanding weather patterns can be detected. Therefore, more attention should be paid to the climate of this century, as before. Most remarkable are a cluster of extremely cold winter temperatures during the 1430s – which was the reason for the first part of the title – as well as an extremely cold winter in 1407/08. This cluster of cold winters has been underestimated in recent research. A number of dry and hot spells occurred; amongst them the year 1473 was unique because of the extent and duration of the heat and the lack of precipitation. Extremely wet weather conditions especially in summer were prevalent at the beginning and the end of the 1480s and at the beginning of the 1490s. Comparison with Dutch and French reconstructions shows very satisfactory results.

The climate indices in Appendix A will provide the basis for further research with regard to climate impacts on human society.

Appendix A: Climate indices

year	**winter**		**spring**		**summer**		**autumn**	
	temp.	**prec.**	**temp.**	**prec.**	**temp.**	**prec.**	**temp.**	**prec.**
1400	-3	1						
1401	-1	1						

year	winter		spring		summer		autumn	
	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.
1402	1	1	1	-1				
1403								
1404	1	-2	-2	2	1	-1	1	-2
1405	-1					1		3
1406	0	1	0		-3	3		1
1407	1	1			1	-1	1	-1
1408	-3	1	1		0	2	1	-1
1409	2	2	0	-2		-1		
1410								
1411								
1412		1			2	-2		
1413					2	-1		-2
1414						-2		2
1415	1	3		2	0			
1416						1		
1417	-2				1	-2		
1418	-1		0	0	1			
1419					-1	0	-1	1
1420	-2	1	3		1	-1		
1421	2	1	-2				0	
1422	-1	1	0		2	-3		1
1423	-3		1			3	1	3
1424	-2			-3	2	-3		1
1425	2	1						
1426	-2							
1427	-2		-2	2	0	0	-1	
1428	0		-1	2	-3	3		
1429	0							2
1430	1	1	-2		1			

year	winter		spring		summer		autumn	
	temp.	**prec.**	**temp.**	**prec.**	**temp.**	**prec.**	**temp.**	**prec.**
1431	0	2				-1	-1	
1432	-3	1	-3	1	2	2	-1	
1433	-3	0	-2					
1434	-2		0	-1				
1435	-3	2	-2		0			
1436	0	1			-2	1		
1437	-3		-1					1
1438	-2				-2	2		
1439	1	2				0	-1	-1
1440							1	
1441	0							
1442	-1			-2	2	-3		-3
1443	-3	1	-3		1	0		1
1444	0		-1	-1			-2	1
1445	0		-1			2		
1446			-3	1			-1	
1447	-1			-2	1	-2	1	-1
1448	0	-3						
1449								
1450	1	-1					-2	
1451	0				-1	1	1	
1452	0	1						
1453	0				-1	2		
1454	0			1		2		
1455						3		
1456						2		
1457	-1	1						1
1458	-3	1		-1		-2		-2
1459	0			1		-1		

year	winter		spring		summer		autumn	
	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.
1460	-2		-2					
1461						-2		
1462	-3	-2	-1	-1				
1463	-1							
1464					1	-2		
1465	-3				-1	0	-2	1
1466	-1		1	0	3	-2	1	-2
1467	0	2	-1	2	0	2		2
1468	0	0			-3	2	-3	3
1469	1	1	2					
1470	-3		-2			2		
1471	2		2		3	-2		-1
1472	1	-1			2			
1473	1	1	3	-1	3	-3	2	-3
1474	2							
1475	0	1	1	-1		1		1
1476	-2		-2	1	1			1
1477	-2					1	-1	
1478	2				1			
1479			2	0	2	-2		
1480			-1		-2	3		2
1481	-3		-3	1	-2	2	1	-1
1482	0		0	0				
1483	3	-1	0			1		3
1484	0	1	-1		-1	1	-2	
1485	1	3	0		-2	2	-1	2
1486	0	2					0	0
1487	0						3	
1488	0		-2	1	-2		-2	

year	**winter**		**spring**		**summer**		**autumn**	
	temp.	**prec.**	**temp.**	**prec.**	**temp.**	**prec.**	**temp.**	**prec.**
1489			0	-1	-1	2		2
1490	2	1	1	-1	2	-1		
1491	-3		-3		-3	3	-1	3
1492	-2			-1	2	-3		1
1493	0	0	-2		0	0		2
1494	0					1	0	
1495	1	1	0		0		1	
1496	-2		-2	2	1			
1497	1	3			-1	1	2	1
1498	-1		2	-2	2	-2	1	0
1499	-1					1		

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Table 1. Classification of documentary sources (Pfister et al., 2009; Camenisch, 2015)

	Institutional sources	Individual sources
Narrative sources	-Annals	-Chronicles -Memoirs -Journals -Letters -Weather diaries -Travel reports
Administrative sources	-Monastic accounts -Town accounts -Toll accounts -Charters	-Accounts of private households

Table 2. Scale of the climate indices (Pfister, 1999).

Temperature indices	Index point	Precipitation indices
Extremely warm	3	Extremely wet
Very warm	2	Very wet
Warm	1	Wet
Normal	0	Normal
Cold	-1	Dry
Very cold	-2	Very dry
Extremely cold	-3	Extremely dry

Table 3. Refined scale of the winter temperature index (Camenisch, 2015).

Index point	Description	Criteria
3	Extremely mild	no frost or extremely few frost periods mentioned considerable phenological anomalies winter described as extremely mild
2	Very mild	almost no frost periods mentioned remarkable phenological anomalies winter described as mild
1	Mild	more rain than snow little frost mentioned
0	Normal	few frosts sporadic days with drifting ice
-1	Cold	repeated periods with drifting ice repeated frost periods
-2	Very cold	small rivers or brooks frozen frost mentioned over a period of about one month plants damaged by frost
-3	Extremely cold	large rivers and lakes frozen and passable frost mentioned over a period of about two months rye or trees damaged by frost

Figure 1. The Burgundian Low Countries (map: Marco Zanoli).

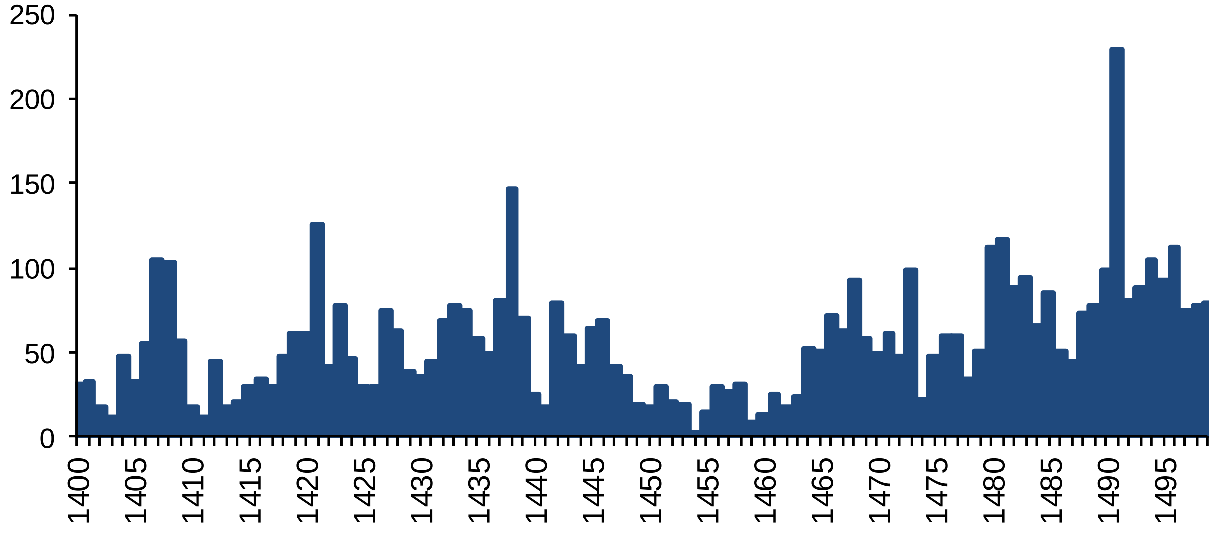

Figure 2. Annual distribution of the sources (Camenisch, 2015).

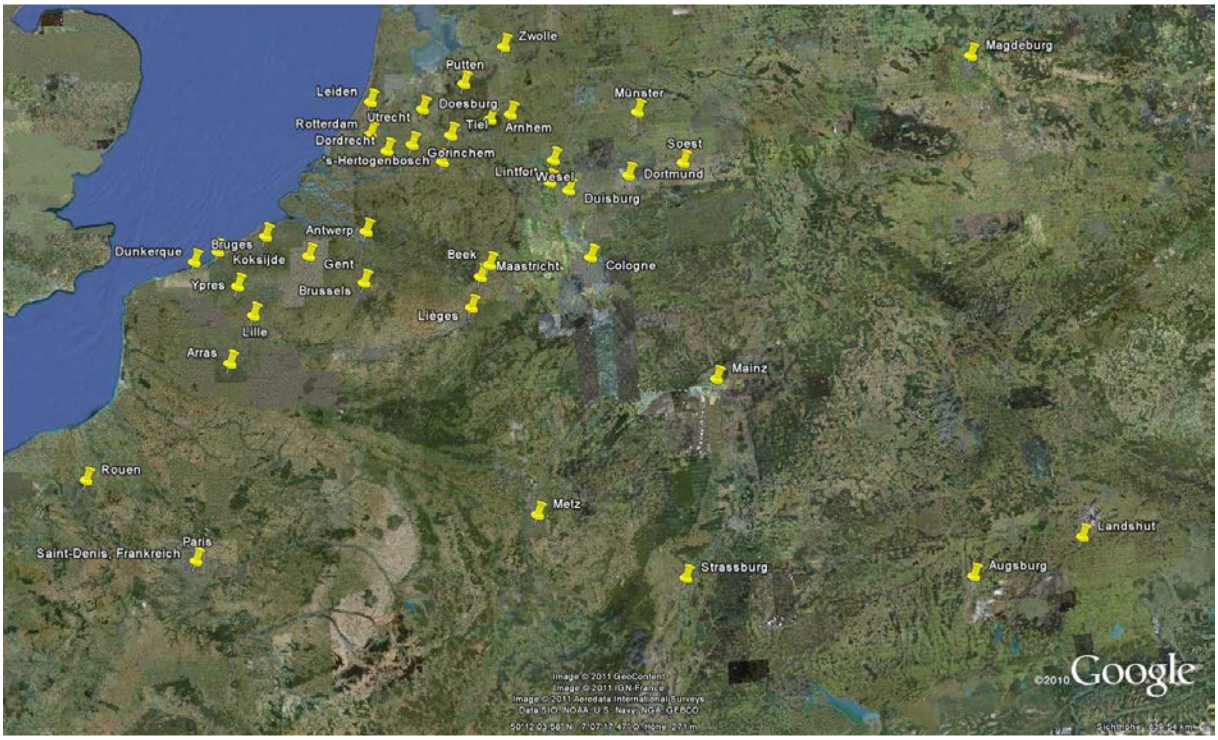

Figure 3. Geographical distribution of the origin of the sources.

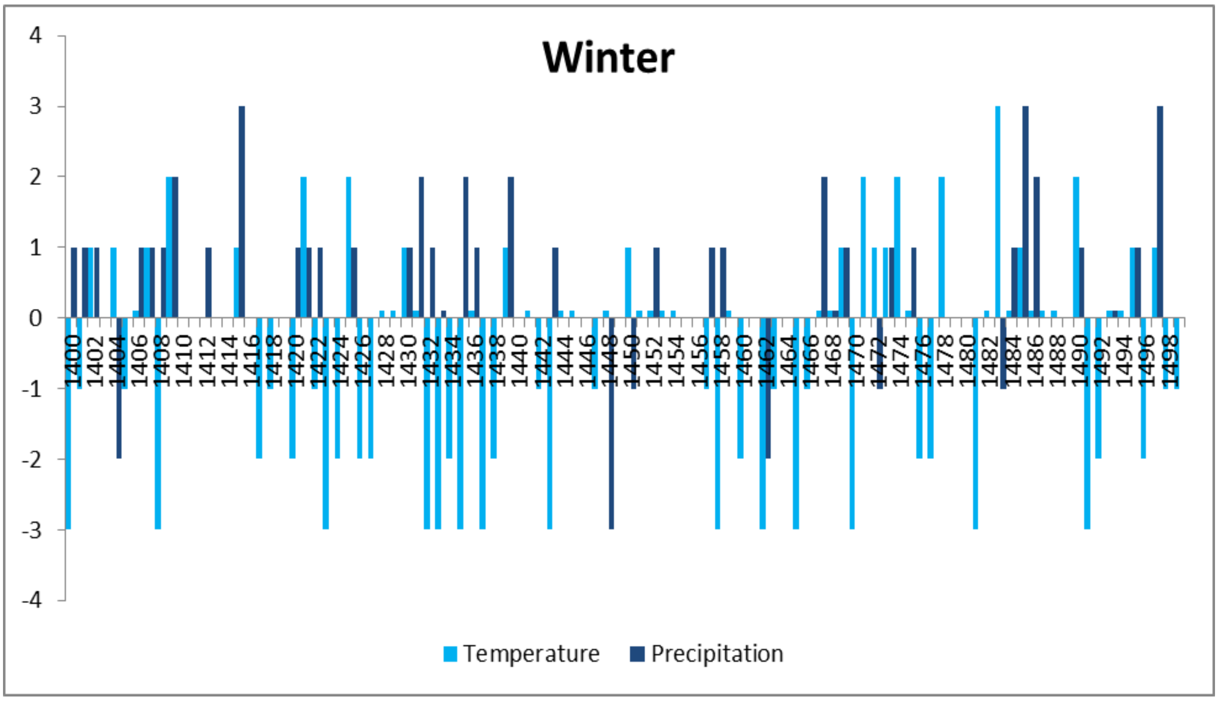

Figure 4. Winter indices.

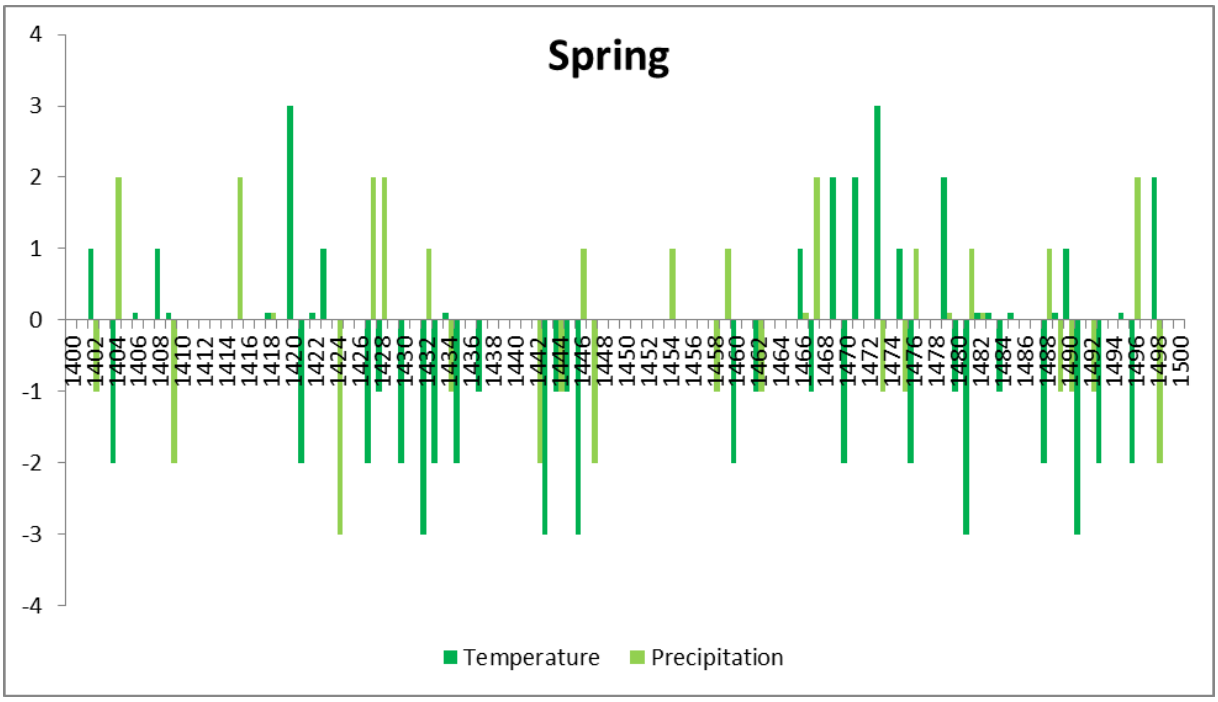

Figure 5. Spring indices.

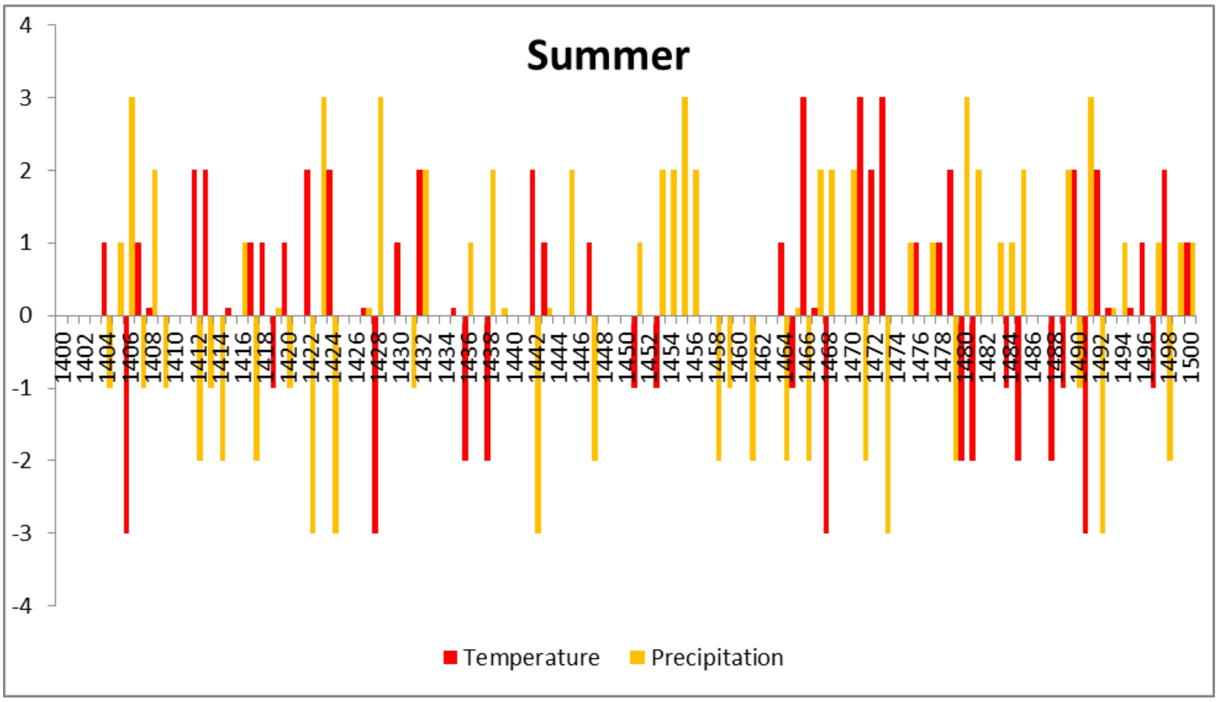

Figure 6. Summer indices.

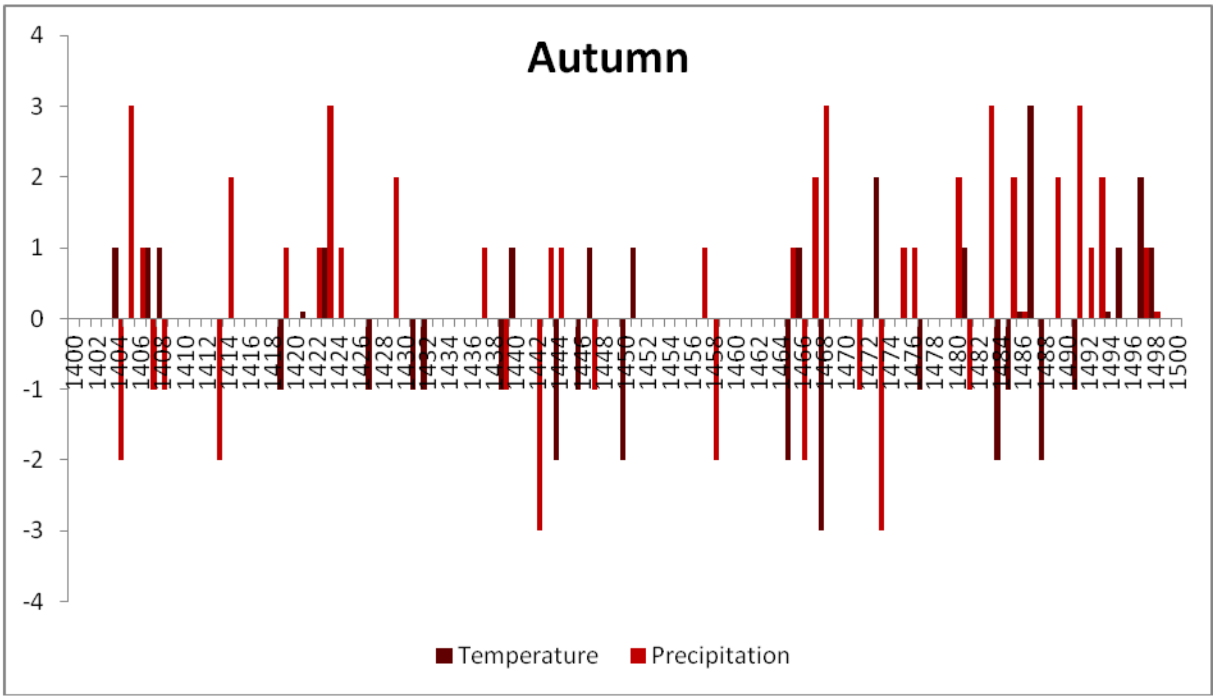

Figure 7. Autumn indices.

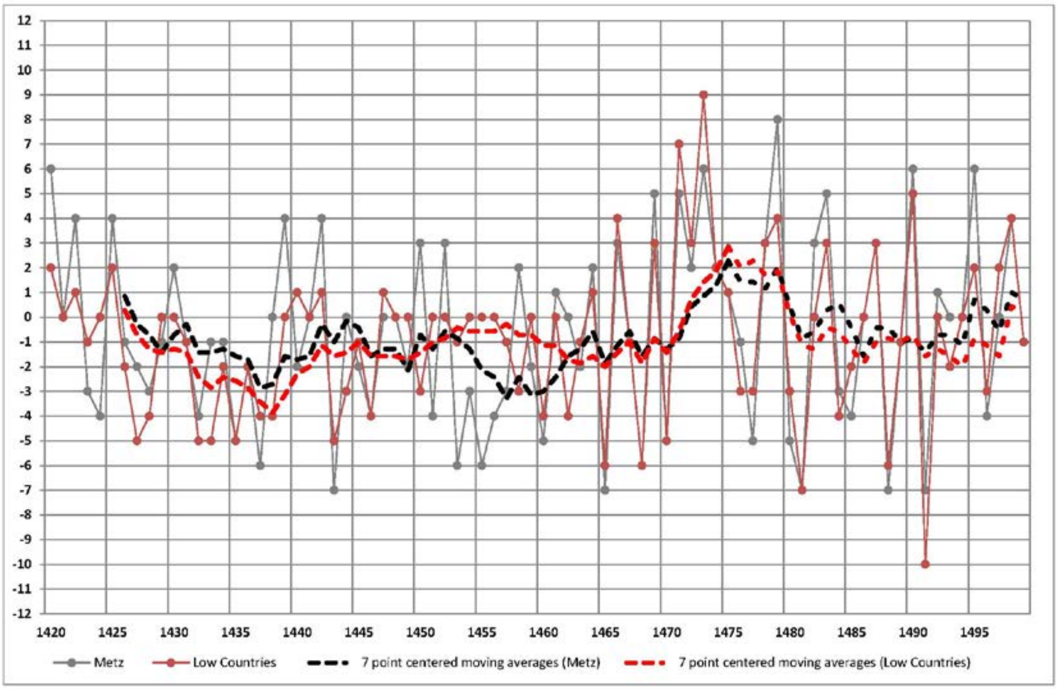

Figure 8. Comparison between temperature indices from Metz (Litzenburger, 2015) and the Low Countries (Camenisch, 2015).