

# Holocene Climate in Central and Southern Sweden

*Quantitative Reconstructions from Fossil Data*

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#### **Abstract**

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In quantitative palaeoecology modern species-environmental relationships can be statistically modelled, and recent development has made the calibration models more statistically robust. These models are used to transform fossil assemblages to quantitative estimates of past environmental conditions. The aim of this thesis is to infer Holocene temperatures from fossil pollen data sampled from lakes in central and southern Sweden. This reconstruction is done by using a north-European pollen-climate calibration model, which was extended with 37 modern pollen samples from the southern deciduous vegetation zone in Sweden within this project. A statistical method is used for deriving the pollen-climate calibration model, weighted averaging partial least square (WA-PLS) method. The long term trends in pollen inferred temperatures from this study reflect low, but rapidly rising temperatures in the early-Holocene, a trend that was temporarily interrupted by a cool period about 8500 cal yr BP, but continued after 8000 cal yr BP. A Holocene thermal maximum (HTM) with temperatures roughly 2°C higher than at present was recorded about 7000 cal yr BP and by 4000 cal yr BP pollen inferred temperatures starts to decline. In order to create a more comprehensive picture of past climate patterns in the investigated area inferred temperatures from this study are compared with independent palaeorecords, a stable oxygen isotope record for moisture variability (paper I) and chironomids for summer temperature (paper II). Taken all together, these records reflect a coherent Holocene climate pattern which also is supported by several studies from Scandinavia and the north Atlantic region. Pollen inferred temperatures and the moisture record are indicating markedly dry, continental climate conditions in southern Sweden during the HTM possibly as a result of reorganisations in regional atmosphere circulations. The local observations in this study of regional climate events, such as the cold period at about 8200 cal yr BP and the dry period at about 7000 to 4000 cal yr BP are of particular interest because they suggest that vegetation in the study region has responded sensitively both to long-term climatic trends and more transient climate events.

**Keywords:** pollen analysis, climate reconstructions, transfer functions, vegetation dynamics, Sweden

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*Till mamma och pappa, er kärlek till fjället blev också min. Tack!*



## List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

- I        Seppä, H., Hammarlund, D. and Antonsson, K. 2005: Low-frequency and high-frequency changes in temperature and effective humidity during the Holocene in south-central Sweden: implications for atmospheric and oceanic forcings of climate. *Climate Dynamics*, 25: 285-297.
- II       Antonsson, K., Brooks, S.J., Seppä, H., Telford, R.J. and Birks, H.J.B. 2006: Quantitative palaeotemperatures records inferred from fossil pollen and chironomid assemblages from Lake Giltjärnen, northern central Sweden. *Journal of Quaternary Science* (in press).
- III      Antonsson, K. and Seppä, H. Holocene temperature and forest dynamics in Bohuslän, SW Sweden. *Boreas* (submitted).
- IV      Antonsson, K. and Seppä, H. The warm and dry mid-Holocene climate in central Scandinavia: a possible analogue to anticyclonic conditions (manuscript).

Paper I: Karin Antonsson contributed with surface samples for the Swedish pollen-climate calibration set, sampling, processing and analysing of pollen samples.

Paper II: Karin Antonsson sampled, processed and analysed pollen from the sedimentcore. Shared writing, chironomid parts written by Stephen Brooks.

Paper III: Karin Antonsson sampled, processed and analysed pollen from the sedimentcore and wrote most of the manuscript.

Paper IV: Shared writing with Heikki Seppä.



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# Introduction

A fundamental definition of global climate could be the occurrence of solar energy which is primarily unevenly distributed over the globe both spatially and temporally and is therefore redistributed by the atmospheric circulation. Then, surface winds driven by atmosphere circulation generate a coupled ocean-atmosphere circulation pattern partly organized in large-scale variability modes with characteristic timescales (Rahmstorf and Sirocko, 2004).

Climate patterns vary on annual to million year timescales and they are mostly oscillatory, annual seasons or ice ages for example. The spatial feature of the climate deal with questions of for example, how increasing global temperatures of  $0.4^{\circ}\text{C}$  over the last 100 yrs have affected local temperatures for the same period or, how a  $2^{\circ}\text{C}$  temperature increase in Stockholm during 100 yrs could influence the global climate. Spatial and temporal climate patterns are often strongly connected as for example in the northward shift of the Intertropical Convergence Zone (ITCZ) boundary during northern hemisphere summer. This fundamental definition is a simplification; the complexity of the system with cryo- and biosphere interactions, internal and external forcings and feedback mechanisms requires an essay of its own. Global climate is essentially defined by physical and chemical laws of the atmosphere, and even though it operates in some kind of first order, large scale variability mode, it is highly unpredictable and chaotic (Rahmstorf and Sirocko, 2004).

“Increasing values of  $\text{CO}_2$  in the atmosphere due to burning of fossil fuels are raising atmospheric temperatures and hence also oceanic temperatures. Increased ocean temperatures in the mid-latitudes are causing a higher frequency of tropical storms”. This is often reported by news media, but is it true? Over the last 150 years, instrumental temperature records demonstrate a global rise by about  $0.6^{\circ}\text{C}$  (Jones *et al.*, 2001; IPCC, 2001) and this change has been shown to be unprecedented over the last 1000 years (Mann *et al.*, 1999; Crowley, 2000; Briffa *et al.*, 2001). During the same time (150 yr) greenhouse gases reached values higher than the last 420000 years (Petit *et al.*, 1999) and according to Barnett *et al.*, (1999) and Crowley (2000) there is evidence for an anthropogenic signal in the climate records for the last 35-50 years. These reported changes have led to a growing concern for our future environment among many climatologists and environmentalists, and within palaeo-science.

So, most probably, changing climate, present and future occur as a combination of underlying natural variations superimposed by human induced changes. Global temperatures are rising, but how can we distinguish between human and natural climate impact? What might climate changes herald for the future human societies? Answering those questions will only be successful when we have insight into the full range of natural variability of the climate system. That range is illustrated by the events of the past, and it is only by unravelling those events that we will be able to predict the future with confidence.

## Holocene climate studies

The elapsed time-span since the last glaciation ended comprises the Holocene epoch. This period provide continuous, well dated palaeoclimatic records for climatic variability during the last 10000 yrs. Holocene climate, especially the last 6000 yrs when orbitally driven external forcing was broadly similar to present day conditions have been considered an ideal analogue to modern and near future climate. Initially, Holocene climate was regarded as relatively stable. Temperature records from the Greenland ice cores provided evidence for recurrent and abrupt climate variability during the last glacial period, followed by the Holocene without any major climate variability (Dansgaard *et al.*, 1993).

In the light of new information this view is being progressively replaced by data from a wider region, there are strong evidence of climate variability on all time scales. Long-term trends indicate an early- to mid-Holocene thermal maximum, with a cooling trend in the late-Holocene (deMenocal *et al.*, 2000; Haug *et al.*, 2001). Superimposed on this long-term trend are several distinct oscillations, or climatic cooling steps, which appear to be of widespread significance, the most dramatic of which occurred 8200 years ago, reflected in ice-core data (Alley *et al.*, 1997, 2001), sediments in the North Atlantic (Bond *et al.*, 1997, 2001; Bianchi and McCave, 1999). Holocene climate variations in Scandinavia are also indicated by fluctuations of glaciers (Karlén and Matthews, 1992), tree-lines (Kullman, 1999; Dahl and Nesje, 1996; Barnekow, 1999), and lacustrine sediments (Nesje and Dahl, 2001; Snowball *et al.*, 2002). Even during the second half of the Holocene, with modern boundary conditions, there is evidence for climate variability (Schulz and Paul, 2002). It is against this variability background that we must seek to identify and characterize the imprint of human-induced climate change. Quantitative reconstructions of Holocene climate variability may give a clearer understanding of important forcing mechanisms in the absence of large northern hemisphere ice sheets.

Instrumental climate records provide basic meteorological measurements, and information on modes of coupled air-sea interactions involved in climate

variability at inter-annual to century timescales, like North Atlantic Oscillation (NAO) and variants thereof. The modern expression of NAO is fairly well known but since the current records span a small fraction of the Holocene period, the perspective they provide is too short for a full understanding of the long term-trends in natural climate variability in the past and also for understanding long-term climate development in the future.

## Aims and study area

The study at hand is part of a project that aims to use modern numerical methods in order to quantitatively reconstruct Holocene climate from fossil pollen in Scandinavia. Scandinavia has clear-cut climatic and ecological boundaries and abundant sedimentary regions, an appropriate feature when using modern statistical methods for reconstruction of vegetation response to climate (Seppä *et al.*, 2004). The Scandinavian climate is also a component of the north Atlantic region, a key-region in the global climate (Hurrell and van Loon, 1997; Kerr, 1997).

Modern pollen data selected from lakes in closed, forested areas in central and southern Sweden (figure 1) provide an extension of a north-European pollen-climate calibration data set (Seppä *et al.*, 2004) by adding species types from the southern deciduous vegetation zone. The lakes from Sweden mostly fulfil the criteria listed by Seppä *et al.*, (2004). The range in temperatures will be extended with higher mean annual temperatures, and relative to previous temperature data the westerly extension will reflect a more maritime climate type (table 1). The application of the numerical method on fossil pollen data will contribute with quantitative Holocene temperature estimates from central and southern Sweden. Finally, by comparing pollen inferred temperatures with independent proxy records, e.g. chironomids (paper II) and oxygen isotopes (paper I), it is possible to create a more comprehensive picture of past climatological settings in Sweden and climate patterns in Scandinavia.



Figure 1. Map of Scandinavia, the study region encircled. Modern pollen data in the north European pollen-climate calibration model are indicated with dots, the Finnish-Estonian data set (Seppä *et al.*, 2004) and Swedish data set (unpublished data). The Holocene sampling sites are marked with stars. Lake Flarken was sampled and analysed for pollen by Digerfeldt (1977).

Table 1. Location details and present-day climate data from the Holocene sites. Vegetation zones are according to Sjörs (1999): BN=boreonemoral, N=neomoral, and SB=southern boreal.  $T_{ann}$ =Annual mean temperature 1961-1990,  $P_{ann}$ =Annual mean precipitation 1961-1990

| Site              | Location         | Elevation, m a.s.l. | Vegetation zone | $T_{ann}$ °C | $P_{ann}$ mm |
|-------------------|------------------|---------------------|-----------------|--------------|--------------|
| Lake Gilltjärnen  | 60°05'N, 15°50'E | 172                 | SB              | 4.6          | 611          |
| Lake Flarken      | 58°33'N, 13°40'E | 108                 | BN              | 5.9          | 556          |
| Lake Trehörningen | 58°33'N, 11°36'E | 112                 | BN/N            | 6.1          | 872          |

## Environmental response to climate variability

Terrestrial and marine systems respond to climate change through time and these responses are left in different geological proxy archives like fingerprints to investigate and to interpret past environments. Biotic response to a warming climate could for example be the initiation of a vegetation succession in a newly deglaciated landscape. An abiotic response to the same situation would be expressed as melting of ice caps and raising sea levels. Because both responses involve complex internal processes and feedback mechanisms, it is unwise to assume one simple, causal connection between climate variability and the responding environmental variable. Accordingly, current palaeoclimate studies usually use the multi-proxy approach (Lotter, 2003) in order to better understand the response mechanisms.

### Interpreting climate from fossil pollen assemblages

Pollen grains are produced in abundance by plants and dispersed in to the air, mixed in the atmosphere. Apart of the grains are deposited on surfaces such as lakes and bogs to become a well-preserved, integrated part of the sediments or deposits. Pollen rain over a given area is thought to be uniform due to mixing of the pollen grains by the atmospheric turbulence (Birks and Birks, 1980). Deposits may represent continuous sequences suitable for reconstructions of past vegetation dynamics, tree-lines or climate.

Representation of pollen taxa in samples is dependent on many factors for example, pollen production and pollination method, the abundance of parent plants, how pollen is dispersed and how it is preserved (Bennett and Willis, 2001). One of the key questions in palynology, which was raised by Hesselman (1916), is how to distinguish pollen from local habitats from regional ones in a sample. The source area of pollen is of importance in relation to the research question, for example; regional climate studies or local ecology studies. Recent developments of theory and models have lead to more quantitative understanding of the source area of pollen (Prentice, 1985, 1988; Sugita, 1993, 1994; Sugita *et al.*, 1999).

The reason why pollen analysis provides a means for reconstructing of past climates is that pollen assemblages at a particular time and space are a function of the regional flora and vegetation, and as the regional flora and vegetation are largely controlled by regional climate, there is some relation-

ship, even though a complex and indirect one, between pollen and climate (Birks, 1981). Since the relationship is not linear, fossil pollen has to be considered as indirect a proxy of past vegetation and climate (Birks and Birks, 2003).

So what climate variables control vegetation? According to Huntley (2001) climate influence on terrestrial plants is mainly expressed through three controlling variables; tolerance of low temperature extremes, requirements for accumulated warmth during the growing season and tolerance of moisture deficiency. According to Dahl (1998) important ecological and physiological variables influencing species distribution and abundance are mean temperature the warmest month or maximum temperature. Regional climate characteristics are of importance when considering pollen-climate relationships. This fundamental factor is pointed out by Faegri and Iversen, (1989), in that the climatic parameters mainly affecting vegetation in a particular region are usually the ones that are at minimum. In the cool and moist climate of north-western Europe, moisture is normally sufficiently provided, while temperatures are too low for optimal development of vegetation types with high temperature affinities. Accordingly, vegetation will respond sharply to temperature changes. Therefore, the major changes observed in a pollen diagram from Scandinavia are probably mainly related to temperature. However, many factors other than climate influence the distribution of plants as well, particularly edaphic, ecological, topographical, disturbance and historical factors.

## Fossil remains of chironomids as climate indicators

Chironomids are non-biting midges that have an aquatic larval stage and an aerial adult stage. Well-preserved head capsules of the larvae are found in lake sediments and are used to infer past environmental conditions (Lotter *et al.*, 1997; Brooks and Birks, 2001; Larocque *et al.*, 2001). Chironomid populations respond rapidly to climate and they occur in a wide variety of environmental conditions. Both air and water temperature has an important influence on many aspects of chironomid biology and ecology including egg-hatching, larval development time, time of adult emergence and swarming behaviour of adults (Brooks, 2003). Reconstructing Holocene air temperatures from chironomids has limitations because expected temperature changes are close to the error margins of the chironomid-temperature models. Additionally, the influence of the relatively small-scale temperatures changes during the Holocene on chironomid assemblages can be overwhelmed by the impact of changes on other environmental variables, especially pH, water-level and dissolved oxygen, and this may compromise chironomid-inferred temperature reconstructions (Brooks, 2003).

## Climate variability reflected in stable isotopes

Stable isotopes of  $^2\text{H}$  and  $^{18}\text{O}$  provide tracers for investigating present and past hydrology and hydroclimatology, and hydrological balance may respond sensitively to changes in net precipitation and humidity.

The method is based on isotopic fractionation in the global water cycle and isotopic labelling of water balance components (Edwards *et al.*, 2004). Isotopic fractionation is a temperature dependent reaction of water molecules that results in various relationships between heavy and light isotopes ( $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$ ) expressed by delta values ( $\delta$ ) of  $^2\text{H}$  and  $^{18}\text{O}$  (Leng, 2003). Distribution of isotopes in precipitation and surface waters is characterized by linear relationships between  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values over a broad range of spatial and temporal scales, usually expressed as Global Meteoric Water Line or Local Meteoric Water Line. The relationship is also reflected in the heavy-isotope enrichment of surface waters during evaporation and similar isotopic composition among neighbouring water bodies is expressed by Local Evaporation Lines (Edwards *et al.*, 2004).

In lake sediment studies, isotopes are extracted from either authigenic carbonates, or from biogenic material such as carbonate fossils, diatom silica or other organic material. Oxygen isotope ratios in lacustrine carbonates have been used to infer Holocene moisture variability (Seppä and Hammarlund, 2000; Shemesh *et al.*, 2001; Hammarlund *et al.*, 2002, 2003,).

## Reconstructing Holocene climate with quantitative methods

The recent transformation of Holocene palaeoclimatology from a descriptive subject into a quantitative science has been made possible by the development of new multivariate statistical techniques. Quantitative biological palaeoclimatology has applications in oceanography, ecology and limnology. In the transfer function approach modern species-environment relationships are numerically modelled and described (Birks, 1995). The transfer function is then used to transform fossil assemblages to quantitative estimates of past environmental conditions. Modern species data are derived from a calibration set and environmental data are derived from for example, a nearby meteorological station or from pH-measurements in lake water. This method has been used in order to reconstruct past environments (Brooks and Birks, 2000; Rosén *et al.*, 2001; Seppä and Birks, 2001; Seppä and Poska, 2004).

Traditionally, there are three main approaches in reconstructing quantitatively Holocene environments from fossil assemblages; indicator-species approach, assemblage or modern analogues approach, and multivariate numerical transfer function approach (Birks, 1981; Birks and Seppä, 2004). All three methods require information on modern environmental preferences and tolerances of the fossil taxa found. Assumption are made that modern observations and relationships can be used to model past conditions and that these relationships are persistent through time.

Fossil occurrence of a species with known modern environmental tolerances provides a basis for environmental reconstructions in the indicator-species approach. The earliest application of this approach was from macrofossils, long before pollen analysis came into use. Andersson (1902) used the value for the summer temperature at the present northern limit of *Corylus* to deduce the summer temperature at the limit of the same species during the Holocene thermal maximum and deduced a drop in summer temperature of 2.5°C since then, which was suggested to have caused the retreat from the limit of the maximum Holocene distribution. To give more precise information about the conditions at the limit of various distribution areas of thermophilous indicator species, Iversen (1944) illustrated the climatic demands of *Viscum*, *Hedera* and *Ilex* by combining mean temperature of the warmest month and mean temperature of the coldest month. Usually, the indicator-species approach assumes that correspondence in “species distribution-



selected climate variables” implies a causal relationship. According to Birks (1981) and Huntley (2001) it is unwise to assume such a straightforward relationship, without any further considerations of other climate factors or intra-specific competition.

The assemblage approach considers proportions of different fossil taxa in the whole assemblage. Inferences about past climate can be derived from different forest types, e.g. tundra vegetation, birch forest, pine forest, growing in present-day climate regions. A quantitative application of this approach is the modern analogue technique, where a modern-fossil analogue is recognized by a numerical procedure, and then a past environment is inferred by using the modern environment from the modern species as an analogue. One of the limitations in this method is the occurrence of multiple analogues; when fossil assemblage is similar to several modern samples that differ widely in climate affinity or a situation where no modern analogues are recognized.

The transfer function approach attempts to overcome some of the problems with the previous methods, for example the no-analogue situation. Multivariate numerical procedures for deriving and estimating modern species-climate transfer functions assume linear or non-linear species response to an environmental factor. The currently most simple and robust approach for inferring environmental conditions is weighted averaging (WA) and its variants e.g. weighted average partial least squares (WA-PLS) methods (ter Braak and Juggins, 1993; Birks, 2003). The temperature reconstructions in this study are based on a transfer function derived from WA-PLS, which assumes uni-modal species response to an environmental variable (Birks, 1995). WA-PLS usually produce lower errors and bias than WA, as a disadvantage a relatively complicated model-selection procedure can be mentioned.

One requirement for quantitative reconstructions is that the prediction errors could be estimated. The reliability of the reconstructed environmental values usually varies from sample to sample, depending on for example composition and preservation. This is why sample-specific prediction errors are needed (Birks, 2003).

Species-environment relationships for reconstructions of the past have been used, on continental scales (Cheddadi *et al.*, 1997; Tarasov *et al.*, 1999) and site-specific (Brooks and Birks, 2000; Rosén *et al.*, 2001; Heikkilä and Seppä, 2003). Continental-scale studies are based on large calibration sets, usually with little or no control of sampling methods and areas, and this is often a limitation for a good result, low quality and inconsistencies in the data sets (Birks, 1995, 2003). In order to improve the performance of the models regionally restricted calibration sets have become more common. Regional calibration models are often carefully designed, and they are more standardized than the continental-scale calibration set. Another limitation to consider is that the range of inferred environmental change is close to the

sample-specific errors of prediction for individual fossil taxa, this is especially common during the Holocene. Statistical biases like distortions at the ends of the environmental gradient, and when reducing this problem creating overestimations at low values and underestimations at high values is yet another problem (Birks, 2003).

Recently, a pollen-climate calibration model was developed to reconstruct quantitatively Holocene annual mean temperatures in northern Europe (Seppä *et al.*, 2004). Model input is derived from modern pollen data-set from Finland, Estonia (Seppä *et al.*, 2004), southern and central Sweden (unpublished data). The modern pollen data range from the northern boreal forest region to the southern deciduous forest region. This north European pollen-climate response model or versions thereof, has been in use to reconstruct Holocene temperature and climate patterns in the northern boreal region (Seppä and Birks, 2001, 2002), in the southern boreal region (Heikkilä and Seppä, 2003).

## Main results and discussion

### Extension of a north-European pollen-climate calibration dataset

The extended pollen-climate training set has provided 37 new samples from central and southern Sweden (figure 1), and the annual mean temperature ( $T_{\text{ann}}$ ) range covered has been extended by 1.6°C compared to the Finnish-Estonian training set (table 2). The performance of the model was assessed by leave-one-out-cross-validation (ter Braak and Juggins, 1993; Birks, 1995). A two-component WA-PLS model was selected on the basis of the low root mean square error of prediction (RMSEP) and high coefficient of determination ( $r^2$ ) between observed and predicted values of annual mean temperature. One effect from extending the gradient length in the data set is that RMSEP becomes larger; this is probably why RMSEP is increased by 0.6°C, after adding the Swedish data set to the north-European model. However, by calculating RMSEP as percentages of the gradient length (table 2), the error has actually decreased and accordingly the model-statistics have improved by adding the Swedish data set. The coefficient of determination ( $r^2$ ) in the new model is 0.88 (table 2), which is exactly the same as in the Finnish-Estonian model (Seppä *et al.*, 2004) and close to other pollen-based reconstructions of  $T_{\text{ann}}$  in Scandinavia (Birks and Seppä, 2004). At the moment, with the statistical methods available  $r^2$  values of about 0.8-0.9 are typical. This statistical high performance of the north-European calibration set is probably due to standardization of the surface sampling and pollen analytical procedures, careful selection of the surface sample sites, and simple patterns of vegetation zones and climate in the study region. Also, the predominantly natural forest composition in northern Europe is relatively higher than in southern and central Europe, which means that vegetation and hence modern pollen data in northern Europe is rather systematically related to its living environment.

Table 2. *Performance statistics of the north-European pollen-climate calibration models Finland-Estonian (Seppä et al., 2004) and Finland-Estonian-Swedish (unpublished data). The models were assessed by leave-one-out-cross-validation (ter Braak and Juggins, 1993) for a two-component WA-PLS model.*

|  | Finland-Estonia | Finland-Estonia-Sweden |
|--|-----------------|------------------------|
| Number of sites                              | 137             | 173                    |
| Temperature gradient                         | -4.7 to 5.5°C   | -4.1 to 7.1°C          |
| Temperature range                            | 10.2°C          | 11.2°C                 |
| Number of taxa                               | 102             | 104                    |
| $r^2$ predicted and modern                   | 0.88            | 0.88                   |
| temperature                                  |                 |                        |
| Root mean square error of prediction (RMSEP) | 0.89°C          | 0.95°C                 |
| RMSEP as % of the gradient length            | 8.8%            | 8.5%                   |
| Maximum bias                                 | 2.13°C          | 2.1°C                  |

## Holocene temperature trends inferred from fossil pollen

Based on the north European calibration model Holocene temperatures have been reconstructed from fossil pollen stratigraphies obtained from lake sediments at Giltjärnen, central Sweden, Flarken and Trehörningen, southern Sweden (figure 1). The pollen-inferred annual mean temperatures (PI-T) from the locations in central and southern Sweden show consistent Holocene temperatures trends (figure 2), with low, but rapidly increasing temperatures in the early-Holocene. Present-day temperatures are attained by 9500 cal yr BP in all sites. This warming trend is interrupted by a cold oscillation between 8300 and 7900 cal yr BP, immediately thereafter temperatures continuous to rise again. A Holocene thermal maximum (HTM) is reconstructed, with generally 2-2.5°C warmer than present day annual mean temperatures between 7000 and 4000 cal yr BP. This observed mid-Holocene pattern is supported by for example, pollen-based temperature reconstructions (Hammarlund *et al.*, 2003a; Bjune *et al.*, 2004, 2005; Seppä and Poska, 2004), tree line reconstructions (Barnekow, 1999; Hammarlund *et al.*, 2002), and reconstructions based on glacier-variability (Nesje *et al.*, 2001). At about 4000 cal yr BP, a gradual temperature decline and a generally more unstable climate is indicated that continues until the present.

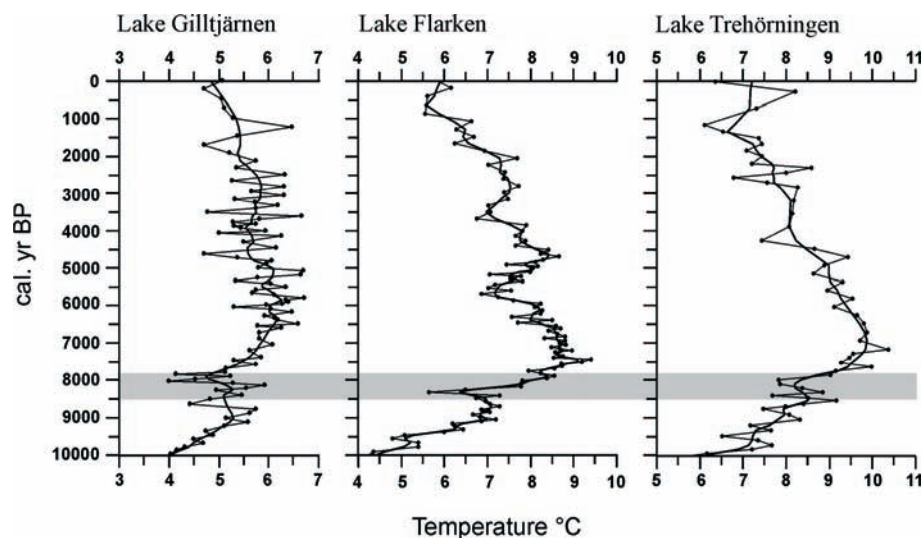


Figure 2. Pollen-inferred Holocene annual mean temperatures for central and southern Sweden. A LOESS smoother with a span of 0.10 fitted to highlight the long term trends. The grey bar highlights the cold event (8300-7900 cal yr BP).

The temperature records reflect present-day climate gradient, with  $T_{ann}$  values in Giltjärnen generally lower than in Lake Flarken and Lake Trehörningen, and values lower in Lake Flarken than in Lake Trehörningen. As for Lake Flarken and Lake Trehörningen, the overall similarity in inferred temperatures does not necessarily prove that the climate has been the main driver of the vegetation dynamics because due to the proximity of the sites the vegetation histories of the sites would be similar even if the post-glacial spread would have taken place in disequilibrium with climate. However, the generally consistent temperature patterns between the two sites strongly suggest that the regional climate controls of vegetation at both sites have been dominant over local controls. The role of such local features may be reflected as the minor differences and inconsistencies in the vegetation and climate records in the sites. It is necessary, however to stress that while climate is an important factor influencing vegetation structure, composition and plant migration, it is not the only one. Other important factors such as soil and light conditions, competition, fire history, human disturbance and grazing are integrated parts in vegetation dynamics.

## Comparing PI-T trends with stable isotope and chironomid records

Independent climate records obtained from oxygen isotopes in paper I and chironomids paper II reflect the overall consistency in the Holocene trends of  $T_{\text{ann}}$ , summer temperatures and moisture balance in this study.

The temperature and moisture record from southern Sweden can be related to enhanced zonal circulation and predominantly humid conditions during the early-Holocene, replaced by a stable period of warm and dry conditions during the HTM, at about 8000 to 4300 cal yr BP, probably due to the increasing influence of blocking anticyclone circulation during the summer. The abrupt end of the HTM at 4300 cal yr BP in south-central Sweden agrees in general with other climate reconstructions from Boreal regions in Europe. Numerous proxy records from the eastern seaboard of the North Atlantic suggest a progressive shift towards cooler and/or wetter climatic conditions, initiated slightly before or around 4000 cal yr BP. These include records of peat humification (Granlund, 1932; Gunnarsson *et al.*, 2003), lake-level variations (Digerfeldt, 1988; Plunkett *et al.*, 2004), mountain glacier status (Dahl and Nesje, 1996; Nesje *et al.*, 2001), speleothem  $\delta^{18}\text{O}$  composition (Lauritzen and Lundberg, 1999; McDermott *et al.*, 2001), alpine tree-limit fluctuations (Kullman and Kjällgren, 2000), and quantitative temperature variations inferred from biological transfer functions (Heikkilä and Seppä, 2003; Seppä and Poska, 2004).

Chironomids are in general useful indicators of summer temperatures unless the lake is receiving melt-water from glaciers or snow beds (Brooks, 2006). Accordingly, one advantage of combining PI-T with chironomid-inferred July mean temperature (CI-T) is the assessment of past seasonal climate patterns. The seasonal patterns in Gylltjärnen are similar in early to mid Holocene even though CI-T does not indicate maximum temperatures during mid-Holocene. The expression of a temperature peaks during mid-Holocene in chironomid records is somewhat irregular (Brooks, 2006; Velle *et al.*, 2005). July temperature at the closest meteorological station from Gylltjärnen is 15.8°C, which means that CI-T underestimates the modern observed temperatures by about 3.0°C, well outside the error of 1°C for the chironomid-temperature model. Accordingly, it is possible that the CI-T are too low during the entire period.

The only major offset from the coherent climate trends is in the chironomid record, which starts to deviate from the trend of declining temperatures and increased moisture at about 4000 cal yr BP, and indicate raising summer temperatures instead. One limitation with chironomid-air temperature inference models as discussed by Brooks (2003, 2006), is that the influence of small-scale changes in Holocene temperatures on chironomids can be overwhelmed by impact of changes in other environmental variables such as pH, water-level and dissolved oxygen. This is why chironomid tempera-

ture records do not always agree with independent climate data, even in broad time-scale Holocene trend (Brooks, 2006). This deviating trend in CI-T in Giltjärnen can therefore be driven by pH change in the catchment and lake water due to the migration of *Picea* or due to increased palufication and peat formation instead of climate variability.

## A cold period 8300 to 7900 cal yr BP

A cold event around 8200 cal yr BP has been recorded in the north Atlantic and northern Europe (Alley *et al.*, 1997; Nesje and Dahl, 2001; Tinner and Lotter, 2001) and frequently discussed (Alley and Ágústssdóttir, 2005; Barber *et al.*, 1999; Clark *et al.*, 2001; Keigwin and Boyle, 2000).

In present material, this cooling event is observed in all pollen based  $T_{ann}$  reconstructions, and the event is particularly distinct in Lake Giltjärnen and Lake Flarken. Additionally, increased moist conditions in southern Sweden are reflected by the isotope record from Lake Igelsjön (Hammarlund *et al.*, 2003a). In the pollen records the cooling is associated with minor decrease in *Alnus*, *Corylus*, *Tilia* and *Ulmus* and a rise in *Pinus*. The pollen-stratigraphical features associated with the  $T_{ann}$  drop in this study are the same features that characterize pollen-stratigraphical response to the cold event in eastern Scandinavia (Seppä and Poska, 2004; Veski *et al.*, 2004). Timing of the cold event, in at least one of these pollen-based records (Veski *et al.*, 2004) is in very good agreement with precisely-dated records such as Greenland ice cores (Alley *et al.*, 1997), and tree-ring records (Spurk *et al.*, 2002) while the event in Giltjärnen has a 300-yr offset from these records. Notably, investigations in northern Sweden (Snowball *et al.*, 2002; Zillén, 2003) show similar pollen stratigraphical feature changes associated with the cold event, and with the same timing as in Giltjärnen. Snowball (2002) argues that a causal link with the drainage of the Laurentide glacial lakes and the cold event is not possible unless a 300 year lag-time is considered. These discrepancies urge the need for better understanding of climate and vegetation dynamics during a period in transition from ice-age boundary conditions.

## A dry and warm Holocene thermal maximum - possible changes in the atmospheric circulation

Temperatures changes have been in main focus for palaeoclimatological reconstructions while hydrological change and moisture balance have been somewhat overlooked (Hammarlund *et al.*, 2003). It also appears that climate variability during mid- and late Holocene partly represents hydrocli-

matic changes that are still poorly understood (Booth *et al.*, 2005). There are however Holocene moisture records available (Digerfeldt, 1988; Almquist-Jacobson, 1995; Hammarlund *et al.*, 2002, 2003) that can be used in an integrated approach with for example temperature reconstructions to create a more comprehensive picture of Holocene climate patterns.

In comparison with generally low lake levels (Digerfeldt, 1988; Almquist-Jacobson, 1995) the isotope and temperature records from central and southern Sweden indicate a mid-Holocene period with high temperatures, and markedly dry conditions, probably due to low precipitation and increased summer evaporation associated with high temperatures. These observed conditions may indicate a more continental climate than in the surrounding periods and hence this would support the suggestions of a more meridional atmosphere circulation mode (Seppä and Hammarlund, 2000; Seppä and Poska, 2004) during the mid-Holocene for Scandinavia.

In addition to the numerical reconstructions, pollen data reflect the HTM at about 8000 cal yr BP by rising values in warm temperate species *Tilia*, *Fraxinus*, and *Quercus*. Accordingly, if the post-glacial distribution changes of tree species took place in an approximate dynamic equilibrium with climate (Prentice *et al.*, 1991; Davis and Shaw, 2001; Post, 2003; Shuman *et al.*, 2004), the population dynamics of these tree species during the HTM can be explained by a major change in the atmospheric circulation pattern. *Corylus* and *Ulmus*, the temperate deciduous species that were abundant before 8000 cal yr BP, require long growing seasons but are relatively sensitive to frost and, along with *Alnus*, have a low drought-tolerance (Hintikka, 1963; Skre, 1979; Prentice and Helmisaari, 1991). Their high values in the pollen record prior to 8300 cal yr BP may therefore reflect relatively humid and oceanic climatic conditions during the early Holocene. *Tilia* and *Quercus* are more continental in their modern distributions ranges (Hultén, 1971; Dahl, 1998) and climatic tolerances, being less sensitive to drought but generally requiring higher mid-summer temperatures than *Corylus* and *Ulmus* (Hintikka, 1963; Pigott and Huntley, 1978; Skre, 1979; Pigott, 1981; Prentice and Helmisaari, 1991). Hence, their absence or infrequent occurrence before 8300 cal yr BP likely resulted from too low mid-summer temperatures and their subsequently rising values were probably connected to the shift towards predominantly dry and warm conditions at about 8000 cal yr BP. For this reason, the occurrence of especially *Tilia*, and *Quercus* provide further evidence for the reconstructed dryness during the HTM.

A modern, equivalent circulation pattern in Scandinavia to the suggested mid-Holocene continental climate with a meridional circulation pattern is the negative phase of the NAO, and on shorter time scale, a blocking anticyclone situation. The mechanisms associated with these patterns are partly well understood and may give answers to the dry mid-Holocene enigma; one problem is that at present they operate on much shorter timescales. Reconstructions of NAO exist and have revealed interannual to interdecadal perio-



dicity similar to modern NAO pattern during the last 1500-2000 years (Keigwin and Pickart, 1999, Luterbacher *et al.*, 2001). And very recently, hydroclimatic proxy record reflects multicentennial-scale variations during the last 7500 years that resemble modern NAO related anomalies, suggesting a prominent role of NAO during the Holocene, not only at interannual to interdecadal timescales (Lamy *et al.*, 2006). Statistical analysis of the North Atlantic sea surface temperature data have suggested that the early to mid Holocene circulation conditions in the eastern North Atlantic region were compatible with an enhanced positive phase of NAO (Rimbu *et al.*, 2004). However, the long-term climatological investigations demonstrate that the circulation-climate relationships may not remain stationary when the period of investigation is extended further into the historical past (Jacobeit *et al.*, 2001; Sutton and Hodson, 2003).

## Inferred climate trends in a wider context, a short reflection

The results from this study support other terrestrial records (Dahl and Nesje, 1996; Karlén and Kuylensstierna, 1996; Brooks, 2003) that reflect similar long term climate trends for Scandinavia and the North Atlantic region, with warm summer or annual mean temperatures in early- to mid Holocene and declining temperatures in late Holocene. In the marine records however, there are discrepancies. Diverse response in different proxies from the same marine sediment-core, diatom- and alkenone SST indicate warm early Holocene and a cooling trend (Birks and Koç, 2002; Calvo *et al.*, 2001) similar to the terrestrial data, while oxygen isotopes indicate cold early Holocene warming trend (Risebrobakken *et al.*, 2003). These contradictions calls for further attention towards an understanding of the mechanisms involved in creating climate patterns of the past.

However, the reconstructions of the occurrence and amplitude of a cooling event in southern and central Sweden and the widespread extent in Scandinavia (Seppä and Poska, 2004; Veski *et al.*, 2004), together with the dry HTM conditions in southern Sweden, with suggested connections to atmosphere circulation demonstrate the possibility that the important link between the Scandinavian climate and the North Atlantic region may be reflected in local palaeodata records.

## Conclusions

- This study contributed with new surface-pollen samples from central and southern Sweden. By including the Swedish surface samples to a Finnish-Estonian surface-pollen data set, a north-European pollen-climate calibration model with high performance statistics was created.
- This highly standardized data collection from a region where vegetation and hence, modern pollen is rather systematically related to its living environment will be an important contribution to European pollen data base.
- Pollen-inferred temperature from central and southern Sweden indicates a coherent long term Holocene climate trend.
- Pollen stratigraphical feature-changes correlate with temperature and moisture changes, with suggested connections to atmosphere circulation, during the Holocene. This result may indicate that, if post-glacial immigration of trees took place in approximate equilibrium with climate, population dynamics in Scandinavia can be explained by reorganisations in atmospheric circulation patterns.
- Independent climate records obtained from oxygen isotopes and chironomids reflect an overall consistency in the Holocene trend of  $T_{ann}$ , summer temperatures and moisture balance. Taken all together, the consistent long-term trends in temperature and moisture can be linked to regional climate variability. Accordingly, regional climate signals from Scandinavia and the North Atlantic may be traced in local Swedish palaeodata records.

## Summary in Swedish

Solens energiinstrålning fördelas olika över jorden såväl avseende tid som rum. Den ojämna fördelningen framkallar atmosfäriska cirkulationer som försöker utjämna skillnaderna. Dessa cirkulationer driver i sin tur vindar vid jordytan som påverkar cirkulationen mellan haven och atmosfären. Jordens klimat styrs till stora delar av dessa cirkulationer.

Klimatets variationer kan beskrivas över olika tidsperioder, som till exempel årstider och istider. De atmosfäriska krafter som driver dessa variationer styrs av fysiska och kemiska lagar som står i strikta relationer till varandra. Trots denna i grunden strikta ordning är relationerna så komplexa att klimatvariationerna kan tyckas högst oförutsägbara och kaotiska.

Tydliga indikationer visar på att atmosfärens temperatur har stigit de senaste hundra åren. Temperaturhöjningen har bland annat kopplingar till den ökade halten av koldioxid i atmosfären som är en effekt av människans förbränning av fossila bränslen. Denna ökning föder tankar om framtiden och vår miljö kopplat till den naturliga förändringen och människans påverkan av denna. Det är en utmaning att kunna skilja den naturliga förändringen från den som är styrd av människan. För att uppnå denna insikt krävs kunskap om spännvidden av alla de variationer som styr klimatet. En väg till insikt kan vara att studera historiska data om klimatet från senaste istiden och framåt (värmetsiden) och ur dessa kunna förutse framtidens klimat.

Det finns rikligt med data om klimatet för tidsperioden efter senaste istiden. Ur geologiska arkiv såsom iskärnor och sedimentprov kan det utläsas att det varit variationer i klimatet med flera kallperioder under den rådande värmetsiden. Med denna kunskap om historiska klimatvariationer som bakgrund kan det bli möjligt att urskilja människans påverkan på klimatet framöver. Eftersom meteorologiska data endast finns för de senaste århundraden är de geologiska arkiven särskilt viktiga för att kunna modellera långt tillbaka från istidens slut.

Genom att studera pollen erhålls en relativt representativ bild över sammansättningen av vegetationen vid en specifik tidpunkt och plats. Denna sammansättning är till stora delar styrd av klimatet. Kopplas analys av pollenförekomst till exakta temperaturmätningar för samma tidsperiod och plats, kan ett statistiskt samband modelleras. Med hjälp av sambandet mellan nutidens vegetation och temperatur är det möjligt att rekonstruera värmetsidens historiska klimatvariationer. En viktig förutsättning för att kunna använda denna metod är att temperatur- och vegetationsgränser följs åt geogra-

fiskt. För att utvärdera resultaten kan en jämförelse göras med andra rekonstruerade data från varmetiden, till exempel chironomider för sommartemperaturer och syreisotoper för hydrologiska tillstånd.

I detta arbete har en modell använts som bygger på pollen- och temperaturdata från Finland, Estland och centrala Sverige. Modellen har använts för att rekonstruera varmetidens klimat i centrala och södra Sverige.

Modellen visar på ett starkt statistiskt samband mellan vegetation och temperatur, samtidigt ska en statistisk felmarginal på  $\pm 0,95^{\circ}\text{C}$  beaktas. Enligt modellen inleddes värmeperioden för cirka 10 000 år sedan med låga men snabbt stigande temperaturer. Denna trend avbröts av en kallperiod för cirka 8 500 år sedan som varade under några hundra år. Den varmaste perioden inföll för cirka 7 000 år sedan, med en medeltemperatur som var cirka  $2^{\circ}\text{C}$  högre än idag. Från 4 000 år sedan och fram till idag har temperaturen sjunkit.

Med hjälp av hydrologiska data kan det konstateras att klimatet för 10 000 år sedan var relativt fuktigt, för att under den varmaste perioden ha varit relativt torrt och därefter åter igen blivit fuktigare och mer instabilt.

Resultaten i denna studie visar samma långsiktiga generella klimattrender som många andra studier i Skandinavien. Det genomförda arbetet med studier av pollen i centrala och södra Sverige indikerar såväl kall- som varmperioden. Detta kan därför tolkas som att lokala klimatvariationer till stor del styrs av storskaliga regionala klimatk mekanismer.

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