1) Title:

comment from Referee #1

The author chose a nice long title which, however, very well covers the content of the paper. The title starts with a statement "Endless cold" - this sounds great, and clearly raises the attention of the reader. Nevertheless, I would suggest to mention either in the Introduction, Discussion or Conclusion why this statement is so important and applied as the main title of the paper (i.e. what does this title refer to? why is it typical for the 15th century?).

comment from Referee #2

The title 'Endless cold' seems to indicate overall conditions colder than in modern times and therefore fitting the Little Ice Age. This subject should be elaborated to a higher degree in the paper.

author's response

Thank you, I really should explain why I chose this title somewhere in the paper. I will do so in that part where I describe the prevailing weather conditions of the fifteenth century and I will underline that not the whole century is meant.

author's changes in manuscript

<u>In chapter 6:</u> 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 is together with other cold periods in the fifteenth century responsible for the chosen title "endless cold".

In the conclusion: 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.

2) Abstract

comment from Referee #1

Abstract: I would suggest to include in the abstract the main results and findings of the paper in 1-2 sentences.

author's response

Thank you for this suggestion, I will summarize the main results in two sentences and add them to the abstract.

author's changes in manuscript

<u>Abstract:</u> 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.

3) Chapter 3

comment from Referee #1

Chapter 3 (Sources): Concerning source types: it would be interesting to know the distribution of information among the different source types: is there any dominant type, or the data is app. evenly distributed among the major sources types? Still concerning this chapter: based on the description it is clear that the author used over 3000 weather information available in more than 100 different contemporary sources. I understand that such an amount of source evidence cannot be simply placed in Supplement or so. However, it would be really interesting to get at least some examples for the actual sources applied. Some typical example could be added, for example, in the 'Source' chapter while listing the major source types; and also in the descriptive part of the reconstruction, while referring to, for example, events occurred in individual years. The author once refers to her other paper where such information is provided in more detail; maybe it would be good to add some more examples to give some insight to the reader (often non-historian) based on what actual evidence the reconstruction (and e.g. the extremes within) is based.

comment from Referee #2

However, the source chapters appears somewhat general and would benefit by being more specifically aimed at the Burgundian Low Countries.

author's response

I agree that my description is rather general. I will add some more explanations focussing on the characteristics of the Belgian and Dutch sources and the distribution of the source types. A few examples can illustrate these characteristics. Such examples will also be added in the reconstruction part.

author's changes in manuscript

Chapter 3:

a) Sources types:

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).

b) examples (concerning the content of the sources as well as concerning the type of sources):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).

[...]

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.

[...]

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).

c) focus on the Burgundian Low Countries:

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.

[...]

In the Burgundian Low Countries these languages were Middle Low German, Middle Dutch or Middle French – each with local variations.

in chapter 5.1:

b) examples:

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."

4) Discussion

comment from Referee #1

I think the paper would need a Discussion chapter: here, for example, such topics could be discussed as the comparison of the present reconstruction with the previous reconstruction (when relevant); comparison with other available, documentary based, reconstructions in Europe; comparison with potentially available reconstructions for the same period, based on non-documentary (proxy, natural scientific) evidence. Moreover, in the Introduction, the author very well placed her subject within the research of the scientific community. I think the author has some major findings which may alter our European understanding and knowledge about the place of the 15th century (e.g. also in the LIA-MWP transition) in general, for example, concerning temperature anomalies. Probably it would be useful to dedicate a sub-chapter in the Discussion part for shortly mentioning these main findings in the course of (and comparing with) the major findings of previous literature concerning European overviews (e.g. frequency of hard winters and warm summers; the author partly refers to these questions in the individual sub-chapters, concerning individual decades or years).

comment from Referee #2

A lot of work went into the creation of good quality indices, but then the paper stops short on capitalising on this work by omitting any analysis. Even though a direct calibration of the reconstructed fifteenth century meteorological conditions is not possible, at least winter conditions would allow a rough comparison to modern meteorological observations and an evaluation of the frequency of extremely cold winters in fifteenth and twentieth century (the classification of such winters being based on (bio-) physical proxies like frozen water bodies and the destruction of winter crops). [...]

The introduction mentions the documentary based climate indices for the Low Countries by van Engelen and Buisman, which go back into medieval times and overlap time wise and spatially with the indices presented in this paper. Even though the scale of the indices and the definition of the seasons differ in the two reconstructions, a comparison of both index series would be of high interest to the reader and should be included. If a direct correlation is not

possible due to gaps in the series or the abovementioned problems, a comparison of (temperature) extremes should still be attempted.

author's response

I fully agree. I will write an additional chapter that compares my indices to other results such as Litzenburger (2015), van Engelen (2001), Glaser (2013) and possibly more. I will analyse the correlations and point out the main similarities and differences. I will also compare the winter temperatures to meteorological observations of the 20th century and the linked biophysical proxies as far as possible.

author's changes in manuscript

a) comparison to other reconstructions:

New chapter 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.

b) contextualisation of the results:

<u>In chapter 6:</u> 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).

c) comparison to the 20th century:

Unfortunately such a comparison is very difficult and would rather be misleading in the case of the here presented indices. There are of course modern analysis of ice and frost days in the Netherlands (e. g. Buisman, 2011). A direct comparison does not really work because the medieval observers do not distinguish between frost and ice days and this is the reason why a direct comparison would be arbitrary. Also a comparison in regard to the frozen waterbodies is very difficult. During the 20th century the big rivers such as the Rhine only freeze four times (1928/29, 1946/47– rather drifting ice than close ice shield, 1953/54 – again rather drifting ice than close ice shield and 1962/63). This is due to the changes in river bed and due to the waste water that flows into the rivers. In the Low Countries a big number of canals already existed during the Middle Ages but also they change their shape and a further comparison with such data would mean that I have to go the local archives again for further studies. This is the reason why I could not add this further analysis to the paper.

5) Conclusion

comment from Referee #1

To the Conclusions: The author could provide a bit more (couple of sentences) conclusion on the overall importance of her findings in an European context.

author's response

Concerning the conclusion, I will add some more sentences that contextualise the results.

author's changes in manuscript

In the conclusion:

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 hot dry 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.

6) Figure 1

comment from Referee #1

A further comment to Figure 1: on the overview map I would suggest to indicate also the present-day country boundaries - this provides some help for non-historian audience in determining the areas where the climate reconstruction refers to. I would also indicate it in 1-2 sentences in Chapter 2 (Scope).

author's response

The modern boundaries would make the map easier to read for non-historians. Since there is already much information on it, I will try to add the boundaries without confusing.

author's changes in manuscript

New Version of the map with added modern bounderies.



1 Endless cold: A seasonal reconstruction of temperature

- 2 and precipitation in the Burgundian Low Countries during
- 3 the fifteenth century based on documentary evidence
- 4

5 C. Camenisch^{1, 2}

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- 9 University of Bern, Länggassstrasse 49, 3012 Bern, Switzerland}
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- 11

12 Abstract

13 This paper applies the methods of historical climatology to present a climate reconstruction 14 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 15 16 to the distinction between contemporary and non-contemporary sources. Approximately 3000 17 written records deriving from about 100 different sources were examined and converted into 18 seasonal seven-degree indices for temperature and precipitation. For the Late Middle Ages 19 only a few climate reconstructions exist. There are even fewer reconstructions which include 20 winter and autumn temperature or precipitation at all. This paper therefore constitutes a useful 21 contribution to the understanding of climate and weather conditions in the less well 22 researched but highly interesting fifteenth century. Outstanding are the extremely cold winter 23 temperatures during the 1430s and an extremely cold winter in 1407/08. Moreover, no other year in this century was as hot and dry as 1473. At the beginning and the end of the 1480s and 24 at the beginning of the 1490s the weather conditions of summers were considerably wetter 25 26 than average.

1 1 Introduction

2 Emmanuel Le Roy Ladurie, one of the pioneers of historical climatology, stated the necessity 3 for a quantitative, continuous and homogeneous series in order to reconstruct climate on the 4 basis of historical documents for the time prior to instrumental records (Le Roy Ladurie, 5 1972). A true treasure of rich narrative texts, including a variety of weather-related 6 information, can be found in documentary sources produced in the late Middle Ages (1300-7 1500 AD). This information consists of direct data (descriptions of temperatures and 8 precipitation), and indirect data (climate proxies - phenomena which are related to climate 9 such as freezing of water bodies or plant phenology). Nonetheless, they are far from being 10 continuous or homogeneous. Moreover, they are not quantitative (Pfister et al., 2009).

11 As this paper demonstrates, there are methods that facilitate the transformation of this varied 12 information into a reliable climate reconstruction on the basis of quantitative series. The 13 presented paper aims to give an overview of weather conditions during the fifteenth century in 14 the Burgundian Low Countries and surrounding areas in a seasonal resolution with separately 15 reconstructed temperature and precipitation. Leading questions are as follows: what were the 16 characteristics of these weather conditions? what are the advantages of using documentary 17 data and what are the limits of these sources? Selected examples give a deeper insight into the 18 characteristics of the sources and the applied methods in order to analyse them and convert 19 them into homogeneous temperature and precipitation index series. The climate 20 reconstruction not only provides an overview of the prevailing weather conditions of the 21 whole century but presents detailed results. Since the source density in most cases is high 22 enough, it is possible to detect not only anomalies but also less spectacular weather 23 conditions. This is unusual because most reconstructions based on this type of data focus on 24 extreme weather events. Moreover, many climate reconstructions are limited to temperature. 25 As the inclusion of precipitation in reconstructions is crucial in order to obtain a more 26 complete picture of past climates, this is a substantial gain in knowledge (Pfister, 2014). The 27 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 28 29 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, Post, 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).

3 In 1987 Pierre Alexandre established a benchmark for the reconstruction of medieval climate 4 using documentary sources. Apart from analysing sources all over continental Europe he 5 defined the necessity of a critical source assessment in order to improve the quality of such 6 examinations. Jan Buisman collected an enormous number of documentary sources 7 concerning the climate of the Low Countries. By 20154 sixfive volumes with Dutch 8 translations of weather-relevant records had appeared, covering the period from 1000 to 9 1800750, and another three volumes are in preparation (Buisman, 1995; Buisman, 1996; 10 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, 1382). 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).

23 The aim of the present paper is different. First of all, indices with a higher resolution were 24 necessary because a comparison with economic development is intended and for that purpose 25 at least seasonal reconstruction is indispensable (Camenisch, 2015; Pfister, 2014). 26 Furthermore, it was mandatory to read the original texts since it is not possible to produce a 27 reliable reconstruction with summarised and translated excerpts of totally diverse sources. 28 The high-quality source compilations of Pierre Alexandre and Jan Buisman were consulted as 29 well. Further important contributions related to medieval climate in the Low Countries were 30 published by Elisabeth Gottschalk and Adriaan de Kraker (e.g. Gottschalk, 1975; de Kraker, 31 2005; de Kraker, 2013). In addition there are useful climate reconstructions focusing on 32 regions in the neighbourhood of the Low Countries such as Germany (Glaser, 2013), 33 Switzerland (Schwarz-Zanetti, 1998) France (Le Roy Ladurie, 2004), Lorraine (Litzenburger, **Kommentar [CC1]:** Volume six appeared in February.

1 20154) and the British Isles (Kington, 2010) that are based either on similar source types or 2 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.

8

9 **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).

15 The methods used in this paper require a sufficient number of data. For this reason the 16 Burgundian Low Countries have been chosen as a geographical frame. During the end of the 17 fourteenth and in the course of the fifteenth century several parts of today's Belgium, the 18 Netherlands, Luxembourg and Northern France fell under the rule or at least into the sphere of 19 influence of a cadet branch of the French royal dynasty (see Fig. 1). This house of Burgundy 20 reigned for almost hundred years over the Burgundian Low Countries before the male line 21 became extinct (Calmette, 1996; Schnerb, 1999). In 1477 when the last of the dukes of 22 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 23 24 Duchy of Luxembourg in the South (Blockmans and Prevenier, 1999; Prevenier and 25 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 Kommentar [CC2]: I changed the reference and the bibliography because Litzenburger published his thesis as a book a month ago.

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.

8

9 3 Sources

10 **3.1 Classification**

11 In order to reconstruct temperature and precipitation several methods based on a variety of 12 data are required. Besides the rich archives of nature consisting of organic proxies such as tree 13 rings or non-organic proxies including ice cores, varves or terrestrial sediments man-made 14 archives exist. Those archives contain documentary data and are the basis of climate 15 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. 16 17 Depending on the type of information, annual, seasonal, monthly or even daily observations 18 exist. Early instrumental measurement did not begin until the seventeenth century and is 19 therefore not available for the Late Middle Ages (Behringer, 2010). Instead, other direct and 20 indirect data provide information on climate. Direct data are descriptive records on weather 21 spells, climatic anomalies or weather-induced disasters. Indirect data or proxy data comprise 22 accounts of both organic and non-organic evidence that allow inferences regarding 23 temperature and precipitation such as plant phenology (e.g. date of blooming or ripening of 24 vines) or ice phenology (e.g. date of freezing or opening of water bodies) (Pfister, 1999; 25 Pfister et al., 1999). The following example contains both direct and indirect data:

26 27

28

29

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

30 31 Formatiert: Französisch (Schweiz)

Formatiert: Schriftart: Kursiv

1 This short text is part of a chronicle written by the Benedictine monk Jean de Stavelot, a

2 <u>contemporary eye witness from Liège. He gives not only account on heavy frost in the winter</u>

3 1407/08 but describes in addition that the Meuse was so firmly frozen between Jemeppe and

4 Liège that chariots loaded with grain and other foods were driven on the ice. This frost lasted

5 for ten weeks before the ice started to melt around the 28 January 1408 (the date is given in

6 the Julian calendar style and means in the Gregorian calendar stile the 7 February 1408).

7 Another distinction is made between institutional and individual sources on the one hand and 8 between narrative and administrative sources on the other hand (see Table 1). The first 9 classification takes note of the origination process of the text and the second focuses on the 10 text type and its use (Pfister et al., 2009; Camenisch, 2015). Both have a direct impact on the 11 quality of the sources, as discussed subsequently. Concerning the Late Middle Ages 12 especially, chronicles, memoirs, and journals constitute the individual narrative sources, 13 whereas annals belong also to the group of narrative sources but have an institutional origin. 14 The lines between the two groups are blurred since many texts show characteristics of both 15 types (Geary, 2013). Amongst the administrative sources accounts (written records on 16 bookkeeping) and charters (documents for legal purpose) of different origin need to be 17 mentioned. In this paper the first group was mainly used and charters did not play a major 18 role. Also, administrative sources were generated either in an institutional context such as a 19 monastery, town, and toll station or in a private individual context (Camenisch, 2015).

20 The fifteenth century is rich in narrative texts, mainly chronicles, annals, memoirs and 21 journals. In the area of the Burgundian Low Countries and the neighbouring regions a true 22 treasure of such manuscripts are preserved until today and many of them are published as 23 edited books. The tradition of writing chronicles originates from antiquity and has survived 24 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 25 Late Middle Ages interested laypersons wrote chronicles, some of them on behalf of town 26 27 authorities or nobles, others for a more private purpose (Schmid, 2009; Schmid, 2012). Those 28 narrative texts were often written in a vernacular language. In the Burgundian Low Countries 29 and the close neighbourhood these languages weresuch as Middle Low German (e. g. Lamprecht et al., 1895; Cardauns et al. 1877), Middle Dutch (e. g. Kuys et al., 1983; De 30 Jonghe, 1840; Fris 1904) or Middle French (e. g. Borgnet, 1861; Tutey, 1903) - each with 31 32 local variations.

1 Usually, chronicles consist of a compilation of older texts followed by a second part 2 composed by the chronicler and covering his life span. This second – contemporary – part is 3 usually richer in information, more detailed and clearly more reliable. Some chroniclers 4 summarise the crucial events year by year, others write their text many years after the events 5 (Lambert, 1993; van Caenegem, 1997). In narrative texts, the authors often describe weather 6 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). 7 8 The reasons why weather conditions or proxy data are mentioned in administrative sources 9 differ from those in narrative sources. The important source type of accounts is characterised

10 by standardised records of cost and revenue. Either the climate proxies lead to costs or 11 revenues and were listed for that purpose in the accounts or short descriptions of weather 12 conditions appear as justification for extraordinary costs (Wetter and Pfister, 2011; Pribyl et 13 al., 2012). In this paper narrative sources <u>clearly form the main body of the data set and have</u> 14 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, 15 1967; Jappe Alberts, 1969; Jappe Alberts, 1971; Jappe Alberts, 1978; Jappe Alberts, 1985) 16 17 and further unedited town accounts relying on Jan Buisman's compilations have been 18 included in the data set (Buisman, 1996; Buisman, 1998).

19 **3.2 Critical source assessment**

A critical assessment not only for every source but for each record is crucial for the quality of 20 21 the entire reconstruction because the characteristics and quality of the sources vary and they 22 contain different types of information. Critical source assessment includes information on the 23 author, especially dates of birth and death, the place where he lived and the context of his 24 oeuvre (Alexandre, 1987). This information allows a distinction to be drawn between original 25 text and copies of older manuscripts and is extremely important because of the significantly 26 greater reliability of the records in the original (contemporary) part of the source. The closer 27 the events occurred in relation to the time when the authors wrote their texts on paper or 28 parchment the more reliable they are. The best quality is given in the case of year by year 29 reports. Accounts and journals are usually produced in this way as well as the last part of 30 annals and chronicles. If an event is convincingly proved by contemporary records, additional 31 non-contemporary reports can be taken into account insofar as they confirm the main 32 statement of the contemporary evidence. Since each source has its own dynamics that become 1 clear by reading the text as a whole, it would be a fatal error just to pick the records from

- 2 older or newer compilations without the critical source assessment and its context.
- 3 For this paper approximately 3000 records from about 100 sources were evaluated. Two-
- 4 thirds of them are related to weather conditions whereas the last third focuses on economic
- 5 impacts caused by these weather conditions. Many of the records contain long descriptions.

6 3.3 Source density

7 The density of the sources is not equal throughout the entire century as Fig. 2 shows. Because 8 of the different time span of the sources not all decades have the same source density. In 9 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 10 11 depends on the quality of the sources covering the year in question and it is consequently the 12 reason why years without enough evidence cannot just be interpreted as average (see Section 13 4). 14 Within the calendar year the distribution of the records is almost equal in terms of winter

15 (27%), spring (25.5%), and summer (29.5%). In 18% of the records only autumn is less

16 documented (Camenisch, 2015).

17 The distribution of the sources also differs with regard to their place of origin, as Fig. 3

18 shows. Most of the used sources have their origin in the Burgundian Low Countries but a

19 number of texts derive from neighbouring areas and were included in the data set because of

20 their excellent quality.

21 3.4 Dating

22 Confusion in dating is one of the most serious problems that can arise in a reconstruction. The 23 reasons are closely linked to the fact that different calendar styles were in use during the 24 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; 1 Grotefend, 1991). This means that in all the texts date indications deviate from the modern 2 calendar style and need to be converted.

3 Another problem derives from the fact that during the Middle Ages six possible days for the 4 beginning of the calendar year exist: 1 January, 1 March, 25 March, Easter, 1 September, 25 5 December (Grotefend, 1991). The first of September is used rather seldom so one has to take 6 care, especially concerning events occurring between Christmas and Easter. If one chronicle 7 uses the Easter style and another one uses the Christmas style the same events can be written 8 down as two different years. This could result in the misinterpretation that two similar events 9 happened in two subsequent years. A clear analysis of the correct dating of events is 10 indispensable, keeping in mind that the non-contemporary part of a narrative text is a copy of 11 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 12 13 usually did not give sufficient information on how they converted the dates. In this paper 14 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).

27

28 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

1 enables the integration of all the source types in one reconstruction. Christian Pfister chose a 2 scale of seven degrees because fewer degrees would not be detailed enough, whereas a more 3 extended scale would in most cases lead to numerous gaps. There are separate indices for 4 temperature and precipitation. Because of the remarkable source density in the late-medieval 5 Burgundian Low Countries a seasonal resolution is adequate. This means the entire climate 6 reconstruction comprises eight different indices. The meteorological year forms the basis of 7 the seasonal subdivision of the indices. Therefore the winter season covers the period from 1 8 December until 28 February, spring the period from 1 March until 31 May, summer from 1 9 June until 31 August and autumn from 1 September until 30 November. 10 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).

16 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.

24 Table 3 shows as an example the basic structure of the indices in the first row and the refined 25 criteria for the reconstruction of the winter temperatures in the second row. The criteria 26 include measurable or at least comparable physical and biological proxies (Pfister, 1999). 27 Concerning the winter temperatures this means for instance that in order to set a -3 in the 28 reconstruction, records on the freezing of large water bodies such as the Rhine, Scheldt, and 29 Meuse or even the shores of the North Sea are required. This information does not indicate 30 absolute temperatures since those water bodies freeze after the temperature sinks below a 31 certain threshold and it is not possible to determine the temperatures beneath that threshold 32 (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.

9 The analysis of winter precipitation before instrumental measurement records is challenging. 10 The reason for this is that in the winter season precipitation often occurs as snowfall. It is 11 extremely difficult to deduce the water content of snowfall only from descriptions. A further 12 peculiarity of the contemporary descriptions is that in many cases the chroniclers do not 13 clearly distinguish between the duration of snowfall and the timespan during which the snow 14 cover did not melt, resulting in misinterpretations. In addition, floods are no clear indicator of 15 the amount of precipitation because several causes exist and some of them, like ice jam and 16 sudden snow melting, are linked to temperature (Wetter et al., 2011; Kiss, 2009). The 17 chroniclers pay less attention to dryness and drought in winter. These problems are the reason 18 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.

3 For the reconstruction of summer precipitation the refined criteria are mostly linked to 4 descriptions of damages that were caused by either dry or wet anomalies. Since a sufficient 5 but not excessive amount of precipitation during summer is crucial for the harvest in the Low 6 Countries, the medieval chroniclers paid much attention to it. This is also the reason why this 7 index is the best documented in terms of the precipitation reconstruction. A certain problem 8 derives from the fact that medieval authors often do not clearly distinguish between heat and 9 drought, and the terms are used synonymously. 10 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).

28

29 5 Reconstruction

30 The climate reconstruction comprises four indices for each season concerning temperature 31 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.

3 **5.1 Winter**

12

15

The temperature index for the winter season is the most complete of the reconstruction (see 4 5 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 6 7 winter of 1407/08 for instance was one of the coldest in the century and the best documented 8 season in the whole dataset. Many chroniclers emphasise that nobody could remember a 9 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 10 11 years, as the Flemish monk affirms in his text (Kervyn de Lettenhove, 1870):

13 <u>"1407 [...] Hoc anno [...] hyemps sicca et frigida, ita ut gelu asperum esset a principio</u>
 14 <u>decembris usque in finem januarii, ut a C annis tantum frigus et tantum gelu non fuerit."</u>

16 -Thanks to the excellent source density, different phases of cold can be identified in the 17 weather conditions of these months. Around the feast of Saint Martin on 11 November 1407 18 (20 November converted into Gregorian calendar style) temperatures sank in widespread 19 areas, as is reported in texts from Liège, Paris, Cologne, Lübeck, Magdeburg and Dortmund 20 (Camenisch, 2015). Another cold front reached the Burgundian Low Countries some days 21 after the beginning of December (Gregorian calendar style - all following data are converted 22 into this style). Several water bodies froze after Christmas, such as the Seine, the Rhine and 23 the Meuse with its tributary stream, the Sambre. The ice cover was thick enough for people to 24 ride horses on it or drive loaded chariots from one river bank to the other (Camenisch, 2015). 25 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. Formatiert: Französisch (Schweiz) Formatiert: Schriftart: Kursiv Formatiert: Französisch (Schweiz)

For more average winters (index points of -1, 0 or +1) fewer sources exist. During the 1 2 fifteenth century three clusters of very cold and extremely cold winters can be detected. The 3 clusters during the 1420s and during the 1460s are remarkable but that during the 1430s is 4 outstanding. This decade is one of the coldest of the whole millennium if not the coldest 5 (Lamb, 1982). In contrast are the extremely or very mild winters of the first half of the 1470s 6 and the beginning of the 1480s. Less is known about the winter seasons of the middle of the 7 century, especially the 1440s and 1450s because of the lack of contemporary sources. 8 Concerning precipitation the medieval authors remain rather silent in the first years of the

9 century. As a consequence there is a remarkable gap in the reconstruction from 1410 to 1417.
10 In addition, the second half of the 1430s, the last years of the 1440s and the 1450s in general
11 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.

17 **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.

29 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

1 describing weather conditions during periods when a lot of agricultural work had to be done. 2 As a consequence fewer gaps exist in the two summer indices. Nonetheless, there is a lack of 3 information at the beginning of the century and during the 1450s. Apart from that, shorter 4 gaps are spread across the whole century. In 1406, 1428 and 1468 the weather conditions 5 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 6 7 temperatures, possibly topped only by the year 1540 (Wetter et al., 2014). A cluster of warm 8 anomalies at the beginning of the 1470s and clusters of cold anomalies during the 1480s and 9 at the beginning of the subsequent decade are also remarkable. 10 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

13 anomalies is documented during the 1450s, this rather unknown decade.

14 **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.

25

26 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.

12 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 13 14 seasons had the same characteristics. This remarkable temperature cluster is together with other cold periods in the fifteenth century responsible for the chosen title "endless cold". 15 Horace Hubert Lamb suggested with regard to the winter temperatures that the 1430s belong 16 17 together with the 1690s to the coldest episodes of the last millennium (Lamb, 1982). Most recent research even brings this decade together with an early phase of the Spörer Minimum 18 19 (Camenisch et al. 2014). There is less information about summer temperatures because they 20 were not as remarkable as the winter and spring temperatures. However, in 1432 there was a 21 very warm summer and in 1436 and 1438 the summer temperatures were very cold. In the 22 same decade a number of above-average wet seasons occurred such as winter 1430/31, winter 23 1434/35, summer 1432 and summer 1438.

24 During the 1440s, there were three extremely cold seasons in winter 1442/43, in the 25 subsequent spring 1443, in spring 1446 and in addition one very cold season in autumn 1444. 26 Only in summer 1442 were temperatures very warm. The decade was characterised by rather 27 dry weather conditions in the Burgundian Low Countries, especially in 1442, 1447 and 1448. 28 There are fewer sources available which describe the 1450s. However, there is a remarkable 29 cluster of above-average wet summer seasons from 1453 until 1456. There is more 30 information on the subsequent decade. Winter 1461/62 was extremely cold and very dry; in 31 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

10 outstanding because of an above-average amount of precipitation and considerably low 11 temperatures. In contrast, the winter of 1483 experienced extremely mild temperatures. The 12 below-average temperatures of 1488 returned again in 1491 when almost the whole year was 13 characterised by extremely cold weather conditions. With regard to precipitation the wet 14 anomalies in summer 1491 and winter 1496/97 need to be mentioned as well as the drought in 15 summer 1492.

16 7 Discussion

17 A comparison of the here presented indices to a number of other reconstructions was made. 18 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 19 Netherlands based on documentary evidence are the closest reconstruction regarding methods 20 21 (9 degree indices) and geographical coverage. Nonetheless, there are differences because the 22 winter (DJF) and summer (JJA) temperature indices presented in this paper and the van 23 Engelen indices do not exactly cover the same months and the van Engelen indices have 24 considerably less gaps especially in summer. However, the Pearson correlation coefficients 25 are remarkably high. Concerning the winter temperatures a coefficient of -0.893 (N=81; Sig. 26 < 0.01, the van Engelen indices for winter temperatures are reciprocal to the here presented 27 winter indices) and concerning summer temperatures a coefficient of 0.783 (N=50; Sig. < 28 0.01) show the close relation between the two reconstructions. The relation between the van 29 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 30 spring precipitation index (Corr. 0.585; N=31; Sig. < 0.01) is also remarkably close. 31

1	Laurent Litzenburger (2015) presented most recently a further climate reconstruction from
2	Metz (Lorraine, France) based on documentary data and containing seasonal temperature and
3	precipitation indices. A comparison of the two reconstructions shows remarkable similarities.
4	Very close are the summer temperatures (Corr. 0.844; N=40; Sig. < 0.01) and autumn
5	precipitation (Corr. 0.708; N=31; Sig. < 0.01). Also rather similar are winter temperatures
6	(Corr. 0.658; N=70; Sig. < 0.01), spring temperatures (Corr. 0.671; N=41; Sig. < 0.01) and
7	precipitation (Corr. 0.609; N=27; Sig. < 0.01) as well as summer precipitation (Corr. 0.641;
8	N=48; Sig. < 0.01), though N is rather low in some parts of the analyses. The comparison of
9	the annual temperature (obtained by summing up the seasonal indices as Christian Pfister and
10	Rudolf Brázdil propose; Pfister and Brázdil, 1999) and precipitation series show even higher
11	correlations (see figure 8). The most obvious difference occurs during the 1450s when the
12	here presented indices are much closer to the average as Litzenburger's. This is due to the fact
13	that the here presented indices have many gaps in this decade what leads to a rather average
14	and misleading result regarding the summed up indices of the whole year.
15	A comparison to the indices presented by Rüdiger Glaser and Dirk Riemann (2009) shows
16	weaker correlations. The closest relations exist between the summer temperature indices
17	(Corr. 0.494; N=50; Sig. < 0.01), the spring temperature indices (Corr. 0.415; N=47; Sig. <
18	(0.01) and the winter temperature indices (Corr. 0.393; N=82; Sig. < 0.01). The reason for this
19	is most probably the further distance between the two researched areas and the different scales
20	of the indices because Glaser applies a 3 degree scale for the fifteenth century.
21	Furthermore, the here presented indices were compared to the grape harvest dates and spring-
22	summer reconstruction for Burgundy presented by Chuine et al. (2004). Also in this case the
23	results show a considerable relation between the Chuine et al. data and the here presented
24	indices. The grape harvest dates are sensitive to spring and summer temperatures. The highest
25	Pearson correlation coefficient were obtained in comparison to these indices (spring
26	temperatures: Corr. 0.521; N=47; Sig. < 0.01 and summer temperatures: Corr. 0.637; N=50;
27	Sig. < 0.01). Obviously, the summer precipitation index is also rather similar (Corr. 0.548;
28	N=60; Sig. ≤ 0.01). In addition, a certain relation but with a weaker level of significance is
29	given between the grape harvest dates and the spring precipitation (Corr. 0.435; N=32; Sig. <
30	0.05) and the autumn precipitation (Corr. 0.348; N=39; Sig. $<$ 0.05). The results of the
31	comparison with the Chuine et al. data are insofar very important as these data were obtained
32	with completely independent methods and sources. The Litzenburger, van Engelen and Glaser

<u>indices were also produced independently but the applied method and also a number of</u>
 sources are very similar to the here presented indices.

3 The comparison between the indices and the reconstruction of Büntgen et al. (2011) shows

4 only weak similarities. The rather far distances between the two researched areas and the

5 <u>completely different methods are most probably the reason for this.</u>

6

7 **78** Conclusion

8 This paper gives an overview of seasonal temperature and precipitation during the fifteenth 9 century. The reconstruction contains eight climate indices (separate indices on temperature 10 and precipitation for every season) based on documentary evidence. The main body of the 11 data set consists of narrative sources such as chronicles, annals, memoirs or journals and 12 administrative sources such as accounts. These sources have an individual or institutional 13 background. The sources contain either direct data or indirect data (proxy data that can be 14 converted into climate indices). The basis of the indices is a seven-degree scale starting with -15 3 for extremely cold or extremely dry conditions and going up to +3 for extremely warm or 16 extremely wet conditions. A catalogue of criteria was defined for every index point in order to 17 evaluate as many seasons as possible. The indices for winter temperatures, summer 18 temperatures and summer precipitation are the most complete. During the fifteenth century a 19 number of outstanding weather patterns can be detected. Therefore, more attentions should be 20 paid to the climate of this century as has been done before. Most remarkable are a cluster of extremely cold winter temperatures during the 1430s – which was the reason for the first part 21 22 of the title – as well as an extremely cold winter in 1407/08. Especially this cluster of cold 23 winters has been underestimated in recent research. A number of dry and hot spells occurred; 24 amongst them the year 1473 was unique because of the extent and duration of the heat and the 25 lack of precipitation. Extremely wet weather conditions especially in summer were prevalent 26 at the beginning and the end of the 1480s and at the beginning of the 1490s. A comparison to 27 Dutch and French reconstructions shows very satisfying results.

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

30 Appendix A: Climate indices

year	winter		spring		summer		autumn	
	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.

vear	winter		spring		summer		autumn	
ycai	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.
1400	-3	1						
1401	-1	1						
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		

voor	winter	-	spring		summer		autumn	-
year	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.
1429	0							2
1430	1	1	-2		1			
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

vear	winter	1	spring		summer		autumn	
ycai	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.
1458	-3	1		-1		-2		-2
1459	0			1		-1		
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

VICON	winter vear		spring		summer		autumn	
year	temp.	prec.	temp.	prec.	temp.	prec.	temp.	prec.
1487	0						3	
1488	0		-2	1	-2		-2	
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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			-Memoirs
			-Journals
			-Letters
			-Weather diaries
			- Travel reports
	Administrative	-Monastic accounts	-Accounts of private households
	sources	-Town accounts	
		-Toll accounts	
		-Charters	

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

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

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

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 frost 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		

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





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





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



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









