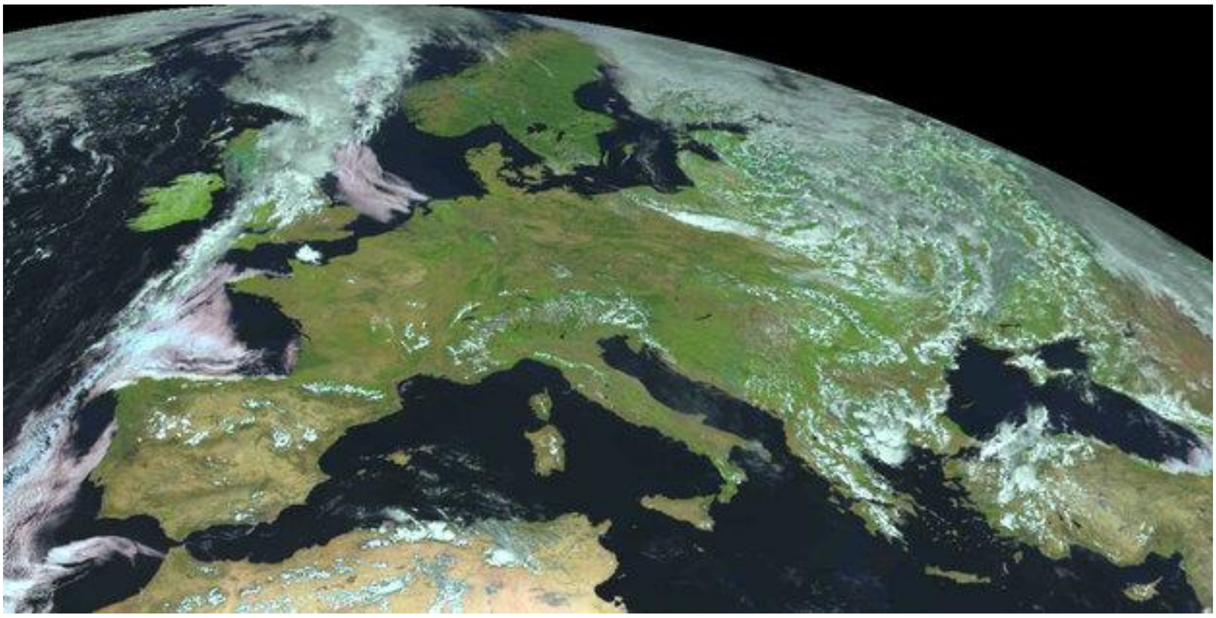
Climate change and human activity during the pre-industrial period

—

An overview of climate reconstructions in Europe during the Holocene and the link to human activity



June 2013

Utrecht University
Farilde Steur (3699269)
Mentors: Karin Rebel & Kees Klein Goldewijk

Abstract

There is no consensus in climate science whether influences of human activity had influences on climate change in the pre-industrial period. The early-anthropogenic hypothesis states that great scale changes in land-use starting thousands of years ago with the Neolithic Revolution caused increased greenhouse gas(GHG) concentrations which led to temperature increases. This study investigates possible connections between climate change and human activity during the Holocene in Europe. In this research the factors temperature, GHG concentrations and human activity are reconstructed and compared with each other. The most notable periods found in the temperature reconstructions are 1000BP and 300BP which show a temperature increase and decrease respectively in several temperature reconstructions. Reconstructions for GHG concentrations show peaks of N_2O and CH_4at 1000BP and low concentrations of CO_2 and N_2O at 300BP. Reconstructions for human activities show increases in population, cropland and pasture at 1000BP. At 300BP there are no declines for human activities. This shows a potential connection between climate change and human activity at 1000BP, but a low potential for a connection at 300BP.

Samenvatting

In de klimaatwetenschappen is er geen consensus over de invloed van menselijke activiteiten op klimaatverandingin de pre-industriële periode. De 'early-anthropogenic' hypothese stelt dat het begin van groot schalige veranderingen in landgebruik tijdens de neo-lithische revolutie hebben gezorgd voor een verhoging van de broeikasgas concentraties wat leidde tot een temperatuur verhoging. Deze studie onderzoekt mogelijke connecties tussen klimaatverandering en menselijke activiteiten tijdens het Holoceen in Europa. In de studie worden de factoren temperatuur, broeikasgas concentratie and menselijke activiteiten gereconstuëerd en vergeleken met elkaar. De meest opvallende periodes in de temperatuur reconstructies zijn 1000BP met een temperatuur verhoging en 300BP met een temperatuur verlaging in verschillende reconstructies. De broeikasgas concentratie reconstructies laten een piek van N_2O en CH_4 zien in 1000BP en een verlaging van CO_2 en N_2O op 300BP. Reconstructies van menselijke activiteiten laten toennames van populatie, akkerland en weiland zien in 1000BP. Er zijn geen afnames in menselijke activiteiten te zien op 300BP. Dit laat zien dat er een potentiële connectie is tussen klimaatverandering en menselijke activiteiten in 1000BP, maar een lage potentie voor een connectie in 300BP.

Acknowledgements

For writing this thesis I received valuable advice and feedback from my mentors Karin Rebel and Kees Klein Goldewijk. I would like to thank Karin for the feedback on structuring my thesis and presenting my results. For feedback concerning the contents of my research and the supply of data I want to thank Kees. Thereby I also want to thank the people who handed me the data from their research which was not openly available. In conclusion, I cannot leave you guys out; I want to thank my fellow students for preserving me from lonely days in the library and the members of the Storm committee for the provision of my daily cup of coffee. This all helped me to write my bachelor thesis and I hope you will have pleasure reading it.

Table of contents

Introduction

The publication of the IPCC fifth assessment report in 2014 shows the recognition for climate change as a global problem by scientists and policy makers. Impacts of human activities since the Industrial Revolution are seen as a major cause for climate change (Ellis et al., 2013). This period of large-scale human effects on earth, especially in the earth's climate is also called the Anthropocene (Ruddiman, 2013) and is used more and more in scientific studies for the most recent geological time (A. G. Brown et al., 2013; Gale & Hoare, 2012; Marlon et al., 2013; Schimel et al., 2013; Wolfe et al., 2013). The last decade there has been a debate about the starting point of the Anthropocene. The most common hypothesis is that the Industrial Revolution (1850AD) can be seen as the shift from the Holocene, lasting from 11500 years before present (BP, with present referring to 1950 AD) to the Anthropocene (Steffen et al., 2007). The Industrial Revolution is considered important by supporters of this theory because of the great population increase and the burning of fossil fuels (Steffen et al., 2007).

Another, more provocative, hypothesis is that the Anthropocene started thousands of years ago, long before the start of the Industrial Revolution. Ruddiman (2013) is an important defender of this second hypothesis, also calling it the early-anthropogenic hypothesis. He argues that in the line of the reconstruction of the last 350.000 years of atmospheric concentrations, an anomaly in the CO_2 and the CH_4 concentrations can be seen beginning at 8000BP and 5000BP respectively. Also, evidence gained from palynology, archeology, geology, history and cultural anthropology show human influences on the landscape starting at small scale between 8000BP and 6000BP and growing much larger in the bronze and iron ages (5000BP-present). This alteration on the landscape starting between 8000BP and 6000BP explains, according to Ruddiman, the anomalies of CO_2 and CH_4 concentrations starting respectively 8000BP and 5000BP. The alteration in landscapes due to human activity coincides with innovations in agriculture (Ruddiman, 2003). And so, Ruddiman (2013) proposes the Neolithic revolution as the beginning of the large-scale alterations of humans on the earth's environment and climate. These two ideas show that no consensus has been reached for the starting point of the Anthropocene in science. This topic is, however, of great importance for the understanding of anthropogenic impacts on climate change, for now and in the future.

More insight in the problem described above is obtained by studying human-climate relations in the preindustrial period. Therefore reconstructions of both climate and human activity are required since instrumental data don't reach that far back in history (Bradley, 2000). There are reconstructions in a great amount of different temporal and spatial scales. The temporal focus of this study will be the Holocene, since this period is seen as the dawn of civilization where some important growths in population have occurred (Chiarelli & Magherini, 2011). I am, however, interested in the human impacts before the industrial revolution. Therefore I investigate the period between 11500-100BP). Population growth in the Holocene was strongest in Europe and Asia (Goldewijk et al., 2010). The spatial focus of this study will be Europe.

The aim of this study is to detect relations between climate change and human activity in the Pre-Industrial period. In this paper I will study reconstructions of temperature, GHGs and human activity and see if there is any connection between them. I will focus on these three factors because the early-anthropogenic hypothesis is based on the change in GHG concentrations due to human activity, with a temperature increase as consequence. This specific aim results in the following research question:

Are there any connections observable between climate change and human activity in Europe in the period of 11500-100BP and what are, according to the scientific literature, the greatest causes for these connections?

I expect to find an increase of temperature and greenhouse gas(GHG) concentrations in periods with a growth in human activities and a decrease of temperature and GHG concentrations during periods of a decline in human activities.

In order to answer the research question, I formulated the following sub questions:

1. What was the temperature during the Holocene in Europe, and which periods show notable temperature fluctuations?
2. What was the GHG concentration during these periods in Europe?
3. What was the human activity during these periods in Europe?
4. Are there common anomalies observed in reconstructions of temperature, GHG concentrations and human activities which indicate a connection between these three factors?

For answering these questions I will start with a short description of the most relevant concepts for my research concerning climate change and climate reconstruction. In the next chapter I will explain the method used in order to answer the sub questions, followed by the results wherein I answer the sub questions one by one. In the discussion I will compare my results with other research concerning this subject. The last chapter is the conclusion where I will answer the research question by means of the results of the study.

1. Theoretical framework

In order to study human-climate relations in the pre-Industrial period, different concepts are important to bear in mind. In the following chapter I will discuss some concepts important for the interpretation of climate change and the possible link to human activities.

1.1 Natural factors

For the interpretation of climate reconstructions concerning the impact of human activity on climate change, it is important to have an idea of the natural climatic fluctuations of the earth. Fluctuations in solar irradiance in the form of cyclical patterns are identified on different time-scales. The Milankovitch theory explains the past glacial-interglacial cycles by defining three different orbital characteristics of the earth: eccentricity causing, a 100 kyr cylce, which is the shape of the earth's orbit varying form nearly circular to elliptical; precession, causing a 23 kyr cycle, which is the direction of the earth's axis relative to the sun; and obliquity, causing a 41 kyr cycle, which is the fluctuation of the earth's axis (Benton & Harper, 2009). These characteristics determine the amount of solar radiation which is received by the earth's surface (Ojala, 2012). During last glacial-interglacial cycles, eccentricity was the dominant factor in the Milankovich cycles which gives cycles of 100 kyr (Beer et al., 2000). Another theory for cycles of the total amount solar irradiance on earth are the Bond cycles. These cycles are driven by surface winds and surface ocean hydrography, which are, probably, driven by a solar forcing mechanism (Prokopenko et al., 2001). This theory gives cycles of 1470±500years (Bond et al., 2001). Even shorter periods of solar irradiance cycles are caused by solar magnetic activity. These cycles last 11 years and are also called sunspot cycles (Sharma et al., 2013). Besides solar irradiance, volcanic aerosols also influence temperatures on earth (Mann et al., 1998). Volcanic eruptions cause higher concentrations of aerosols in the atmosphere, which causes a higher reflection rate of solar irradiance (Jones & Mann, 2004). So, volcanic eruptions should also be included when studying human-climate relations (Hegerl et al., 2007).

1.2 Anthropogenic factors

Identification of anthropogenic factors causing climate change is necessary when investigating human-climate relations. The most common anthropogenic factor is the emission of GHGs as a consequence of bio-mass burning and land-use changes (Ruddiman, 2013). Land-use change also has several other consequences which cause climate change. Conversion of forests into agricultural land tends to lead to a decrease in evaporation, and therefore a decrease in the moisture- and latent heat fluxes. This leads again to a temperature rise (Betts, 2001). Also the albedo of the surface becomes usually larger with conversion of forests to agricultural land, which causes a cooling effect (Betts, 2001).

1.3 Climate proxies

Climate reconstruction of earlier history is dependent on climate proxies. Climate proxies are preserved objects which carry climatic information of the times they originate from. This information is also called indirect evidence of past climates (Pittock, 2005). Examples of climate proxies are ice cores, tree rings, chrionomids and pollen. The interpretation of climate proxies is a complex process since the proxies can have a weak climatic signal, the signal can be interrupted by random background noise or the signal can show the interaction of several climatic indicators (Ojala, 2012). So proxies respond to temperature change, but they can also respond to other environmental factors like pH, salinity and changes in ecology (Velle et al., 2005). The actual response to temperature is calibrated by the application of statistical regression models on response of the proxy on instrumental temperature data (Jones & Mann, 2004). Reconstructions inferred from different proxies form the same period and location can differ in several ways from each other. First of all it depends on the proxy what the time resolution of the climate reconstruction will be. Some proxies like pollen and chironomids have a low time resolution which means these proxies are only useful for investigation of climate changes at a millennial scale or more (Jones & Mann, 2004). Tree-rings on the other hand have a high time resolution which creates the possibility to study climate change over a shorter time period. This study uses several reconstructions inferred from different proxies to give a more objective and complete view of the paleoclimate of Europe. A great amount of temperature reconstruction data are available for Europe in the Holocene, based on several different techniques and using different climate proxies. The data used in this study are based on tree-rings, pollen, chironomids (non-biting midges) and multi-proxy studies, which put different kinds of proxies together in one reconstruction (Jones & Mann, 2004). This study uses local, regional and hemispheric reconstructions.

1.4 Time-space relations

In climate reconstruction time and space relations are of great importance. When giving a historical overview of the relation between climate change and human activity, time can be seen as the leitmotif. When separating natural and anthropogenic drivers on climate change, an important tool is the detection cyclical patterns in the climate system (Loehle, 2004). This also refers back to the cycles in solar irradiance discussed in the natural factors. Hence time is an important aspect to include in an overview of climate change and the relation with human activity. Since climate change is variable across landscapes and doesn't occur in a uniform of consistent way (Beier et al., 2012), the spatial aspect of climate reconstructions has to be included as well. At higher latitudes, for instance, effects of climate change are most of the time rapid warming, while at lower latitudes and in the tropics effects are more complex and variable.

2. Method

2.1 Sub question 1: temperature reconstructions

To give an overview of the temperature of Europe during the Holocene, I will present several reconstructions based on different types of proxies in different time-lines. I will make a distinction between reconstructions inferred from different types of proxies in order to compare these different proxies with each other. I am most interested in temperature fluctuations present in several time-lines since these fluctuations are more likely to be responses to actual temperature change instead to other climatic factors. When a temperature change is present only in one proxy-inferred reconstruction, there is a chance this fluctuation is a response to another environmental factor than temperature.

Since the time-lines include local, regional and hemispheric reconstructions, there are different types of climate which must be assembled in one figure. Therefore the reconstructions will be expressed as functions of time and temperature anomalies, instead of actual temperatures. A temperature anomaly is 'the departure of a reference value or long-term average'(NCDC, 2012). In this study the anomalies will be expressed with respect to the modern average temperature of the site of reconstruction.

I will create the time-lines in Excel, using the scatterplot function. This makes it possible to put different data-sets, which use the same variables, in one graph. In this way I can compare the different data-sets with each other and investigate the similarities and differences. Access to raw data of temperature reconstructions is required for this method. These are, however, in many cases not openly available (Antonsson & Seppä, 2007; K. J. Brown et al., 2012; Litt et al., 2009; Magny et al., 2009; Seppä & Poska, 2004). Some data of climatic reconstructions are collected at the National Oceanic and Atmospheric Administration (NOAA), and this is where most of the data used in this study will be obtained from. Also some data are handed to me by the researchers themselves. I will discuss the time-lines of reconstructions inferred from different proxies separately in the results.

2.2 Sub question 2: greenhouse gas reconstructions

I will use data for CO_2, CH_4, and N_2O concentrations in order to give an overview of the GHG concentration during the relevant periods found in the results of sub question 1. These three gases are included since conversion of forest to cropland can give a great loss of CO_2 storage, and the change from forestry to pasture causes great losses of CH_4 and N_2O (Kirschbaum et al., 2013), which makes them important for investigation in human-climate relations. I will create three different time-lines, one for each GHG.

For the GHG concentrations it is less important if the data are obtained in Europe since the concentration of the gases is more or less the same in the whole atmosphere. CO_2, CH_4 and N_2O are all well-mixed gases which have an atmospheric life span of more than a year. Mixing-times in the atmosphere don't exceed one year, which explains the uniform concentration of CO_2, CH_4 and N_2O (Harvey, 2000).

The data will again be presented in a scatterplot made in Excel. The purpose of this scatterplot is to put several data-sets of reconstructions of one GHG in one graph. In this way I will again be able to compare these different reconstructions with each other. The variable for the vertical-axis will be parts per million or billion volume. Again, raw-data are required for the creation of a scatterplot; these will also be obtained from the NOAA.

2.3 Sub question 3: reconstructions for human activity

For the reconstructions of human activity I chose to focus on the factors human population, cropland and pasture (cropland and pasture together show the total land-use data), since these can be seen as the most important driving factors for anthropogenic climate change in the pre-industrial period (Klein Goldewijk et al., 2011). Reconstructions for population numbers and land-use in Europe during the Holocene will be made using data published by the Netherlands Environmental Assessment Agency (PBL) in the Historical Database of the Global Environment (HYDE). In this data-base statistics for historical population, cropland and pasture are combined with spatial information in order to create reconstructions for population and land-use for the time-period 12000-0BP (Klein Goldewijk et al., 2011).

2.4 Sub question 4: possible connections

In order to answer the fourth sub question I will perform a qualitative analysis on the quantitative results I obtained by answering the first three sub questions. In this analysis I will compare the results for temperature, GHG concentration and human activity reconstructions with each other in order to detect any common anomalies. These common anomalies are important since this is an indication for a connection between climate change and human activity. The climate system is sensitive for the GHG concentrations since an increase in GHG concentrations leads to an increase in temperature (Kaplan et al., 2009). Ruddiman (2005) showed increases in greenhouse gases during the Holocene could have had anthropogenic origins, so common anomalies in temperatures, GHG concentrations and human activities imply a potential anthropogenic cause for climate change.

3. Results

In this chapter I will present time-lines for temperature, GHG concentrations and human activities in Europe. I will start with the time-lines containing temperature reconstructions and on basis of these time-lines I will name the most notable periods. In the next section I will show the time-lines for the reconstruction of GHG concentrations for the periods named in the first section. Then I will do the same for the reconstructions of human activities. This chapter will end with a comparison of the observations made in the three sections, temperature, GHG and human activity.

3.1 Temperature reconstructions

The temperature reconstructions were divided by the different proxies which were used to obtain the data. The time-lines contain reconstructions inferred from tree-rings, pollen, chironomids and multi-proxies. An overview of the data used for the time-lines and the time-span and location of the reconstructions is shown in table 1. The data are sorted by type of proxy and they are labeled separately for every study used. The time-lines will be presented as graphs for each proxy separately and the graphs use the same labels as in the table (column 1).

series	proxy	location	time-span	nr.	reference
1(a-c)	chironomids	Northern Sweden	10000 - 0	3	Larocque & Hall, 2004
2	chironomids	East Switzerland	1000 - 0	1	Larocque-Tobler et al, 2010
3(a-f)	chironomids	Southern Scandinavia	11000 - 0	5	Velle et al., 2005
4(a-k)	pollen	Northern Scandinavia and Russia	2000 - 0	11	Bjune et al., 2009
5	pollen	Northern Norway	8750 - 0	1	Bjune & Birks, 2008
6	pollen	Central Italy	11700-4600	1	Finsinger et al., 2010
7	tree-rings	Northern Sweden	1500-0	1	Grudd, 2008
8(a,b)	tree-rings	Polar Urals and Northern Sweden	2000-0	2	Mann & Jones, 2004
9	tree-rings	Central Europe	2500 - 0	1	Büntgen et al., 2011
10	tree-rings	Eastern Europe	900-0	1	Büntgen et al., 2013
11	tree-rings	Northern Hemisphere	1200-0	1	D'Arrigo et al., 2006
12	tree-rings	Northern Hemisphere	1500-0	1	Hegerl et al., 2007
13	multi-proxy	Northern Hemisphere	2000-0	1	Christiansen & Ljungqvist, 2012
14	multi-proxy	Global	2000 - 0	1	Ljungqvist, 2010

Table 1. Data used for time-lines temperature reconstructions. The following information is given in the columns from left to right: Series (the name of the series used in the time-line); Proxy (type of proxy used for the reconstruction) ; Area; Time-span; Nr.(number of reconstructions per reference); Reference

3.1.1 Chironomids

The chironomid inferred temperatures were obtained from three different studies, together giving ten different local temperature reconstructions. The time-line for the chironomid inferred reconstructions is shown in figure 1. Series 1a-c in the figure show three reconstructions for Northern Sweden, series 2 shows a reconstruction for Eastern Switzerland and series 3a-f shows 6 reconstructions for Southern Scandinavia. Data of series 1 and 3 were given in T_{jul}, so it had to be converted in the temperature anomaly with respect to the modern T_{jul}, which was given in both articles. Chironomids have a higher temporal resolution than pollen (Jones & Mann, 2004), but still not very high. Therefore this time-line shows the overall temperature trend of the Holocene, but it is not useful for detection of annual or decadal temperature changes. Notable is the difference in time-resolution between series 1 and 3 which cover the whole Holocene, and series 2 which covers only the period 1000-0BP. Time resolutions of series 1 and 3 are 200 years (Velle et al., 2005), while the resolution of series 2 is only 1-20 years (Larocque-Tobler et al., 2009). This makes the reconstruction of the last 1000 years in this time-line more detailed and better to investigate concerning human-climate relations than the reconstruction for the whole Holocene.

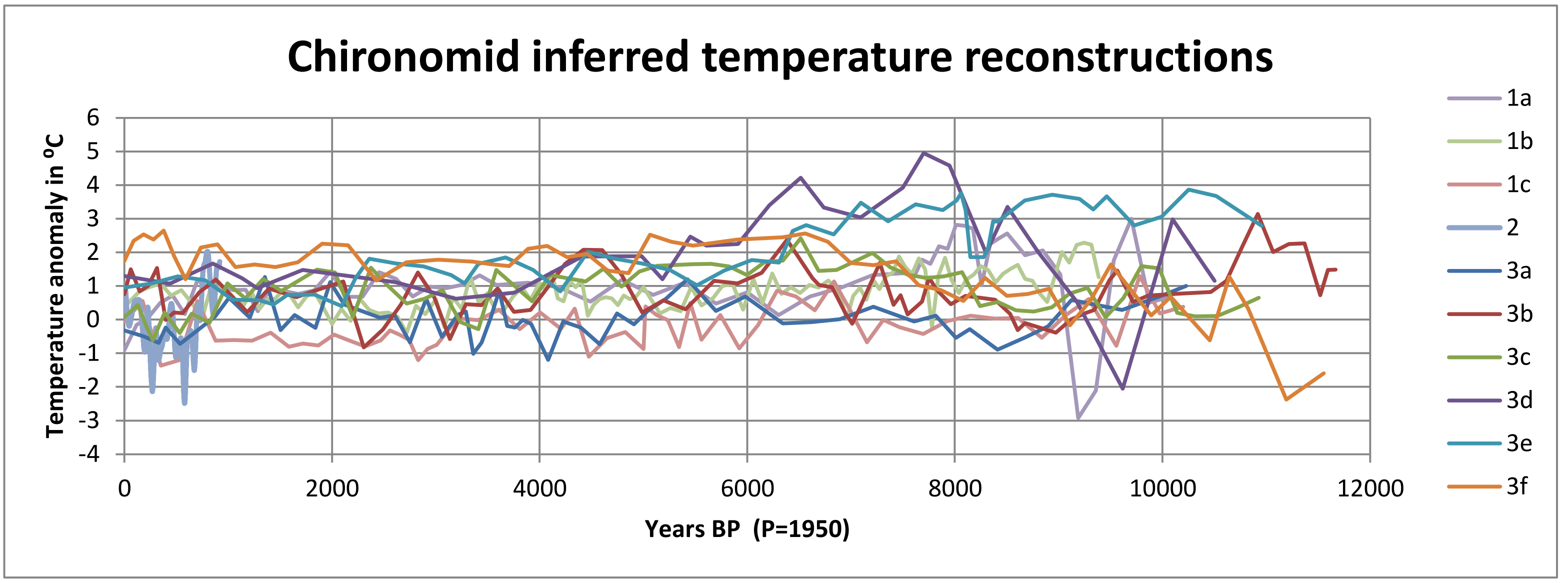


Figure 1. Chironomid inferred temperature reconstructions. Series 1 from Laroque & Hall (2004) (lakes as referred in article: 1a Njulla, 1b lake 850, 1c Vuoskku). Series 2 from Larocque-Tobler et al. (2010). Series 3 from Velle et al. (2005) (lakes as referred in article: 3a SPA, 3b RAT, 3c BRU, 3d FIN, 3e HOL, 3f OYK)

The time-line shows high temperatures the early Holocene. Between 8000-6000BP temperatures decline and after 6000 BP they become quite stable until present. The description for the last decennium is only based on series 2, since the time resolution of the other reconstructions is too low to say something about this short time scale. Here temperatures are high in the period 1000-750BP. After this period temperatures decline and a cold period begins, lasting until 200BP. During this period of low temperatures, there is a little peak around 450BP.

3.1.2 Pollen

Figure 2 shows the time-line for the chironomid inferred temperature reconstructions. Series 4a-k are 11 local reconstructions from North-West Russia and Northern Fennoscandia which cover the period 2000-0BP (A. Bjune et al., 2009; A. E. Bjune & Birks, 2008). Series 5 is a reconstruction from Northern Norway covering the period 8750-0BP (A. E. Bjune & Birks, 2008). Series 6 is a reconstruction for central Italy covering the period 11700-4600BP. Data for series 4 and 5 were expressed in T_{jul} and data for series 6 in T_{jan}, so I have converted these in temperature anomalies, using the modern T_{jul} and T_{jan} given in the articles.

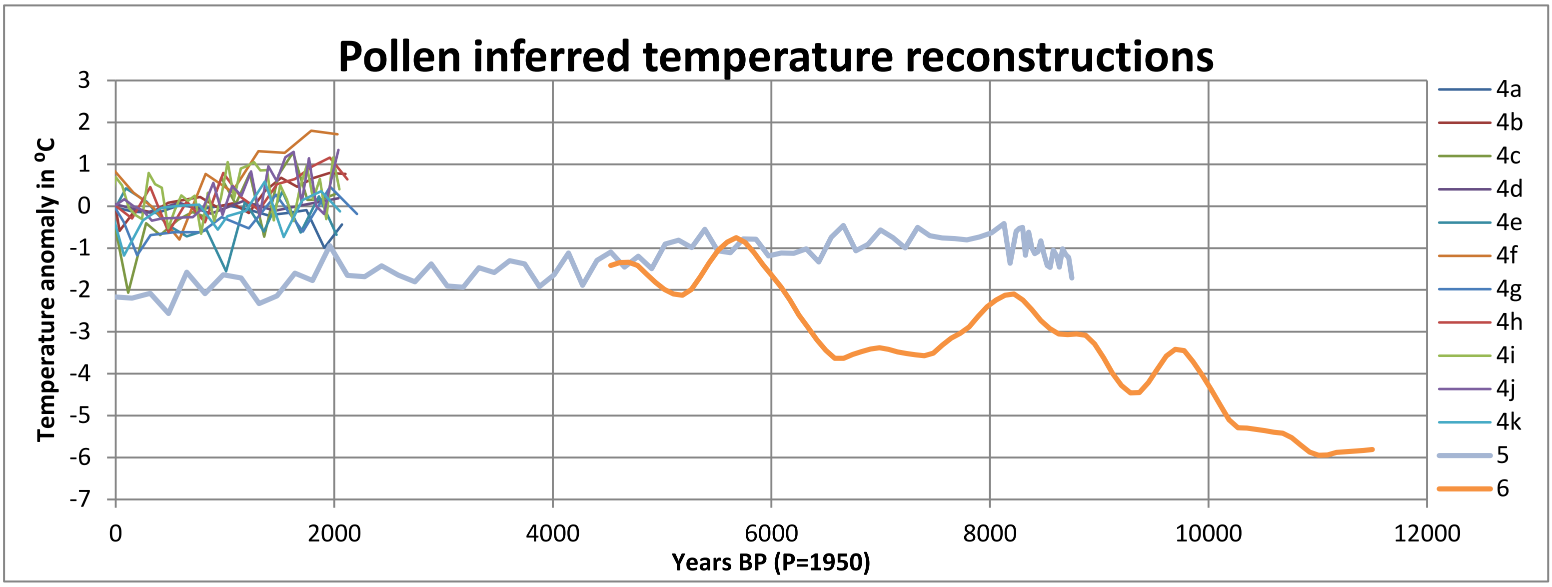


Figure 2. Pollen inferred temperature reconstructions. Series 4 from Bjune et al. (2009) (lakes as referred in article: 4a Bjorn, 4b Dalmu, 4c Gamme, 4d Hopse, 4e, KP-2, 4f Litlv, 4g Myrva, 4h Svana, 4i Toska, 4j Tsuol, 4k Vuosk) Series 5 from Bjüne & Birks (2008). Series 6 from Finsinger et al. (2010).

Notable is that series 6 is more jagged than series 5. This is probably because series 6 goes further back in time and is therefore more difficult to reconstruct on a high time-resolution. It is difficult to conclude something out of the pollen-inferred reconstructions, since they have a low time-resolution which makes them only suitable for detection of climate changes on a decennial scale or longer (Jones & Mann, 2004). Thereby the reconstructions do not show a clear, uniform trend of temperature change. This time-line contains therefore no useful information for this study.

3.1.3Tree-rings

The reconstructions inferred from tree-rings are shown in figure 3,4 and 5. The time-resolution of tree-ring inferred reconstructions is very high, which makes them very suitable to study climate change at a lower temporal scale than the pollen and chironomid inferred reconstructions. Integration of all the found data-sets in one time-line results, however, in a chaotic figure where individual reconstructions aren't distinguishable anymore. Therefore I separated the reconstructions on basis of spatial scale, what gave three different time-lines: for the local (fig. 3), regional (fig. 4) and hemispheric (fig. 5) reconstructions. The data for temperature reconstructions inferred from tree-rings do not cover the whole Holocene, but merely the last two millennia. Therefore, only the period 2000-0BP is shown in these time-lines.

Figure 3, the time-line for the local reconstructions, contains three different data-sets of two different studies. Series 7 covers the period 1450-0BP and is from Lake Törneträsk in Northern Sweden (Grudd, 2008). Series 8a covers the period 1949-0BP and is from the same lake as series 7. Series 8b covers the period 1036-0BP and is from the Polar Urals (Mann & Jones, 2003).

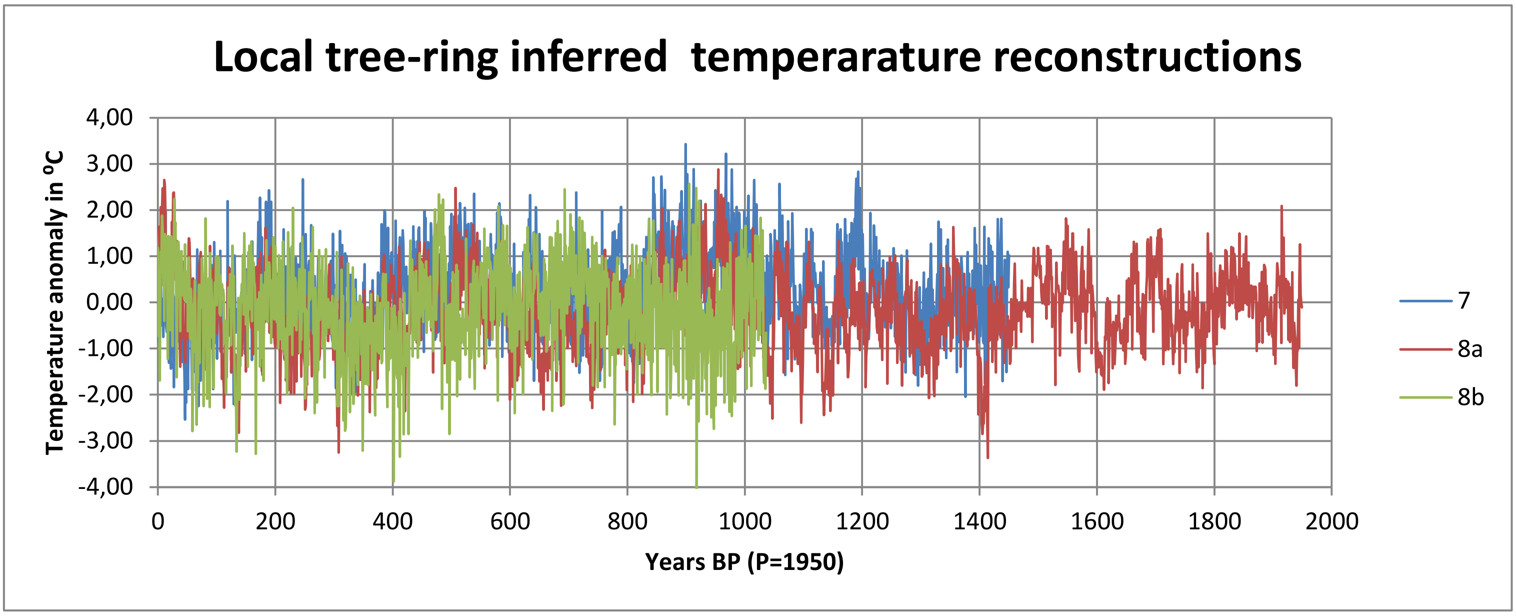


Figure 3. Local tree-ring inferred reconstructions. Series 7 from Grudd (2008). Series 8 from Mann & Jones (2004) (locations as referred as in article: 8a Polar Urals 8b Northern Sweden).

Although local reconstructions are usually not very uniform, the expectation is differently in this case, sine the time-line contains only reconstructions from Northern sites and even two reconstructions which are based on proxies from the same lake (series 7 and 8a). This expectation is verified in the time-line. The two reconstructions from Lake Törnetrask are very similar. Both reconstructions show a temperature peak around 1000BP followed by a period of lower temperatures until present. Around 500BP there is a little temperature peak and lowest temperatures are observed around 300BP. The reconstruction of the Polar Urals in series 8a shows a quite similar trend, but with less high temperatures around 1000BP. The temperature drop around 300BP is, however, very clear.

Figure 4, the time-line for the regional temperature reconstructions, contains two data-sets. Series 9 is a reconstruction for Central Europe (Büntgen et al., 2011) and series 10 is a reconstruction for Eastern Europe (Büntgen et al., 2013). Series 9 covers the period 2450-0BP and series 10 covers the period 910-0BP.

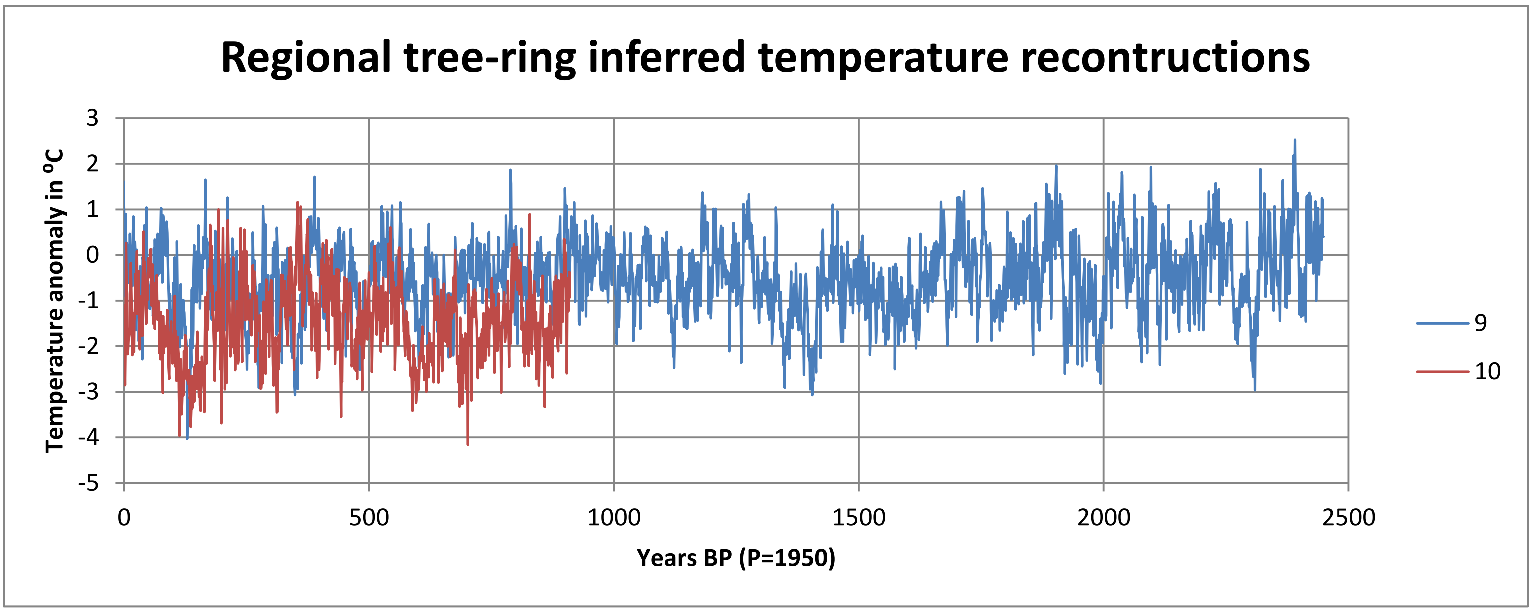


Figure 4. Regional tree-ring inferred temperature reconstructions. Series from Büntgen et al. (2011). Series 10 from Büntgen et al. (2013).

The reconstruction for Central Europe (series 9) shows higher temperatures from 2500-1750BP compared to the rest of the reconstruction. After this period temperatures drop and a minimum is reached around 1400BP. Then temperatures show a small increase until 750BP, followed by a little drop. The reconstruction of Eastern Europe (series 10) starts not earlier than 910BP, where low temperatures are observed until 600BP. Temperatures increase until 200BP, where there is a sudden drop.

Figure 5 contains two reconstructions showing the average temperature of the Northern Hemisphere. Series 11 covers the period of 1237-0BP (D'Arrigo et al., 2006) and series 12 the period between 699 -0BP (Hegerl et al., 2007).

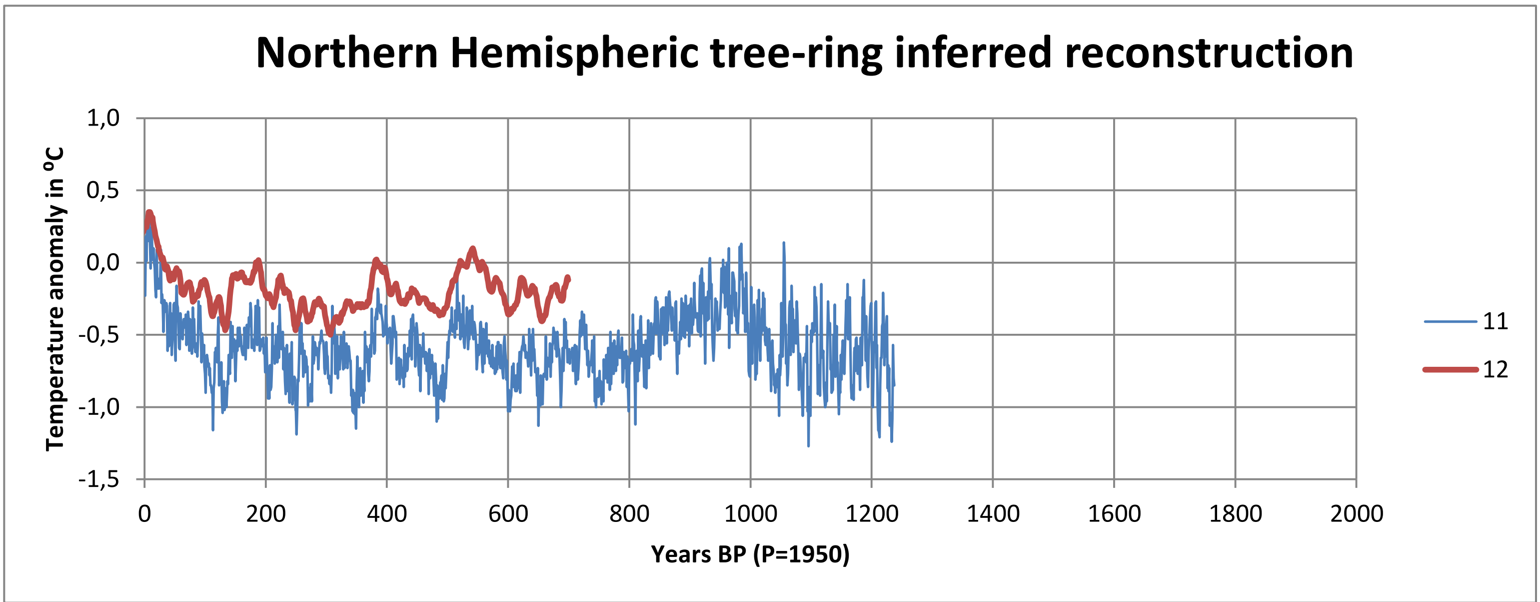


Figure 5. Northern Hemisperic tree-ring inferred temperature reconstructions. Series 11 from D'Arrigo et al. (2006). Series 12 from Hegerl et al. (2007).

The first thing to notice is that temperatures of series 11 are consistently lower than series 12. This can be explained by different calibration periods the studies use. Series 12 uses the period 1880-1960, while series 11 uses a combination of the period 1856-1987AD and 1938-1978AD for calibration. Series 11 shows bigger variability than series 12. This is probably due to a difference in the method used for the two series This is probably because the reconstruction from series 12 is tested using semi-proxies or 'a perfect model approach'. This method is very useful in order to determine the shape of temperature change, but less for determining the magnitude of these changes. Magnitudes are often smaller when using pseudo-proxies (Goosse et al., 2006). Apart from the differences in temperature height due to different calibration periods, the reconstructions show a very similar pattern. Series 11 shows a temperature peak around 1000BP. From 699BP series 12 begins. There are no notable differences between the two reconstructions, so the following description goes for both reconstructions. Between 800 and 600BP temperatures are quite stable. In the period of 600-400BP there are two temperature peaks visible. Then temperatures are low until 150BP, followed by a temperature rise.

3.1.4 Multi-proxies

The time-line for multi-proxy inferred reconstructions contains two different reconstructions, both covering the last two decennia. Multi-proxy reconstructions were based on several reconstructions of different proxies. In this time-line reconstructions from Ljungqvist (2010) (series 13) and Christiansen & Ljungqvist (2012) (series 14) were used, based on 30 and 32 proxy records respectively. There are some differences in the used reconstruction records, but most of the records were used in both studies.

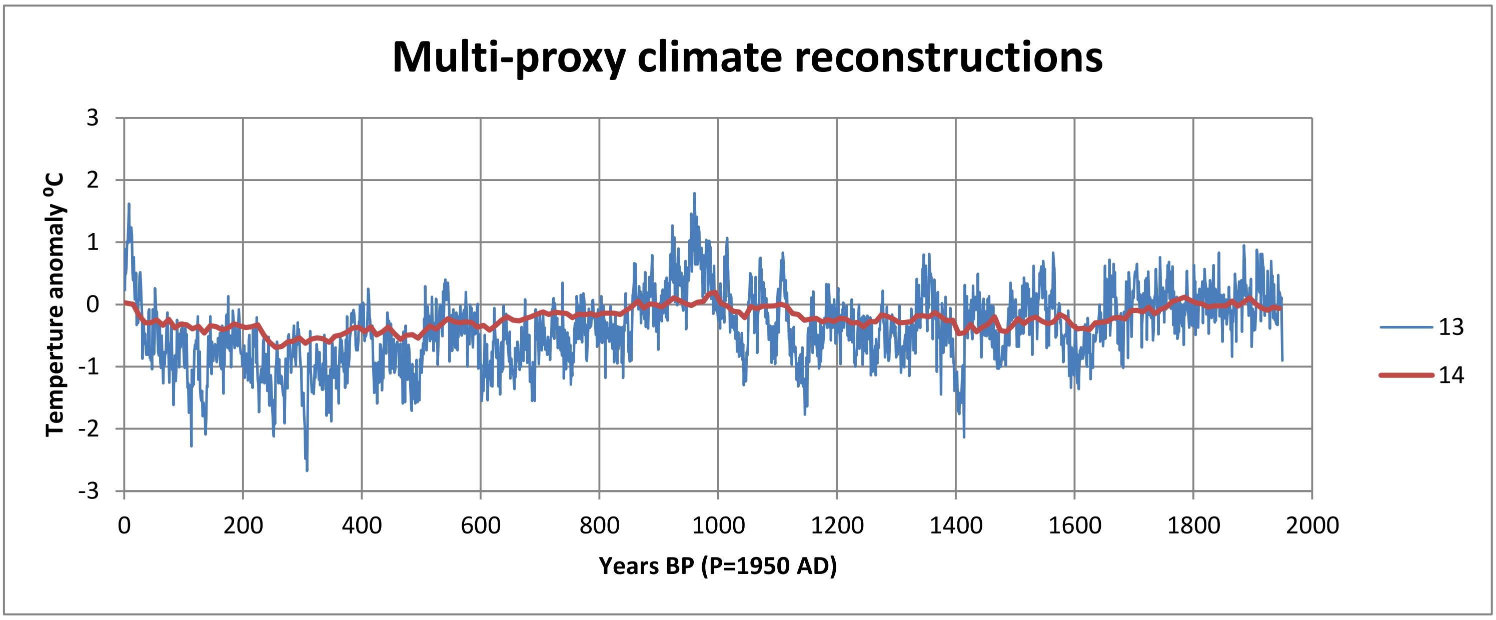


Figure 6. Multi-proxy climate reconstructions. Series 13 from Ljungqvist (2010). Series 14 from Christiansen & Ljungqvist (2012)

The magnitude in temperature changes is smaller in series 14 than in series 13, which was also the case for series 11 and 12 in the tree-ring inferred reconstructions. This difference in magnitude is again due to the use of pseudo-proxies in series 14. The time-line shows that the first millennium (2000-1000BP) was warmer than the second millennium. Around 1000BP there is a peak in both reconstructions. After this peak temperatures gradually decline, reaching a minimum around 300BP. After 300BP both reconstructions show an increase of temperatures.

3.1.5 Temperature observations

The different proxy-inferred reconstructions weren't all useful for the investigation of human-climate connections. The time-lines for chironomid and pollen inferred reconstructions showed a low time-resolution and were quite variable, while tree-ring inferred and multi-proxy reconstructions had a higher time-resolution and were more uniform. The latter were therefore more suitable for the investigation of human-climate connections. The most notable temperature fluctuations were seen in figure 3, 5 and 6. There was a temperature peak around 1000BP and a low-point around 300BP observable in all three time-lines. In figure 7 the time-lines are shown again with the periods of common temperature fluctuations marked with an arrow.

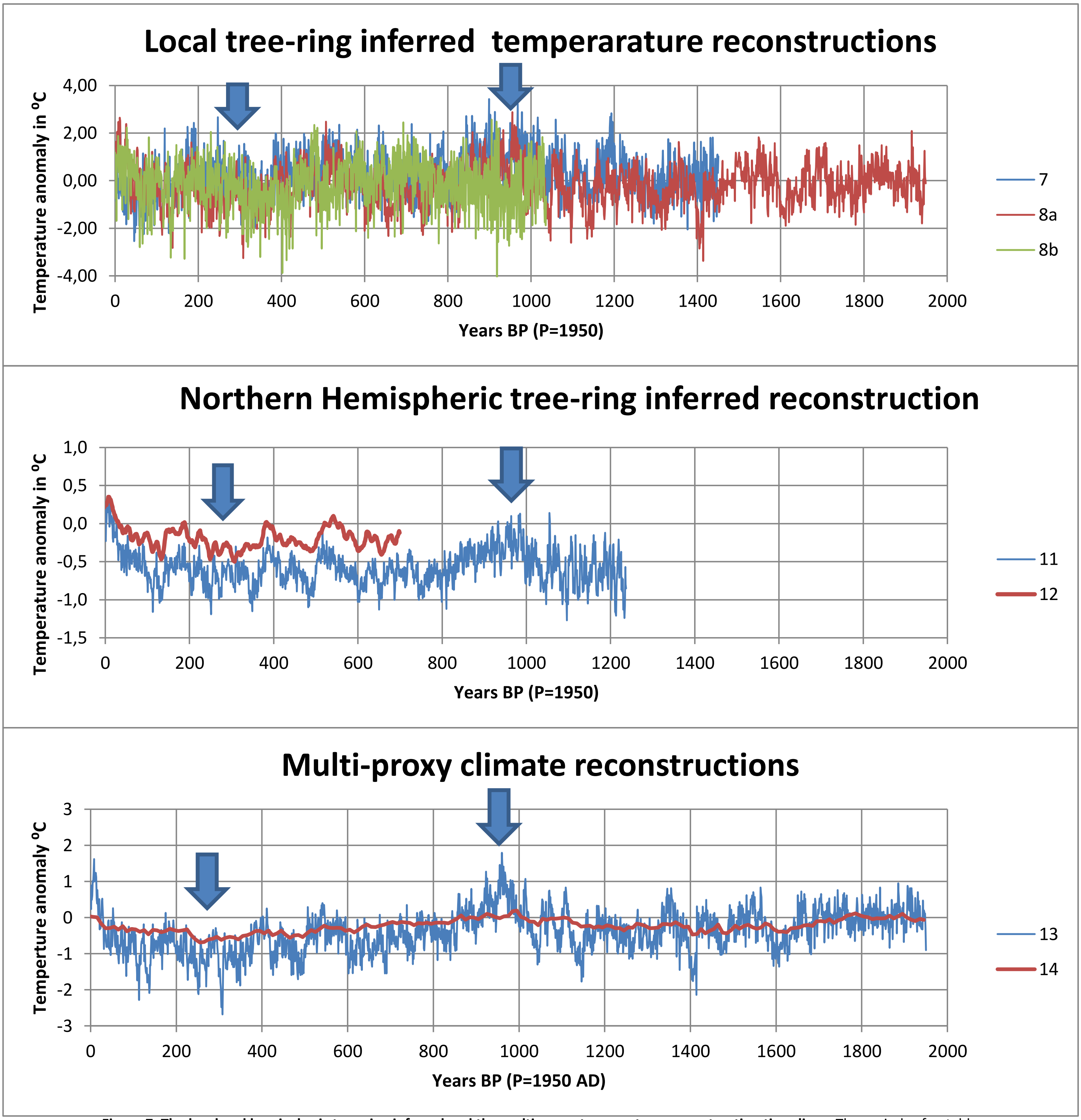


Figure 7. The local and hemispheric tree-ring inferred and the multi-proxy temperature reconstruction time-lines. The periods of notable temperature fluctuations at 1000BP and 300BP are marked with an arrow.

3.2 Greenhouse gas concentration reconstructions

Beneath I will show the results for the reconstructions for greenhouse gas concentrations in the Holocene. The data for the reconstructions were all obtained from ice-cores from Greenland or Antarctica. This shouldn't be a problem for investigating connections between humans and climate in Europe, since concentrations of these three gases are more or less uniform in the whole atmosphere, as already explained in the method. Table 2 shows the data collected for the greenhouse gas reconstructions. The data were sorted by GHG, since there is one time-line for every GHG. The table shows the reference of the data-set and the location of the ice-cores as well. Aim of this section is to compare the time-lines for GHG concentrations with the moments of temperature fluctuations at 1000BP and 300BP. Therefore only the period 2000-0BP is shown instead of the whole Holocene. The moments 1000BP and 300BP are marked with arrows in all time-lines.

series	GHG	reference	Ice-core
1	CO_2	Monnin et al., 2004	Taylor Dome, Dome C and DML (A)
2	CO_2	Flückinger et al., 2002	Dome C (A)
3	CO_2	MacFarling Meure et al., 2006	Law Dome (A)
4	CH_4	Schilt et al., 2010	Talos Dome (A) and NGRIP (G)
5	CH_4	Flückinger et al., 2002	Dome C (A)
6	CH_4	MacFarling Meure et al., 2006	Law Dome (A)
7	N_2O	Schilt et al., 2010	Talos Dome (A) and NGRIP (G)
8	N_2O	Flückinger et al., 2002	Dome C (A)
9	N_2O	MacFarling Meure et al., 2006	Law Dome (A)

Table 2. Data used for the time-lines GHG concentration reconstructions. The following information is given in the columns from left to right: series (name of the series used in the time-line), GHG, reference, ice-core (name of ice-core and area where A=Antarctica and G=Greenland)

3.2.1 CO_2

Figure 8 contains three different reconstructions of CO_2 concentrations. Table 2 shows the reconstructions were based on different ice-cores, all originating from Antarctica. The aging of the ice-cores was done in different ways. For series 1 the concentration of the trace gases CH_4 and CO_2 were used. For series 2 the ice-cores were aged using the trace gas CH_4 and the identification of global signals like volcanic eruptions and the end of Younger Dryas (Schwander et al., 2001). Aging of series 3 was done by three different processes, namely counting the annual layers in isotope ratio, ice electroconductivity measurements and hydrogen peroxide concentrations (Etheridge et al., 1996). So, there are some differences between the ice-cores and the aging methods which explain the little differences between the reconstructions observable in the time-line. The overall trend is, however, very similar for all three reconstructions.

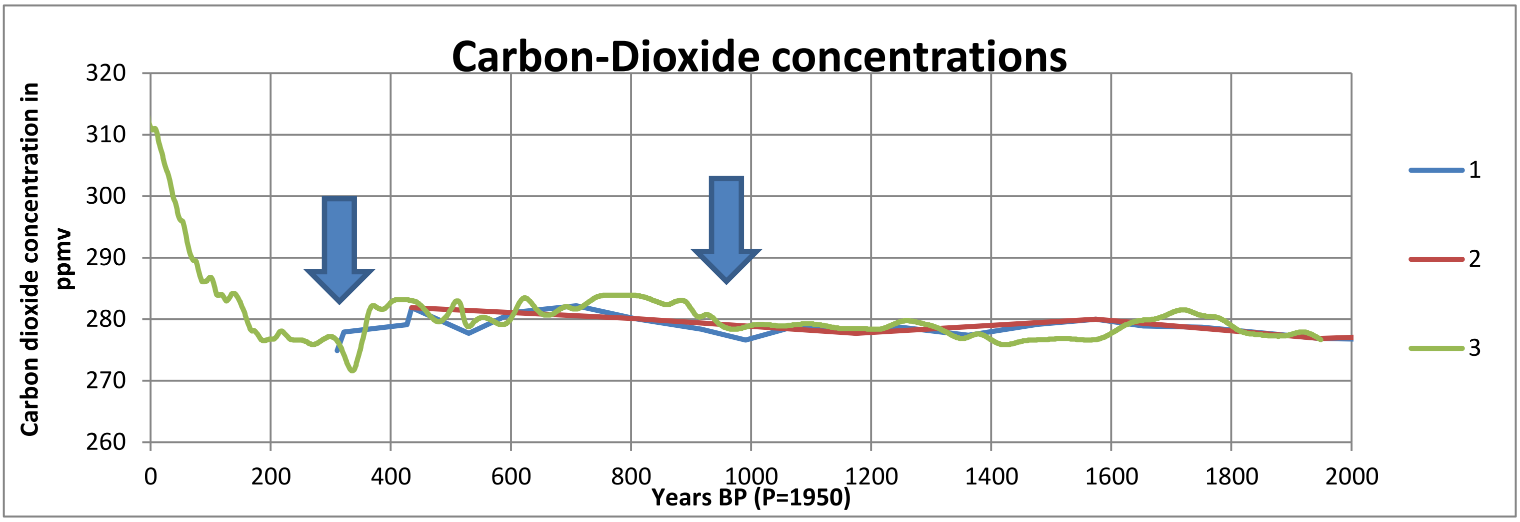


Figure 8. Carbon-dioxide concentrations. Series 1 from Monnin et al. (2004). Series 2 from Flückinger et al. (2002). Series 3 from Macfarling Meure et al. (2006).

The same periods as in figure 7 were marked with an arrow. For the CO_2 reconstructions there is no peak observable around 1000BP. Just after this period, around 9000BP concentrations are increasing. At 300BP there is a low-point for series 3 and 1, series 2 stops earlier.

3.2.2 CH_4

Figure 9 shows the time-line for CH_4 concentration reconstructions. Table 2 shows that ice-cores for series 4 and 6 were from Antarctica and for series 5 from Greenland. Series 4 was aged using concentrations of the trace gas CH_4 by isotope composition measurements and comparison with gas concentrations trapped in the ice (Huber et al., 2006). Series 5 and 6 were from the same studies as series 2 and 3 respectively in figure 8, so aging was done in the same way.

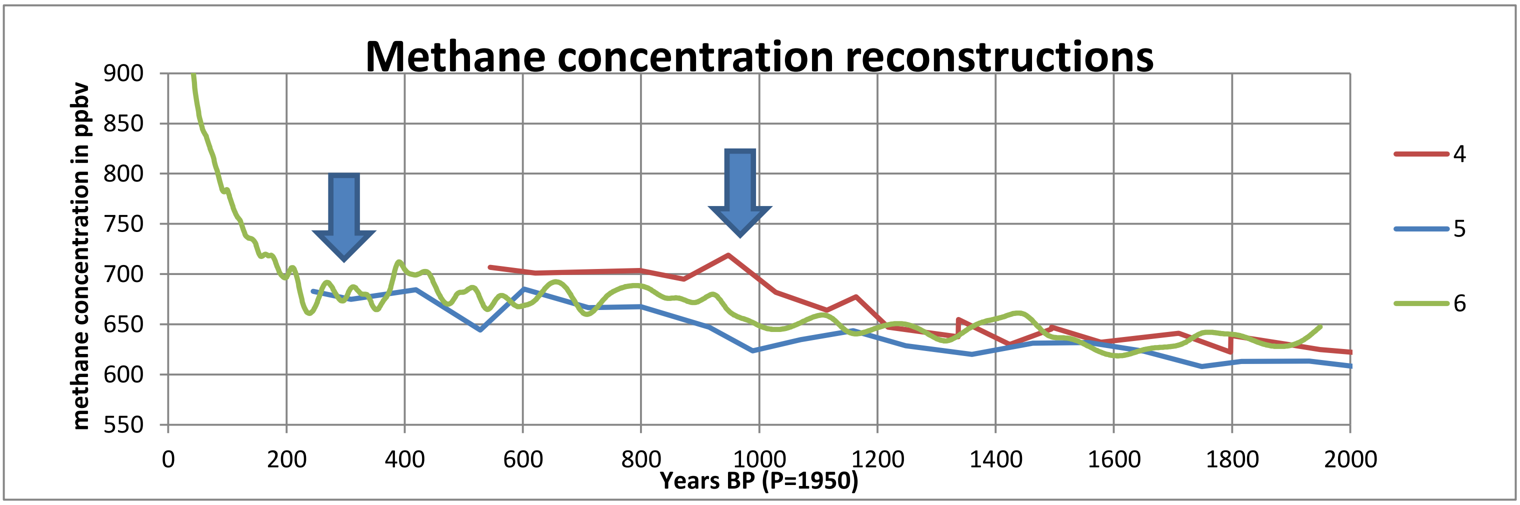


Figure 9. Methane concentration reconstructions. Series 4 from Schilt et al. (2010). Series 5 from Flückinger et al. (2002). Series 6 from MacFarling Meure et al. (2006).

Again, the moments 1000BP and 300BP were marked. All reconstructions for methane concentrations increase around 1000BP. Yet, at 300BP concentrations are quite stable and do not show a low-point.

3.2.3 N_2O

Reconstructions for N_2O concentrations are shown in figure 10. The data originate from the same studies as for the methane reconstructions in figure 9, so the time-line contains again reconstructions from Greenland and Antarctica based on the same aging methods.

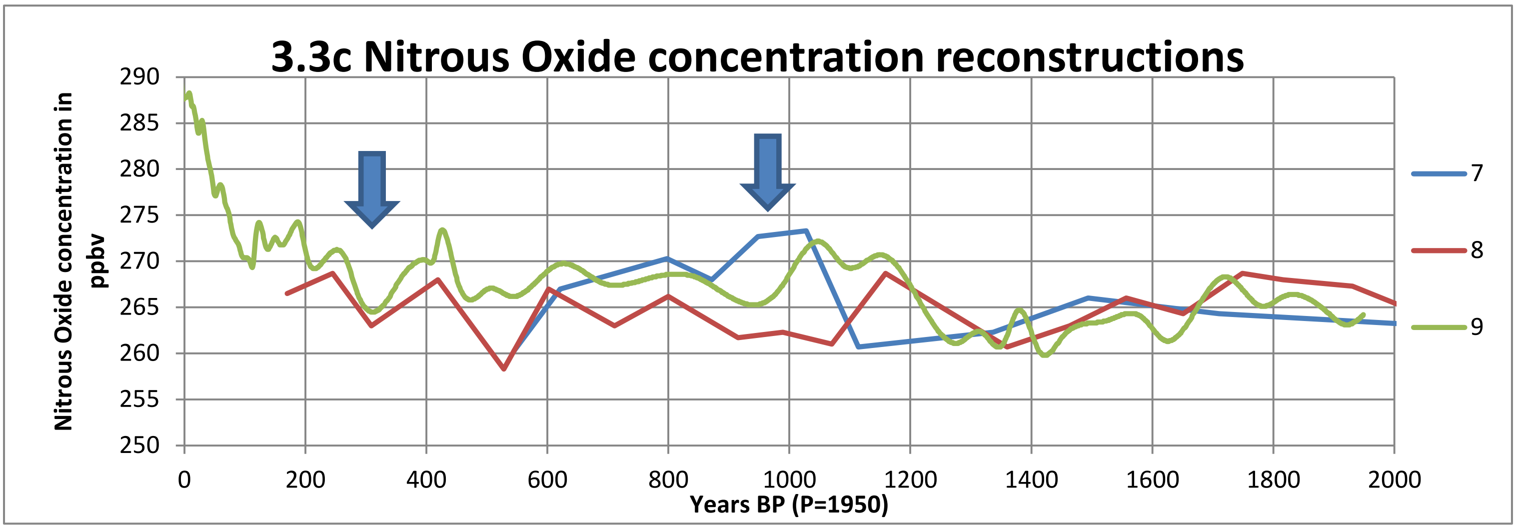


Figure 10. Nitrous-oxide concentration reconstructions. Series 7 from Schilt et al. (2010). Series 8 from Flückinger et al. (2006). Series 9 from MacFarling Meure et al. (2006).

Around 1000BP concentrations are very high for nitrous oxide. Series 7 shows a peak, while series 8 and 9 peak earlier. At 300BP there is a low-point in nitrous oxide concentrations for series 8 and 9 (series 7 stops earlier), but this low-point was preceded by another low-point around 500BP.

3.2.4 GHG concentration observations

Section 3.2 showed the time-lines for CO_2, CH_4 and N_2O for the last 2000 years in order to compare the GHG reconstructions with periods of notable temperature fluctuations (1000BP and 300BP) found in section 3.1. The comparison resulted in the following observations:

- There was no peak in CO_2 concentration reconstructions at 1000BP. A little peak was observed later, around 9000BP. At 300BP there is a low-point in CO_2 concentrations.
- Around 1000BP there is a peak in CH_4 concentrations. There was no low-point at 300BP.
- Two out of three reconstructions of N_2O concentrations showed a peak around 1000BP. There was a low-point at 300BP, and there is also another, low-point at 500BP with a greater magnitude.

At 1000BP there were peaks in CH_4 and N_2O concentrations. This could indicate a high rate of land-conversion from forestry to pasture, since this change in land-use releases great amounts of CH_4 and N_2O (Kirschbaum et al., 2013).At 300BP there is a low-point for CO_2 reconstructions and N_2O reconstructions. This could indicate a lower level of human activity which enables regrowth of forests in Europe and thereby the uptake of carbon (Kaplan et al., 2011).

In the next chapter these observations will be compared with reconstruction for human activity, in order to detect any possible connections between human activity and climate change.

3.3 Reconstruction for human-activity

In this chapter I present three reconstructions for human activity in Europe for the period 2000-0BP; one for human population (figure 11), one for total cropland (figure 12) and one for total pasture (figure 13). The data I used were handed to me by Klein Goldewijk, developer of the HYDE database. Again the periods derived from the temperature reconstructions (1000BP and 300BP) were marked in the time-lines in order to compare human activity with the observations made concerning temperature and GHG concentrations. The aim of the comparison is investigate if there are any connections between human activity and climate change. An important note hereby is that the total release of GHG emission by human activity during the pre-industrial period is determined by the rate of clearance, rather than the total clearance (Ruddiman & Ellis, 2009). When comparing population and land-use reconstructions with temperature and GHG concentration reconstructions, the slope in the graph of human activity should be used instead of the total amount of human activity.

3.3.1 Population

Figure 11 shows the reconstruction for the population of Europe during 2000-0BP. The reconstructions were made by Klein Goldewijk, using several important sources for global population studies which cover the Holocene (Klein Goldewijk et al., 2011).

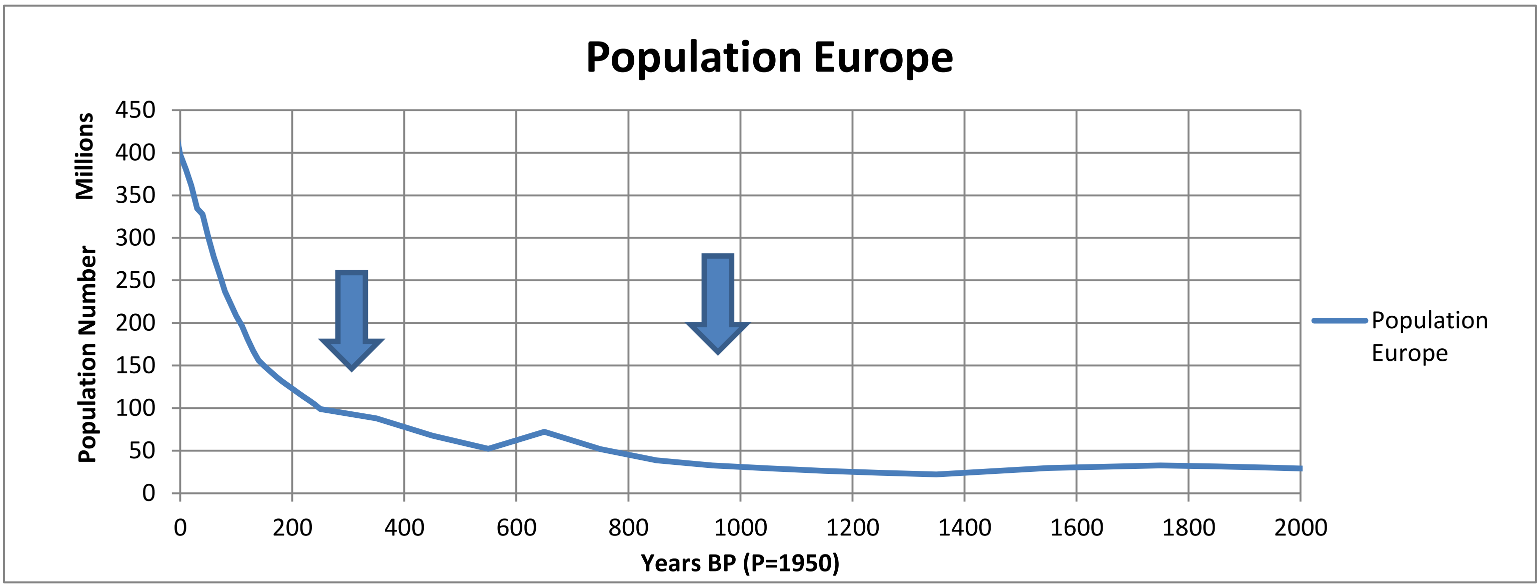


Figure 11. Reconstruction population numbers. Reconstructed population numbers for Europe for 2000-0BP, expressed in millions. Data from Klein Goldewijk (n.p.)

The reconstruction for human population shows a population growth around 1000BP. The growth is, however, not very strong compared to the period around 700BP. Around 300BP there is again an increased population growth.

3.3.2 Cropland

Figure 12 shows the cropland reconstruction of Europe during 2000-0BP. Again the reconstruction was made by Klein Goldewijk. This was done, using a calculation for the per capita use of cropland, linked to the total population (Klein Goldewijk et al., 2011).

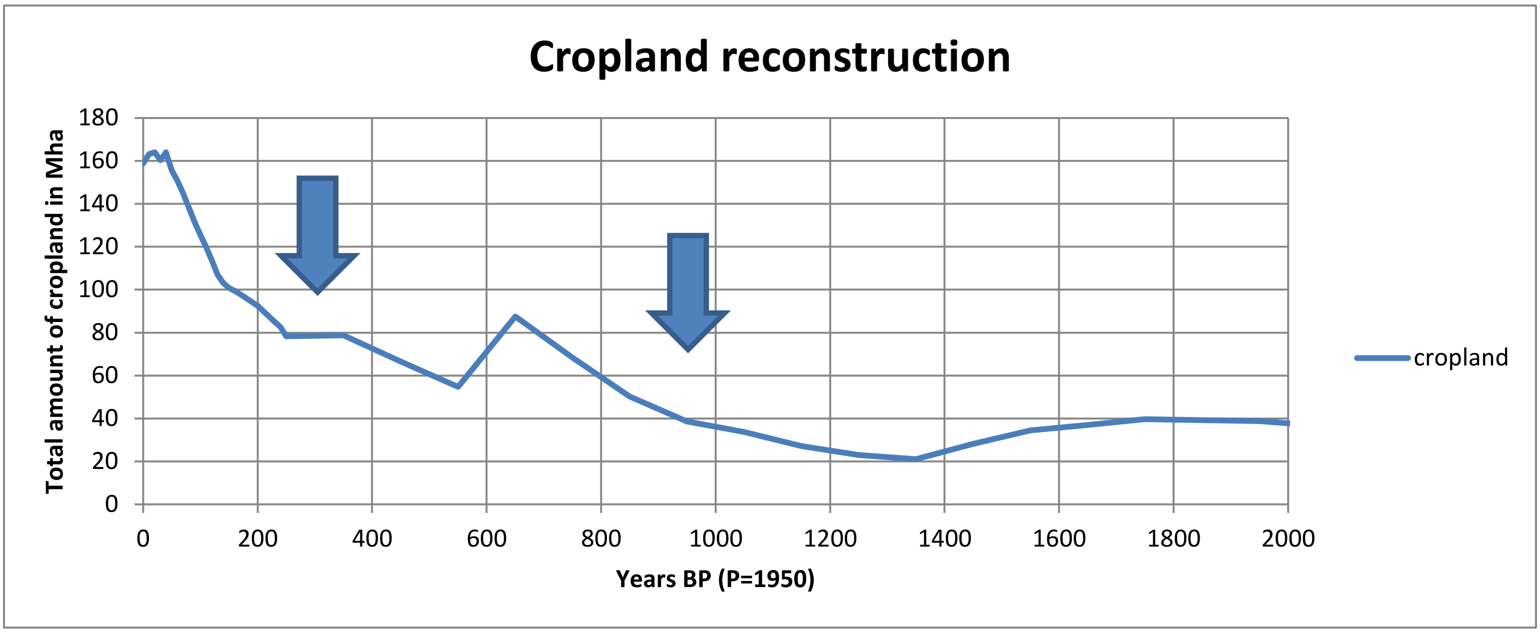


Figure 12. Cropland reconstruction. Total amount of cropland in Europe in 2000-0BP, expressed in Mha. Data from Klein Goldewijk (n.p.)

Figure 12 shows a growth of the total amount of cropland around 1000BP. The growth is quite strong, but it becomes stronger after 1000BP, reaching its maximum around 700BP. At 300BP there is a short period of a constant amount of cropland.

3.3.3 Pasture

In figure 13 the reconstruction of the total amount of pasture is shown. The reconstruction from Klein Goldewijk is made following the similar method as for the cropland reconstruction.

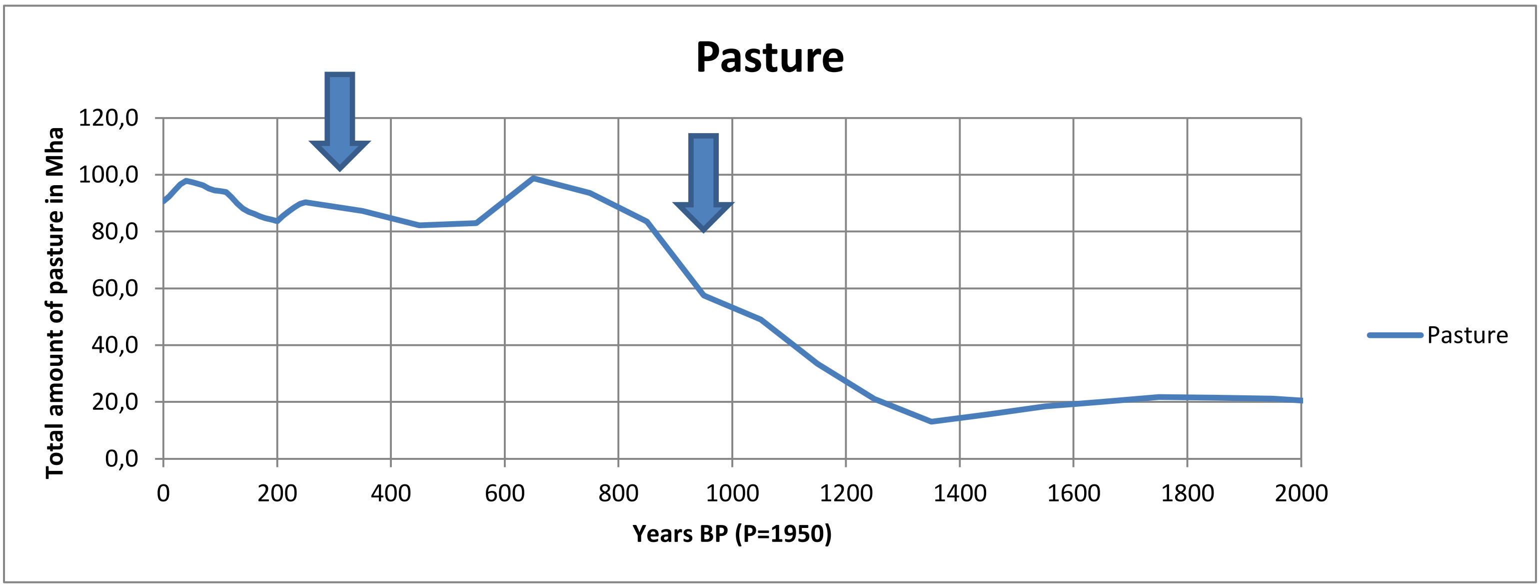


Figure 13. Pasture reconstruction. Total amount of pasture in Europe in 2000-0BP, expressed in Mha. Data from Klein Goldewijk (n.p.)

The reconstruction for pasture shows a very strong growth around 1000BP. At 300BP there is a small increase in total amount of pasture.

3.3.4 Observations human activity

This chapter showed the reconstructions for human activity, and analyzed the reconstructions for 1000BP and 300BP in order to compare human activities with the reconstructions for temperature and GHG concentrations. This comparison resulted in the following observations:

- At 1000BP there is an increase in all reconstructions for human activity, but only the reconstruction for pasture shows a strong increase.
- At 300BP there is a slight increase in human population and pasture. Cropland is stable at 300BP

The strong increase in pasture at 1000BP indicates a possible connection between climate change and human activity, since in this period there were also high concentrations detected of CH_4 and N_2O.

There is no decline in human activity observed at 300BP, which makes the potential for a connection between human activity and climate change weak.

Discussion

In this chapter I will place the findings obtained from the results in context of historical events in Europe during 1000BP and 300BP. I do this in order to get more insight in the human activities during these periods. Thereby it is an evaluation of the reconstructions for human activities, approached from another discipline. I will also evaluate the detections of temperature fluctuations and the potential connections between climate change and human activity by a comparison with results of other studies concerning climate reconstructions and anthropogenic influences on climate change.

MWP and LIA

This study tries to give an overview of climate change in Europe during the Holocene and detect any observable climate fluctuations present in the greatest part of the reconstructions which have a potential to be influenced by human activities. The most notable period meeting these criteria is the peak in temperature and methane and nitrous oxide concentrations around 1000BP and the drop of temperatures and greenhouse gases around 300BP. The latter period is less clear to detect in the greenhouse gas concentrations, but still concentrations are lower than in the period before for methane and nitrous oxide. These periods of temperature increase and decrease are detected for the same periods in a great amount of studies (Axford et al., 2009; Huang et al., 2008; Mangini et al., 2005; Niemann et al., 2011). These periods are this known in literature that the definitions Medieval Warm Period (MWP) and Little Ice Age (LIA) are developed for the warm period around 1000BP and the cold period around 300BP respectively. Due to the great differences in local, regional and global climate reconstructions the use of these terms is, however, limited (Jones & Mann, 2004). Reconstructions differ this much that no detection of a MWP or LIA is detected in a great number of scientific papers (D'Andrea et al., 2012; Jensen & Vorren, 2008). This is also the case for several reconstructions in this study, for instance the temperature reconstructions inferred from tree-rings. Indications for the MWP and LIA are detected in the local and hemispheric reconstructions, while these periods are barely notable in the regional reconstructions. A recent study reconstructed past temperatures from seven continental-scale regions during the past one or two millennia, and found little evidence for the existence of globally coinciding temperature shifts (Ahmed et al., 2013). Still, global uniformity in climate change isn't very probable, since climate change is a process which has different consequences for different places (Beier et al., 2012). Therefore it is difficult to determine whether MWP and LIA were periods of global climate change and should be used as general terms in climate research. For answering this question the number of reconstructions used in research is very important. This study uses several reconstructions, but, I found myriad of other studies giving reconstructions I couldn't use because the raw data weren't openly available (Antonsson & Seppä, 2007; De Vleeschouwer et al., 2009; Heikkilä & Seppä, 2003; Heikkilä & Seppä, 2010; Jensen & Vorren, 2008; Litt et al., 2009). Further research in this subject might want to collect these data in order to give a more complete overview of the climate in Europe during the Holocene.

Anthropogenic and natural influences

Aim of this study is to give more insight in human-climate relations before the Industrial Revolution. Findings are increases of greenhouse gas concentrations during the warmer periods and strong growth of population and agricultural lands around 1000BP. This indicates a potential relation between human activity and climate, but it is hard to say what this relation precisely is. Researchers give different explanations for the causes of these climate fluctuations. A study examining the Holocene climate variability, for instance, gives possible explanations for the temperature fluctuations in the period 12000-1000BP and 600-150BP (Mayewski et al., 2004). According to this study there is a slight increase in CO_2 concentrations during this period, and also changes in solar output are detected. Concentrations of other greenhouse gases are not mentioned for this period. In the period 600-150BP they mention a drop in CO_2 and a rise in CH_4 concentrations, which is also seen in the time-lines in this study. Mayewski et al. (2004) write that the major cause of the temperature fluctuation in this period is the solar variability. This underscores the low potential for anthropogenic causes for climate change in this period I found (300BP). Ljungvist (2010) reconstructed the temperature of the Northern Hemisphere for the last two millennia and his data are used in this study. He does recognize the periods of climate fluctuations (LIA and MWP) I also saw in his results. In his discussion for the potential causes for these fluctuations he, however, doesn't speak of greenhouse gas concentrations or anthropogenic influences at all. An explanation of these temperature fluctuations given in this study is the occurrence of quasi-millennial climatic cycles in the temperature reconstruction which probably represent cyclical Bond cycles (Ljungqvist, 2010). The main cause for the temperature fluctuations during the Holocene is therefore the variation in solar irradiance. A study by Büntgen et al. (2013), also used for the time-lines in this study, investigates the climate fluctuation during the Holocene for Eastern Europe. Although they link the climate fluctuations with human activity, these human activities aren't seen as a cause, but as a consequence of the climate in Europe. I would dedicate this difference in results not to the inaccuracy of one of the studies, but rather to the different approach. The aim of my study is to investigate potential influences of human activity on climate change during the pre-industrial period. Aim of the study by Büntgen et al. is put into words in the following sentence cited as in their report: '*We reconstruct variations in Eastern European springtime temperature over the last millennium, discuss our findings in light of climate forcing and documentary evidence, and place the unique reconstruction in an continental-wide context*'. This approach does show, however, the importance of placing the climate reconstructions into context of the complete history of Europe in order to determine where natural or anthropogenic factors can be seen as causes or consequences. The next section will discuss this subject further.

Historical context

For more insight in the precise human activities and their possible consequences for climate change, it is useful to get more insight in the historical context of Europe. In social sciences there has been done a lot of research in historical populations and economic development (Fossier, 2004; Verhulst, 2002). Information from social sciences can underscore findings based on quantitative reconstructions and give more understanding of potential impacts of human activities on climate change. For instance, Fossier (2004) writes about the eleventh century as the beginning of 'an age of great progress' wherein a general increase of population took place. This period was preceded by the Carolingian period (early eight century until the end of the ninth century (Fouracre, 2005)) where most of the landscape was a natural landscape, consisting of woods (Verhulst, 2002). The increase of population during the eleventh century was reflected in the rapid expansion of villages and colonization of, previously uncultivated, land. In this period customs concerning land-use underwent some changes, with great consequences. First of all, the real estate market became very lively and infrastructure developed. This all indicates the beginning of a period of great developments. The year 1000AD (950BP) is thereby seen by many as the take-off of Europe's agriculture (Fouracre, 2005). Land was mainly used for the production of grain, while waste-land was used for grazing of livestock and gathering for periods when crop fields didn't produces enough.

This is all useful information when investigating interactions between human and climate and therefore not only research by physicists, geologists and biologists should be used in this field of research. Also social sciences as archeology and history can contribute to this subject, as these sciences have a much better overview of the anthropogenic activities during the late Holocene. For further research I would, therefore, recommend a cooperation of climatic scientists and historians.

Conclusion

Now that I answered the research questions and evaluated these results, I shall answer the research question I formulated in the introduction, namely:

Are there any connections observable between climate change and human activity in Europe in 11500-100BP and what are, according to the scientific literature, the greatest causes for these connections?

The results show possible connections during the late Holocene, around 1000BP and 300BP. Around 1000BP a temperature increase is observed in reconstructions inferred from tree-rings and multi-proxy reconstructions. This increase in temperature coincides with an increase in concentrations of CH_4 and N_2O, and a strong growth of pasture. There is also growth of croplands and population during this period, but less strong than for pasture. These results indicate a possible connection between human activities and climate change.

At 300BP a temperature low-point is observed in reconstructions inferred from tree-rings and multi-proxy reconstructions. This coincides with a low-point in the concentration of CO_2. The concentrations of CH_4 do not show a low-point, while concentrations of N_2O are low at 300BP, but show a stronger low-point at 500BP. At 300BP there is a small increase in population and pasture, there is no growth in croplands. There is, however, no decrease in human activities noticed in the reconstructions, so this makes the potential for a connection between human activities and climate change at 300BP weaker.

References

Written references

Ahmed, M., K.J. Anchukaitis, A. Asrat et al. (2013), Continental-scale temperature variability during the past two millennia. Nature Geoscience 6(5), pp.339-346.

Antonsson, K. & H. Seppä. (2007), Holocene temperatures in Bohuslän, southwest Sweden: A quantitative reconstruction from fossil pollen data. Boreas 36(4), pp.400-410.

Axford, Y., Á Geirsdóttir, G.H. Miller et al. (2009), Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. Journal of Paleolimnology 41(1), pp.7-24.

Beer, J., W. Mende & R. Stellmacher. (2000), The role of the sun in climate forcing. Quaternary Science Reviews 19(1), pp.403-415.

Beier, C.M., S.A. Signell, A. Luttman et al. (2012), High-resolution climate change mapping with gridded historical climate products. Landscape Ecology 27(3), pp.327-342.

Betts, R.A. (2001), Biogeophysical impacts of land use on present-day climate: Near-surface temperature change and radiative forcing. Atmospheric Science Letters 2(1-4), pp.39-51.

Bjune, A., H. Seppä & H. Birks. (2009), Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. Journal of Paleolimnology 41(1), pp.43-56.

Bjune, A.E. & H.J.B. Birks. (2008), Holocene vegetation dynamics and inferred climate changes at Svanåvatnet, Mo i Rana, northern Norway. Boreas 37(1), pp.146-156.

Bond, G., B. Kromer, J. Beer et al. (2001), Persistent solar influence on North Atlantic climate during the Holocene. Science 294(5549), pp.2130-2136.

Bradley, R.S. (2000), Past global changes and their significance for the future. Quaternary Science Reviews 19(1–5), pp.391-402.

Brown, A.G., S. Tooth, R.C. Chiverrell et al. (2013), The Anthropocene: is there a geomorphological case? Earth Surface Processes and Landforms 38(4), pp.431-434.

Brown, K.J., H. Seppä, G. Schoups et al. (2012), A spatio-temporal reconstruction of holocene temperature change in southern Scandinavia. Holocene 22(2), pp.165-177.

Büntgen, U., T. Kyncl, C. Ginzler et al. (2013), Filling the Eastern European gap in millennium-long temperature reconstructions. Proceedings of the National Academy of Sciences 110(5), pp.1773-1778.

Büntgen, U., W. Tegel, K. Nicolussi et al. (2011), 2500 years of European climate variability and human susceptibility. Science 331(6017), pp.578-582.

Chiarelli, B. & S. Magherini. (2011), Humankind impact on the Earth Ecosystems. Human Evolution 26(1-2), pp.13-23.

D'Andrea, W.J., D.A. Vaillencourt, N.L. Balascio et al. (2012), Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard. Geology 40(11), pp.1007-1010.

D'Arrigo, R., R. Wilson & G. Jacoby. (2006), On the long-term context for late twentieth century warming. Journal of Geophysical Research 111(D3), pp.D03103.

Ellis, E.C., J.O. Kaplan, D.Q. Fuller et al. (2013), Used planet: A global history. Proceedings of the National Academy of Sciences of the United States of America 110(20), pp.7978-7985.

Etheridge, D., L. Steele, R. Langenfelds et al. (1996), Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn. Journal of Geophysical Research: Atmospheres (1984–2012) 101(D2), pp.4115-4128.

Fossier, R. (2004). The New Cambridge Medieval History. Cambridge: Cambridge University Press.

Fouracre, P., ed. (2005). The New Cambridge Medieval History. Cambridge: Cambridge University Press.

Gale, S.J. & P.G. Hoare. (2012), The stratigraphic status of the Anthropocene. Holocene 22(12), pp.1491-1494.

Goldewijk, K.K., A. Beusen & P. Janssen. (2010), Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. The Holocene 20(4), pp.565-573.

Goosse, H., H. Renssen, A. Timmermann et al. (2006), Using paleoclimate proxy-data to select optimal realisations in an ensemble of simulations of the climate of the past millennium. Climate Dynamics 27(2-3), pp.165-184.

Grudd, H. (2008), Torneträsk tree-ring width and density AD 500–2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers. Climate Dynamics 31(7-8), pp.843-857.

Harvey, L. D. D. (2000). Global warmingPrentice Hall.

Hegerl, G.C., T.J. Crowley, M. Allen et al. (2007), Detection of human influence on a new, validated 1500-year temperature reconstruction. Journal of Climate 20(4), pp.650-666.

Huang, S., H. Pollack & P. Shen. (2008), A late Quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record. Geophysical Research Letters 35(13), pp.L13703.

Huber, C., M. Leuenberger, R. Spahni et al. (2006), Isotope calibrated Greenland temperature record over Marine Isotope Stage 3 and its relation to CH< sub> 4</sub>. Earth and Planetary Science Letters 243(3), pp.504-519.

Jensen, C. & K.-. Vorren. (2008), Holocene vegetation and climate dynamics of the boreal alpine ecotone of northwestern Fennoscandia. Journal of Quaternary Science 23(8), pp.719-743.

Jones, P. & M. Mann. (2004), Climate over past millennia. Reviews of Geophysics 42(2), pp.RG2002.

Kaplan, J.O., K.M. Krumhardt, E.C. Ellis et al. (2011), Holocene carbon emissions as a result of anthropogenic land cover change. The Holocene 21(5), pp.775-791.

Kaplan, J.O., K.M. Krumhardt & N. Zimmermann. (2009), The prehistoric and preindustrial deforestation of Europe. Quaternary Science Reviews 28(27), pp.3016-3034.

Kirschbaum, M.U.F., S. Saggar, K.R. Tate et al. (2013), Quantifying the climate-change consequences of shifting land use between forest and agriculture. Science of the Total Environment

Klein Goldewijk, K., A. Beusen, G. Van Drecht et al. (2011), The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Global Ecology and Biogeography 20(1), pp.73-86.

Larocque-Tobler, I., M. Grosjean, O. Heiri et al. (2009), High-resolution chironomid-inferred temperature history since ad 1580 from varved Lake Silvaplana, Switzerland: comparison with local and regional reconstructions. The Holocene 19(8), pp.1201-1212.

Litt, T., C. Schoelzel, N. Kuehl et al. (2009), Vegetation and climate history in the Westeifel Volcanic Field (Germany) during the past 11 000 years based on annually laminated lacustrine maar sediments. Boreas 38(4), pp.679-690.

Ljungqvist, F.C. (2010), A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. Geografiska Annaler: Series A, Physical Geography 92(3), pp.339-351.

Loehle, C. (2004), Climate change: detection and attribution of trends from long-term geologic data. Ecological Modelling 171(4), pp.433-450.

Magny, M., O. Peyron, E. Gauthier et al. (2009), Quantitative reconstruction of climatic variations during the Bronze and early Iron ages based on pollen and lake-level data in the NW Alps, France. Quaternary International 200, pp.102-110.

Mangini, A., C. Spötl & P. Verdes. (2005), Reconstruction of temperature in the Central Alps during the past 2000 yr from a d18O stalagmite record. Earth and Planetary Science Letters 235(3-4), pp.741-751.

Mann, M.E., R.S. Bradley & M.K. Hughes. (1998), Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392(6678), pp.779-787.

Mann, M.E. & P.D. Jones. (2003), Global surface temperatures over the past two millennia. Geophysical Research Letters 30(15)

Marlon, J.R., P.J. Bartlein, A.-. Daniau et al. (2013), Global biomass burning: A synthesis and review of Holocene paleofire records and their controls. Quaternary Science Reviews 65, pp.5-25.

Mayewski, P.A., E.E. Rohling, J. Curt Stager et al. (2004), Holocene climate variability. Quaternary Research 62(3), pp.243-255.

Niemann, H., A. Stadnitskaia, S. Wirth et al. (2011), Bacterial GDGTs in Holocene sediments and catchment soils of a high-alpine lake: application of the MBT/CBT-paleothermometer. Climate of the Past Discussions 7, pp.3449-3488.

Ojala, A.E. (2012). Late quaternary climate history of northern europe. From the Earth's Core to Outer Spacepp. 199-218Springer.

Pittock, A. B. (2005). Climate change: Turning up the heatEarthscan.

Prokopenko, A.A., D.F. Williams, E.B. Karabanov et al. (2001), Continental response to Heinrich events and Bond cycles in sedimentary record of Lake Baikal, Siberia. Global and Planetary Change 28(1), pp.217-226.

Ruddiman, W.F. (2003), The anthropogenic greenhouse era began thousands of years ago. Climatic Change 61(3), pp.261-293.

Ruddiman, W.F. (2005), Cold climate during the closest Stage 11 analog to recent Millennia. Quaternary Science Reviews 24(10–11), pp.1111-1121.

Ruddiman, W.F. (2013), The Anthropocene. Annual Review of Earth and Planetary Sciences

Ruddiman, W.F. & E.C. Ellis. (2009), Effect of per-capita land use changes on Holocene forest clearance and CO2 emissions. Quaternary Science Reviews 28(27–28), pp.3011-3015.

Schimel, D.S., G.P. Asner & P. Moorcroft. (2013), Observing changing ecological diversity in the Anthropocene. Frontiers in Ecology and the Environment 11(3), pp.129-137.

Schwander, J., J. Jouzel, C.U. Hammer et al. (2001), A tentative chronology for the EPICA Dome Concordia ice core. Geophysical Research Letters 28(4), pp.4243-4246.

Seppä, H. & A. Poska. (2004), Holocene annual mean temperature changes in Estonia and their relationship to solar insolation and atmospheric circulation patterns. Quaternary Research 61(1), pp.22-31.

Sharma, S., J.J. Magnuson, G. Mendoza et al. (2013), Influences of local weather, large-scale climatic drivers, and the ca. 11 year solar cycle on lake ice breakup dates; 1905-2004. Climatic Change 118(3-4), pp.857-870.

Steffen, W., P.J. Crutzen & J.R. McNeill. (2007), The Anthropocene: Are humans now overwhelming the great forces of nature. Ambio 36(8), pp.614-621.

Velle, G., S.J. Brooks, H.J.B. Birks et al. (2005), Chironomids as a tool for inferring Holocene climate: an assessment based on six sites in southern Scandinavia. Quaternary Science Reviews 24(12–13), pp.1429-1462.

Verhulst, A. (2002). The Carolingian EconomyCambridge University Press.

Wolfe, A.P., W.O. Hobbs, H.H. Birks et al. (2013), Stratigraphic expressions of the Holocene-Anthropocene transition revealed in sediments from remote lakes. Earth-Science Reviews 116, pp.17-34.

Online references

NCDC (2012), Global surface temperature anomalies (online). (Cited at 26-4-2013) Available at the World Wide Web: http://www.ncdc.noaa.gov/cmb-faq/anomalies.php