BACC II Book newgeneration

Chapter 2. Past climate variability

2.1.The Holocene (about 11,000 calendar years)

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The aim of this chapter is to summarize the empirical data on spatial and temporal variability of climate in the Baltic Sea Basin beginning with the events at the Younger Dryas/Holocene boundary and throughout the entire Holocene (the last 12 calendar years).

In the previous monograph **"Assessment of climate change for the Baltic Sea Basin" (BACCI)** the issue of past climate variability had not been practically considered.

Chapter 2.1. Climate change during the Holocene (the last 12,000 calendar years)

Introduction

2.1.1. Climate proxy records and methods for paleoclimatic reconstruction over the Holocene

2.1.2. Climate variability during the Holocene relevant for the Baltic Sea basin

2.1.2.1. Climate at the Younger Dryas/Holocene boundary

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Glossary

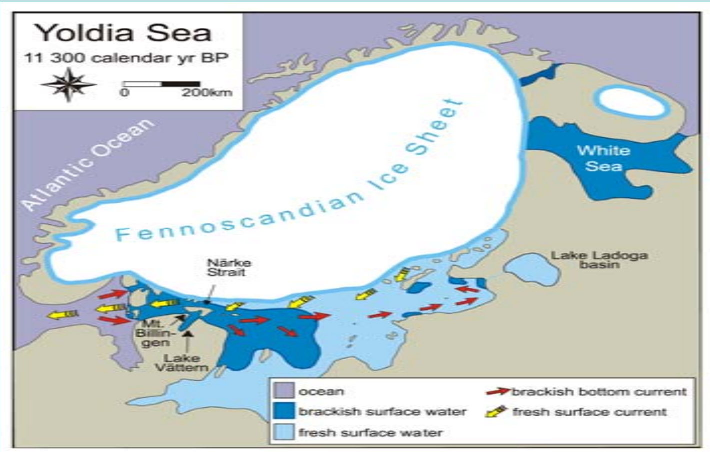
The Lateglacial-Early Holocene history of climate in the Baltic Sea Basin is closely related to its paleogeography at the time of melting the Scandinavian Ice Sheet;

The Lateglacial and Holocene history of the Baltic Sea Basin has been divided into four main stages: the Baltic Ice Lake (BIL) from deglaciation to ca. 11,550 cal yr BP, the Yoldia sea stage ca. 11,550-10,700 cal yr BP (brackish –water basin in the fist part of this stage and fresh water basin during the second phase), the Ancylus Lake (fresh water basin between ca. 10,700-9,500 cal yr BP) and the Littorina Sea (brackish – water basin, ca. 9,500 cal yr BP to present).

Paleogeography of the Baltic Sea Basin between 12,000 and 7,000 cal yr BP (Andren,2003; Heinsalu, Veski, 2007)

The Baltic Ice Lake ca. 11,700-11,600 **yr BP**

The Yoldia Sea stage ca. 11,400-11,300 yr BP



The Ancylus Lake ca. 10,300 yr BP

The Littorina Sea, ca. 9,500 yr BP to present

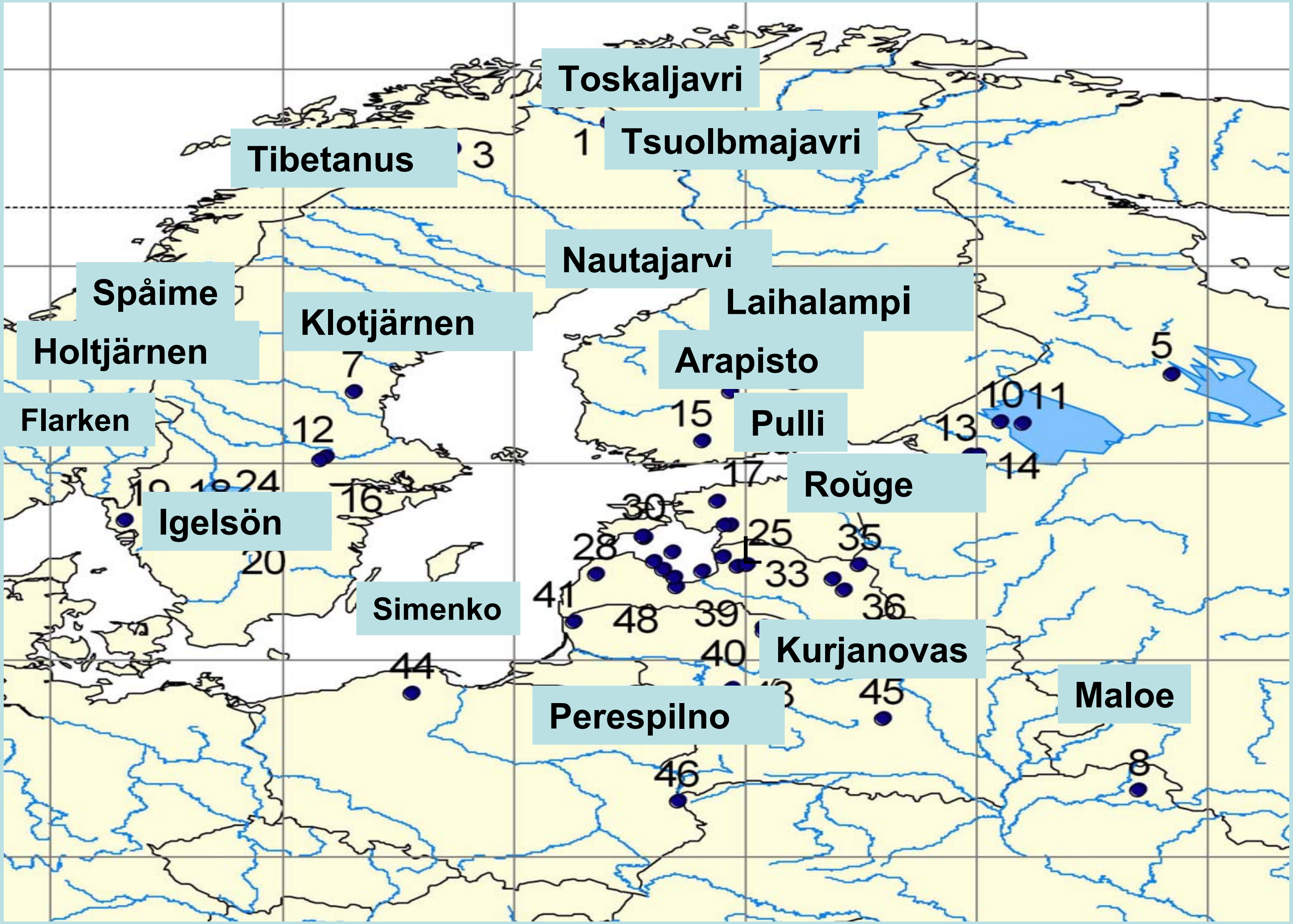
The number of proxy records for the last 10,000 years in the Baltic Sea region has increased remarkably during the last decades.

Lake and bogs sediments, pollen, tree-rings, insect remains, varves, and other proxies have been important in gaining a better understanding of long-term climate oscillations as well as short-term climatic events during this time.

Development of quantified climate records using pollen, macrofossils, coleopteran and chironomid data based on multivariate statistical techniques allow to reconstruct the summer and mean annual temperatures, and sometimes annual sum of precipitation;

However these estimates are scarce, which limits the creation detailed climate reconstruction for narrow time slices (or) periods. At the same time these estimates allow us to imagine the total pattern of vegetation and climate dynamics in the Baltic Sea region for the past 10,000 – 12,000 years. For this purpose about the 50 key sections on the territory of the Baltic Basin have been used.

The map of some key sites



Analysis of these data showed the complicated and mozaic pattern of climatic oscillations in different parts of this region. Rapid cooling periods most explicit in the end of the Lateglacial - early Holocene alternate with longer warming time intervals.

To understand the mechanism of modern and future climate oscillations, of particular, interest is data on rapid climate variations related to the non-linear processes in the atmosphere-ocean-cryosphere system typical of the transition time from the Lateglacial to the Holocene.

The climate at the Younger Dryas/Holocene boundary

This boundary coincides with the final drainage of the Baltic Ice Lake at Billingen area in the Central Sweden and dated at about 11,653 ice years ago and by tree-ring chronology at ~11,590 cal years BP.

Mörner (1980) was the first to estimate air temperature changes at the Younger Dryas/Holocene boundary by oxygen-isotope analysis of lake carbonates from southern Sweden. According to this data, the air temperature increased by about 9°C at the Younger Dryas/Holocene boundary during several decades.

Later, this result was fully confirmed by oxygen-isotope data from Greenland ice-cores (Dansgaard et al., 1989). Independent estimates on the $^{29}N/^{28}N$ and $^{40}Ar/^{36}Ar$ isotope ratio in Greenland ice-cores show that the temperature increase at the Younger Dryas /Holocene boundary was 10± 4°C within less than 50 years (Grachev, Severinghaus, 2005).

At this boundary a cold and dry climate was rapid changed to a warmer and humid one. The summer temperature in northwestern Russia increased from 4° to 10-12°C (Wohlfarth et al., 2007) and in Southern Finland from 7-10°C to 16-22°C (Bondestam et al., 1994);

Tundra-steppe vegetation with predomination of shrubs and grass typical of the Late Dryas changed to vegetation of open forest;

The warming at the Holocene boundary, at about 11,530 and 11,500 cal yr BP was interrupted by a series of a cooling episodes.

The Early Holocene oscillations

The three cold episodes about 11,200 (The Preboreal oscillation), 9,300 and 8,200 cal yr BP are revealed more pronounced. The duration of every cold period is 160 to 200 years, which is compatible with the "Little Ice Age" cooling during the historical time.

The first cool episode (the Preboreal cool oscillation) occurred approximately 250 years after the final drainage of the Baltic Ice Lake and was almost coincides with the short brackish phase of the Yoldia Sea. The coldest part of the Preboreal oscillation is dated at ~11,430-11,350 cal yr BP.

The 8.2 ka cool event

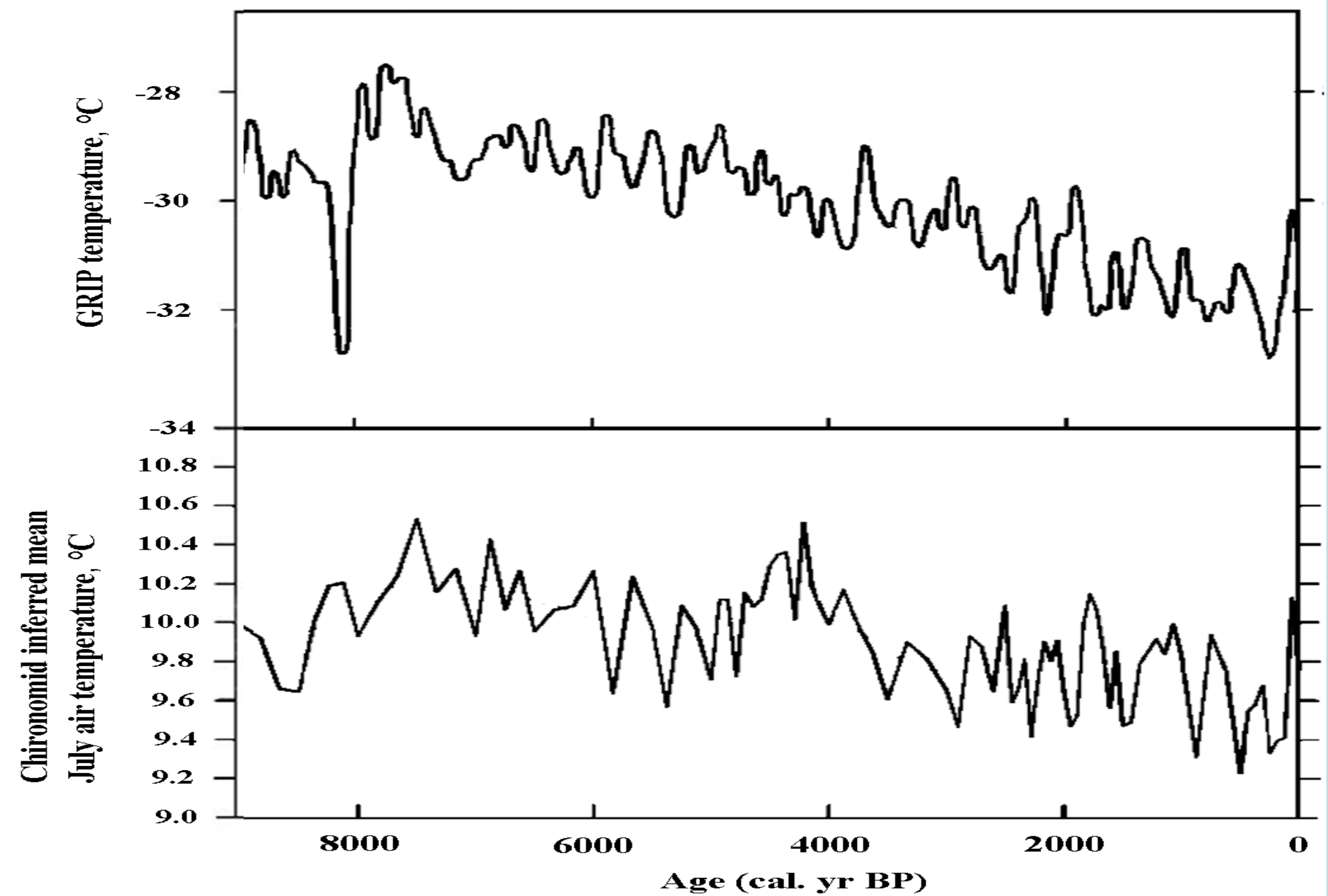
The last cold episode known as an "8.2 ka event" is best of all covered with independent proxy records, including the quantitative estimates of temperature. This cold episode is recorded over the entire Baltic Sea region, excluding the northernmost regions.

The 8.2 ka cooling had been known comparatively long time by changes in oxygen-isotope composition in ice cores from the Greenland. The cooling has been estimated by changes in air temperature by 6 ± 2°C in central Greenland. Later an independent methods were developed to estimate both air temperature change amplitude and the duration of this cooling.

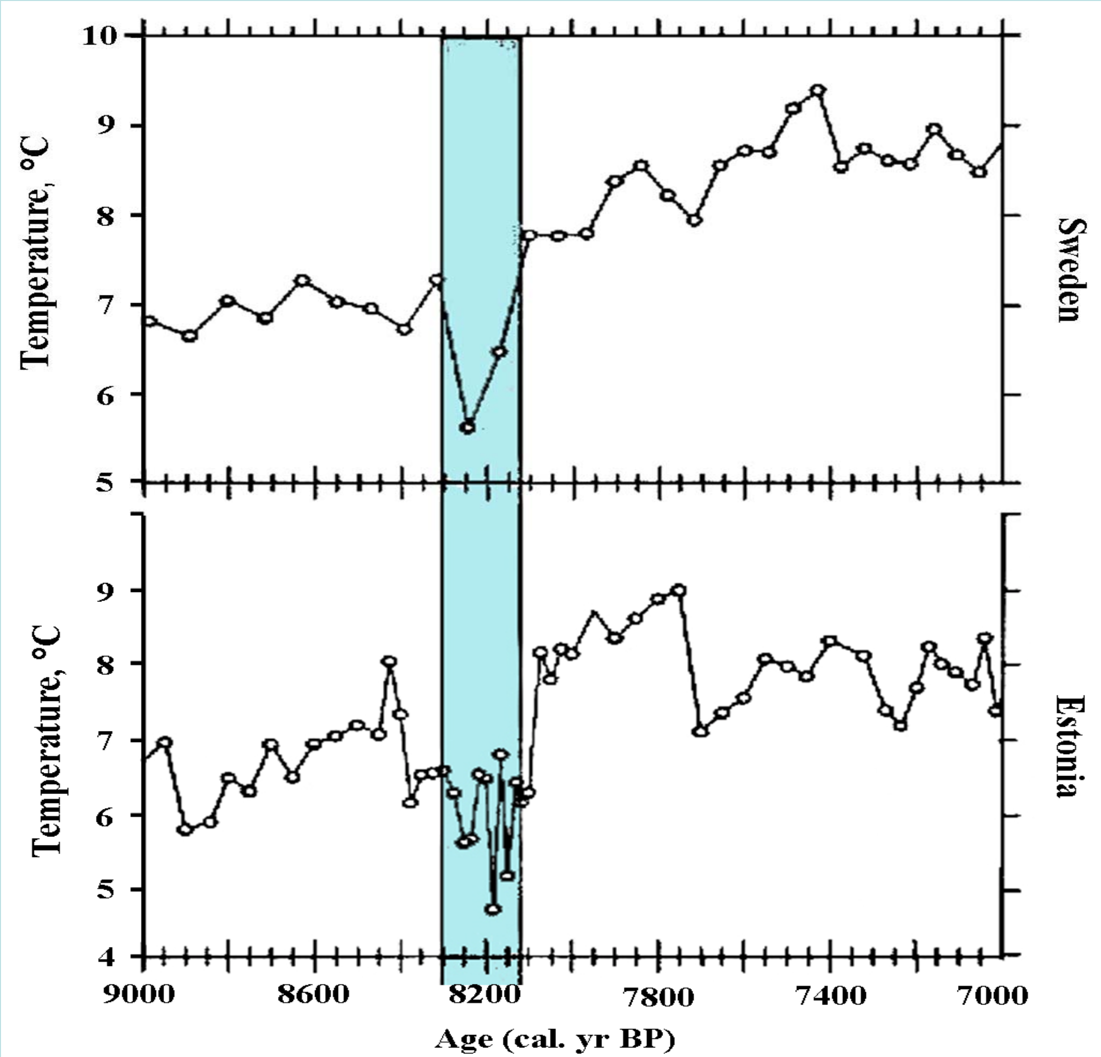
Ice-core data showed a complicated time structure of this event. The coldest phase of about 70 years in duration occurred in the middle of this interval. In central Greenland air temperature decrease of 3 ± 1.1°C occurred within less than 20 years and the entire cooling episode lasted approximately 150 years.

Decreasing of air temperature varied from 1°C to 2°C in the different part of the BSB, and duration of this event changed from 150 to 200 years (Snowball et al., 2002, 2010; Zillén, Snowball, 2009).

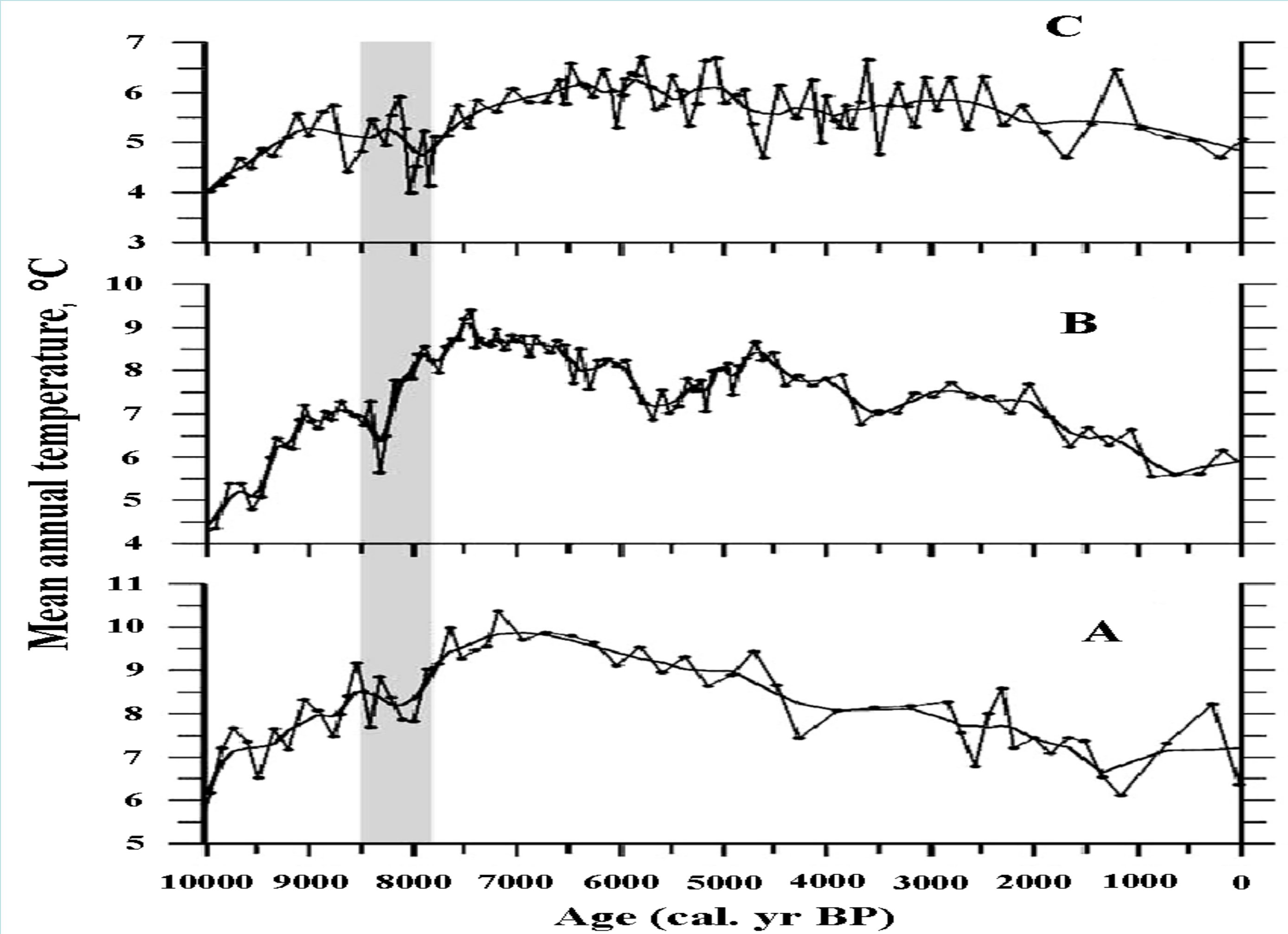
The general trends of the Holocene summer temperatures obtained from ice core data (GRIP) and based on the proxy data (chironomide) from site L. Toskaljavri (Northern Finland)



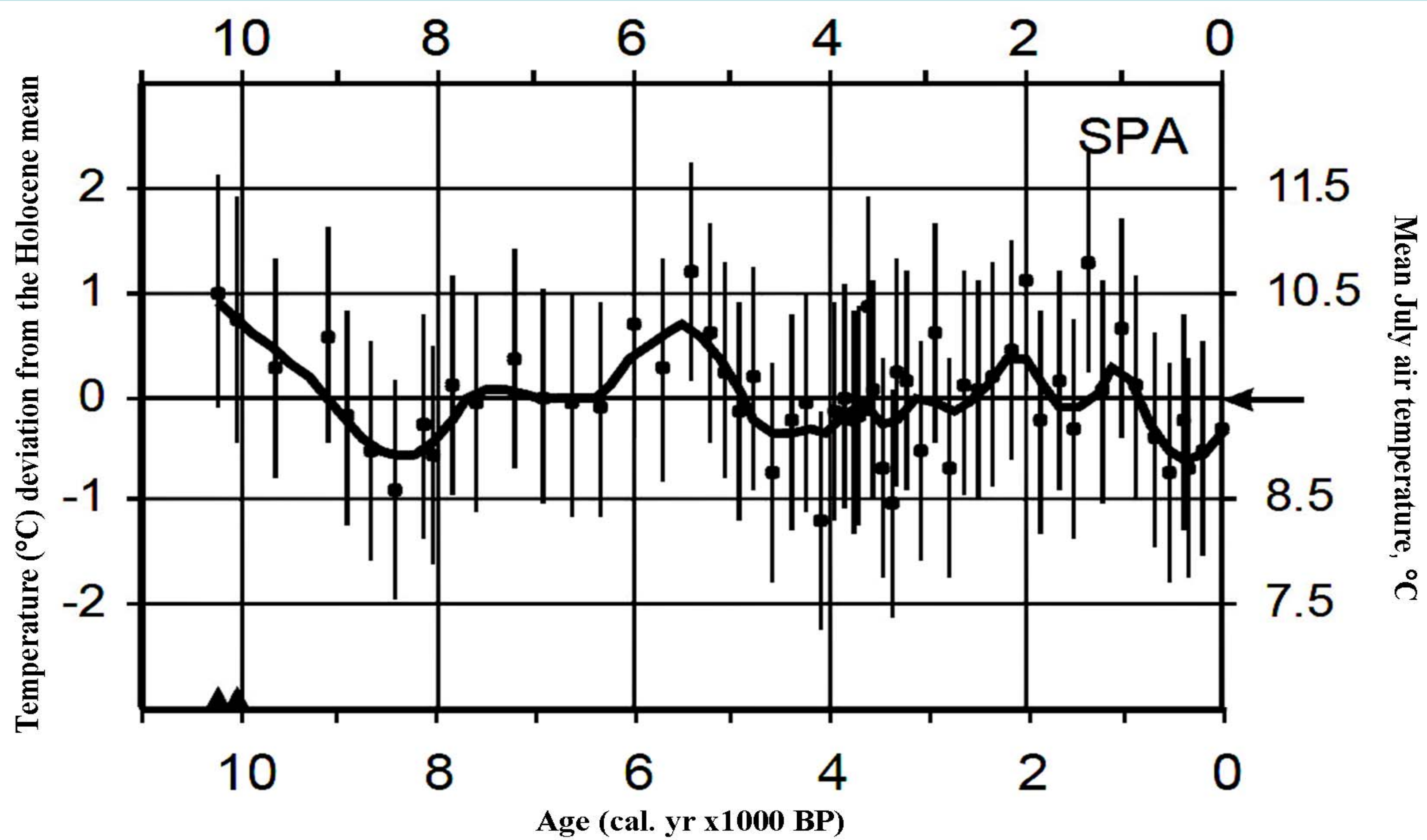
Pollen based reconstructions air temperature (°C) from sites L.Roŭge, Estonia (Veski et al. 2004) and L. Flarken, South-central Sweden (Seppä et al., 2005)



A quantitative reconstructions mean annual air temterature (°C) from fossil pollen data for the 3 lakes sites (C-Gilltjärnen, B-Flarken, A-Trehörningen) from Sweden. (Antonssen, Seppä, 2007)



Chironomide-inferred mean July air temperature (°C) from the L. Spåime (northern Sweden) (Velle et al., 2005)



What is the cause of these drastic climatic changes?

All cooling episodes of the Lateglacial and Early Holocene time occurred against the background of the positive temperature trend, driven by an increasing summer solar radiation, related to astronomical factors and higher concentrations of greenhouse gases, in particular, methane and CO_2, as ice core data show.

Causes of these events have been widely debated. Most researchers believe that the Early Holocene cooling episodes were caused by the influx of large volumes of freshening water into the North Atlantic as a result of draining freshwater lakes formed from the melted Laurentide Ice Sheet.

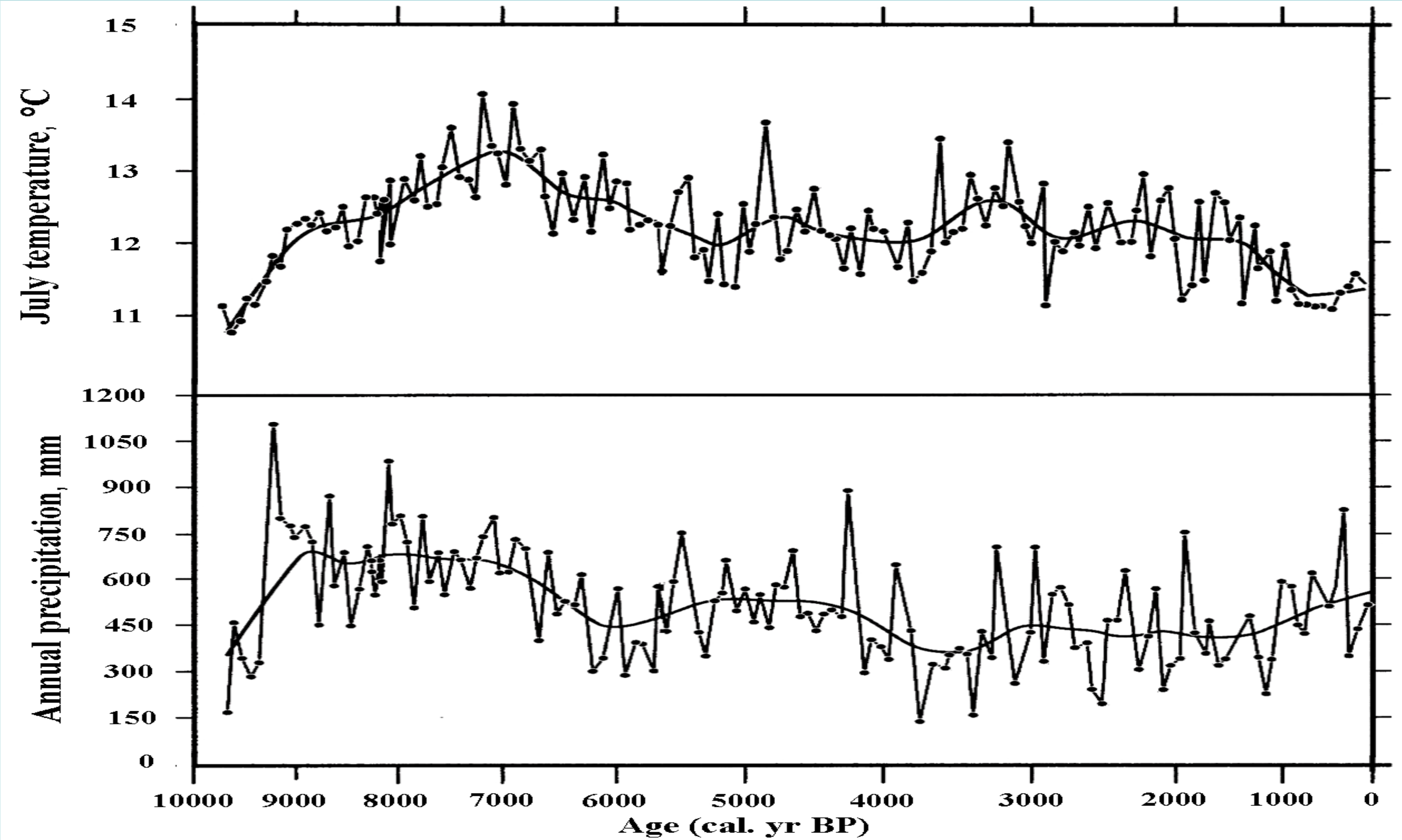
The Atlantic warming (the Holocene Thermal Optimum)

The period between 7,500 and 5,500 cal yr BP ago was the warmest one for the entire Baltic Basin area, though the times of maximum temperatures were not synchronous in different parts of the region.

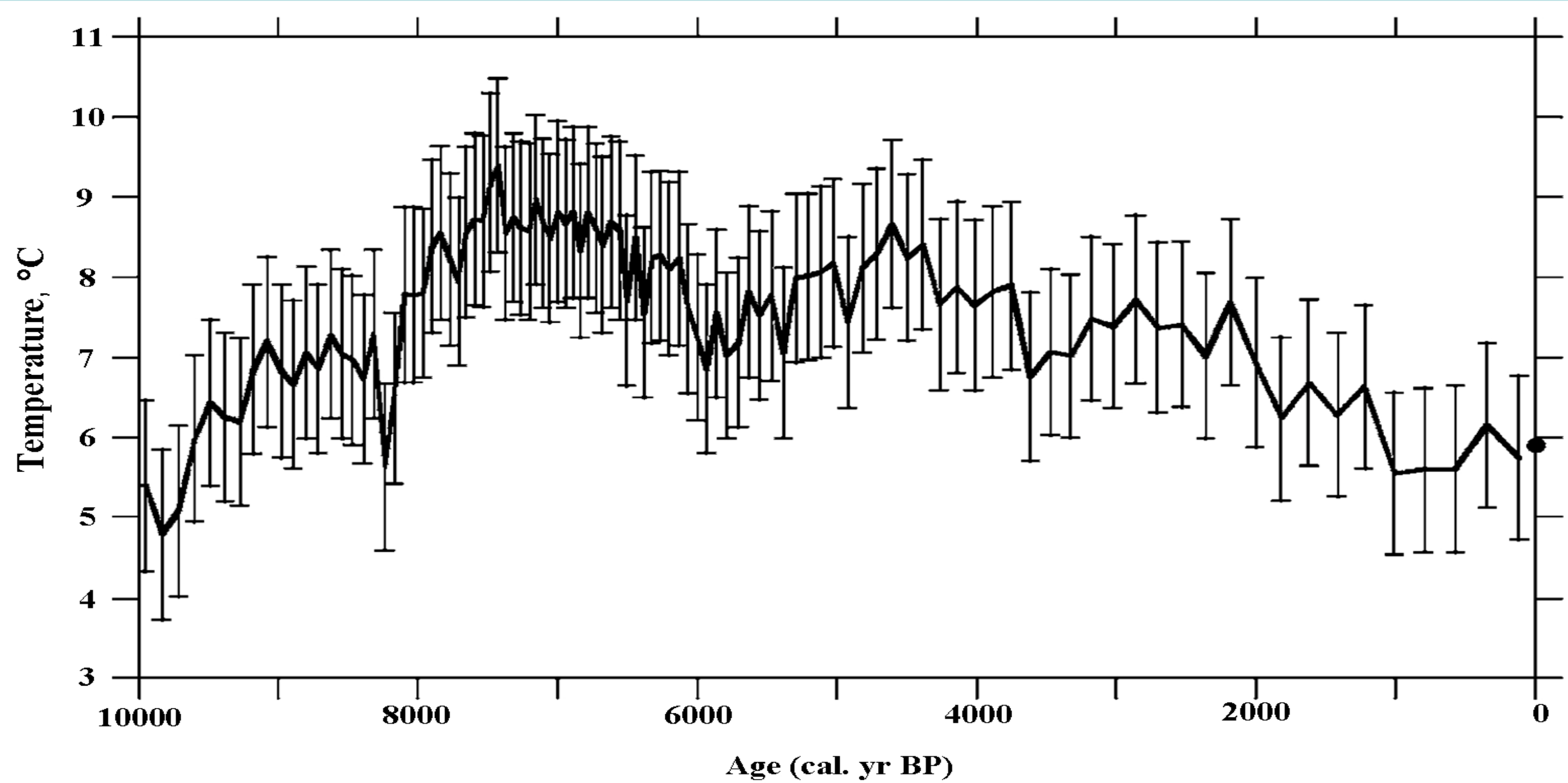
In Sweden, pollen and chironomids records show that the times of maximum temperatures changed in parts of Sweden between 7,900 and 5,700 cal yr BP with the amplitude varying from 1.0 to 1.5°C and higher.

In the Northern Finland, maximum temperatures took place between 9,000 and 7,000 cal BP, and in north-western Russia, about 5800 to 5000 cal yr BP.

Inferred July mean temperature and annual precipitation based on pollen data of the Lake Tsuolbmajavri (Northern Finland) (Seppä, Birks, 2001)

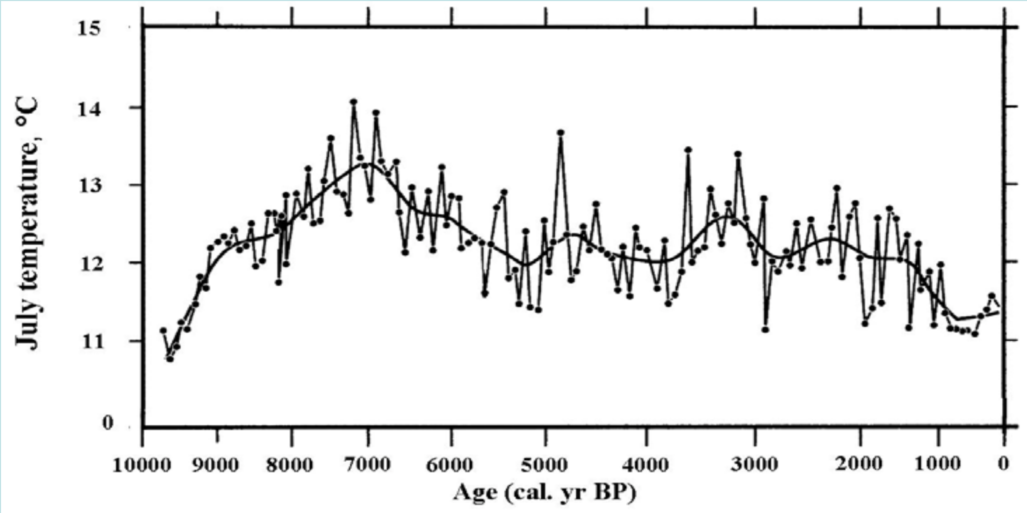


Mean annual temperature reconstructed from pollen data Lake Flarken (south-central Sweden) during the last 10,000 years (black line) (Seppä, Hammerlund, Antonssen, 2005). L.Flaken, 58°33'N



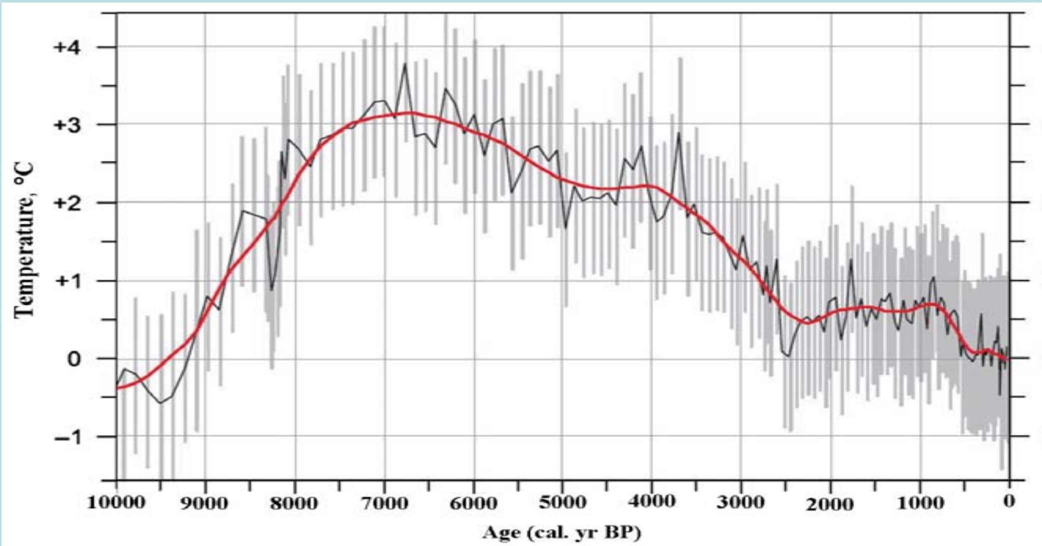
Present day annual temperature – (5.9°C) is marked by point

Summer air temperature (°C) during the Holocene in the different part of the Baltic Sea Basin



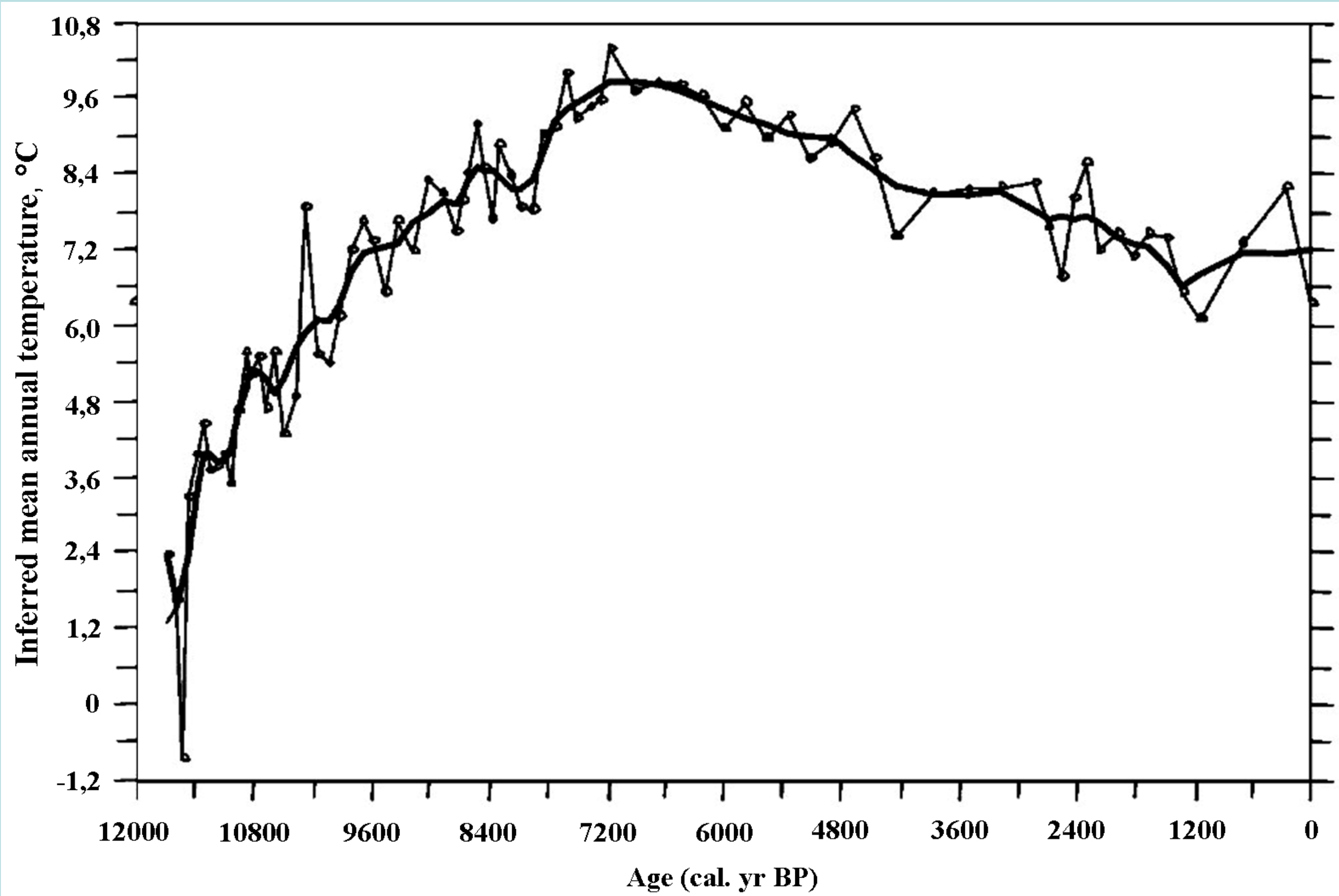
L.Tsuolbmajavri , Northern Finland

68°41'N

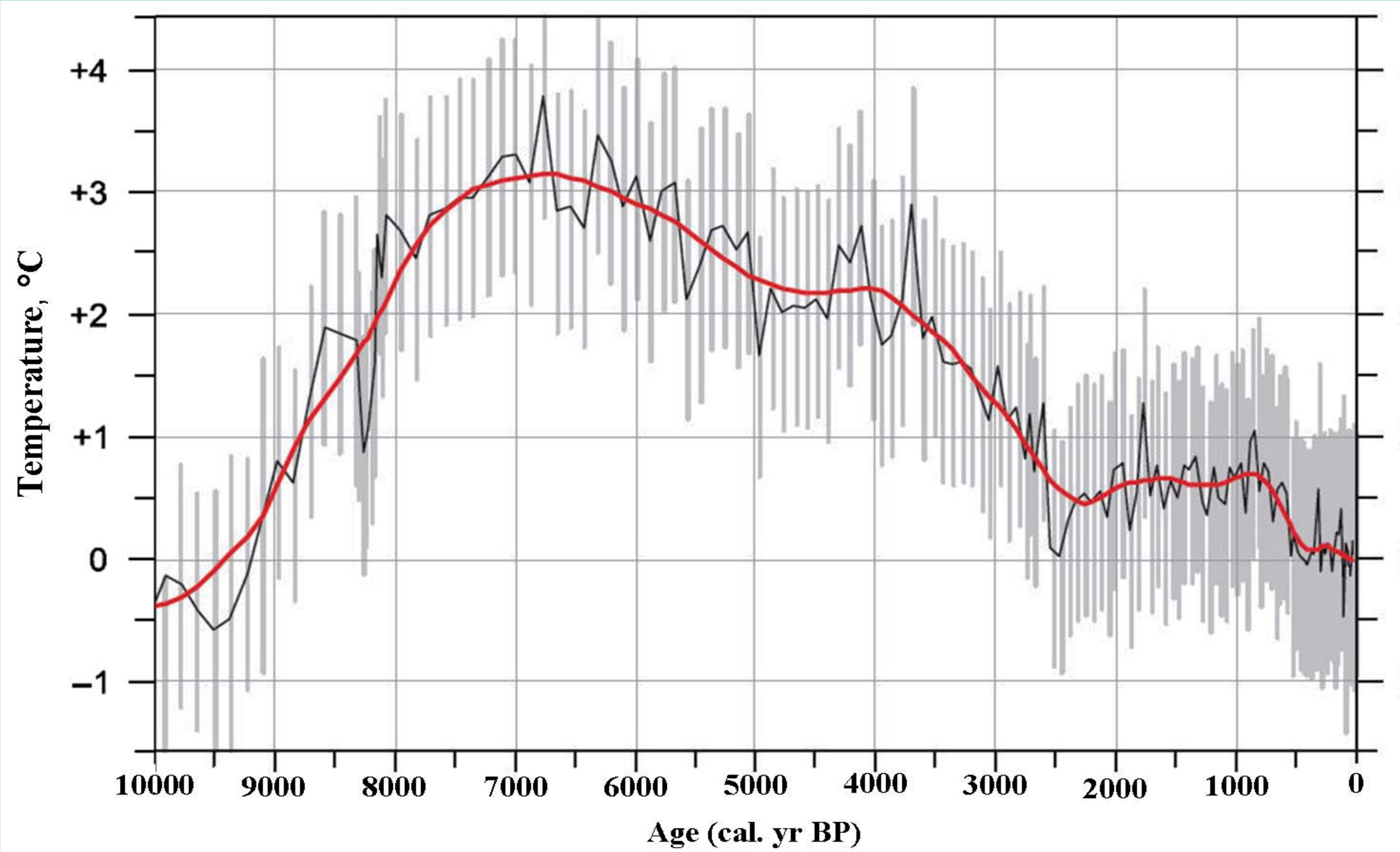


L.Kurjanovas, South Estern Latvia, 56°31'N

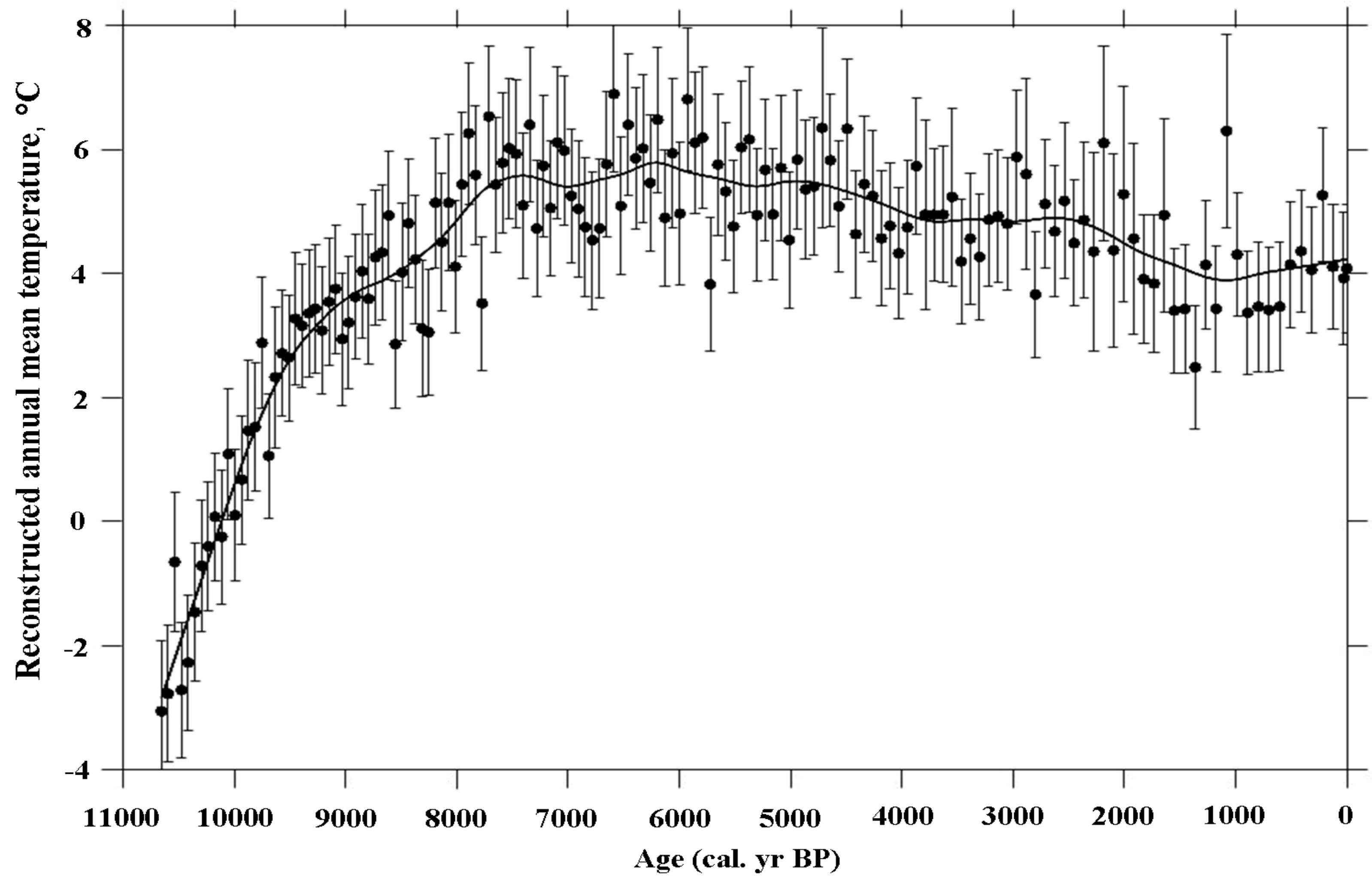
Mean annual temperature reconstruction of Lake Trehörningen for the past 11 700 years, southwest Sweden (Antonsson, Seppä, 2007).



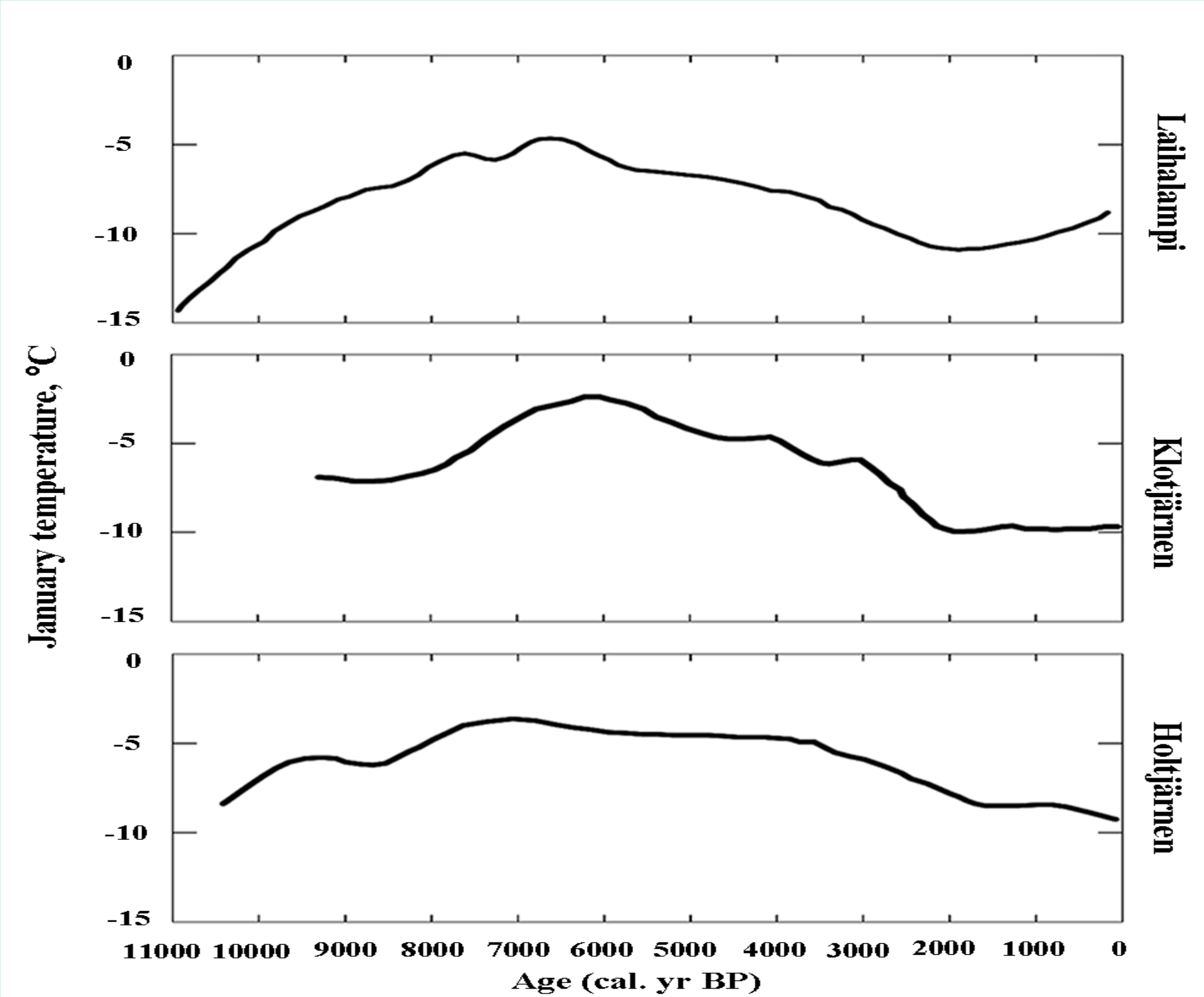
Reconstructed summer temperature (ΔT) anomalies shown as deviations from the modern value, Lake Kurjanovas, Latvia (Heikkilä, Seppä, 2010).



Annual air temperature reconstruction by pollen data from sedimentation of the L.Laihalampi (Finland),61°29‘N, 26°04‘E. Present annual temperature is 3.9°C



The winter (January) air temperature (°C) in the different part of the BSB during the last 11,000 years (Giesecke et al., 2008)



L.Laihalampi, Southern Finland

L. Klotjärnen, Central Sweden

L. Holtjärnen, Southern-central Sweden

The Holocene Thermal Maximum (HTM) was characterized by markedly dry conditions, indicative of stable summer – time anticyclonic circulation which is like modern blocking anticyclonic conditions.

The cooling in the Baltic Sea region began about 5,000 to 4,500 cal yr BP coincided with decreased summer solar radiation, incoming to the earth's surface due to astronomical factors.

Numerous proxy records suggest a progressive shift towards cooler and/or wetter climatic conditions. This evidence suggests that the HTM came to sudden to end as a result of a thereshold response to changes in astronomical forcing and a subsequent cessation of the anticyclonic climatic mode.

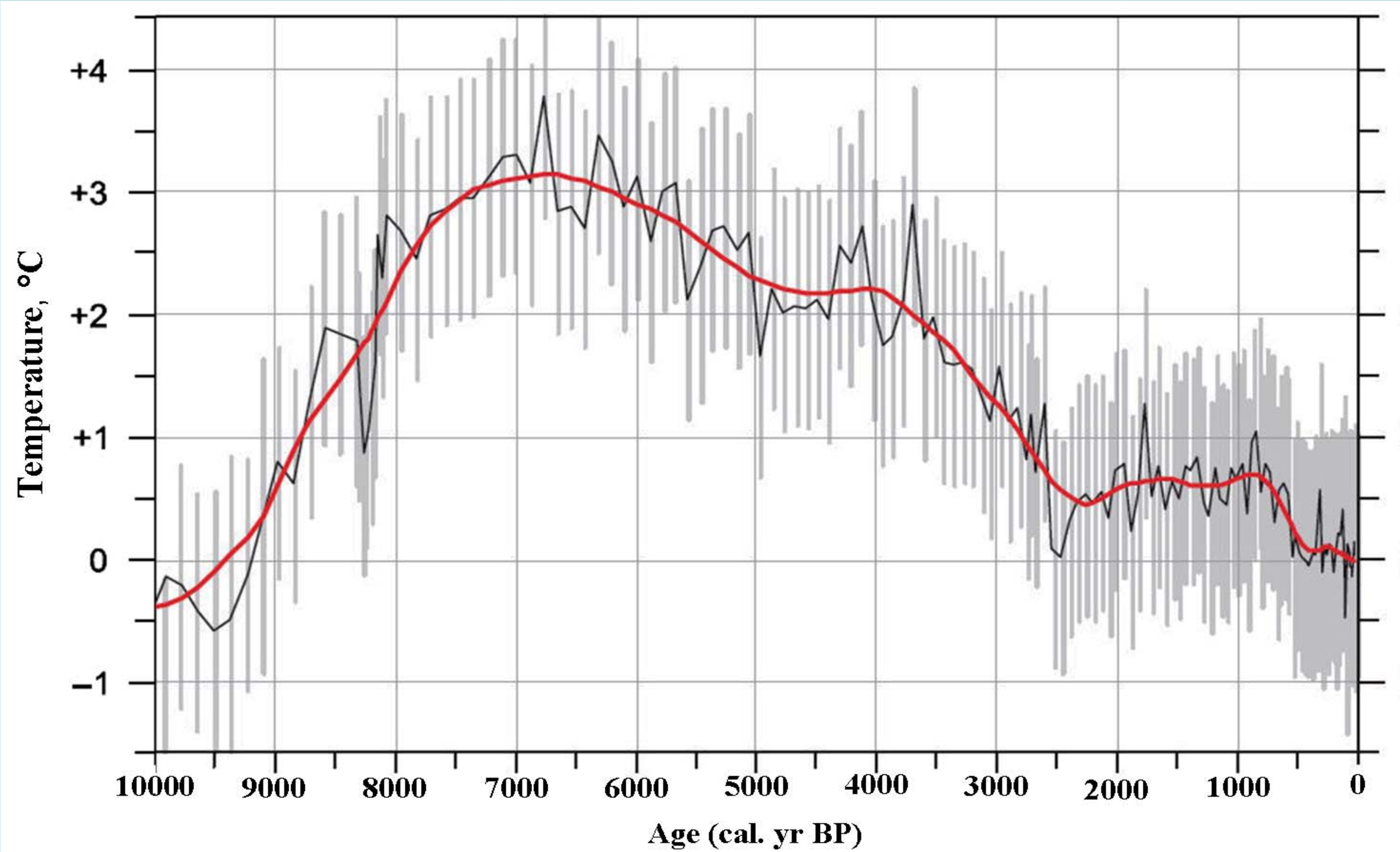
The Late Holocene cooling

The Late Holocene (time between 5,000 and 4,500 cal yr BP), characterized by the temperature decrease trend and increased climate instability.

A cooling of the Baltic Sea region at about 5,000 to 4,500 cal yr BP coincided with decreased summer solar radiation due to astronomical factors.

Different proxy data allow to reconstruct a two-stage air temperature decrease in the Late Holocene. The first stage of cooling occurred between 5,000 and 4,500 cal yr BP, and the second one between 4,300 and 3,300 (2,800) cal yr BP.

Reconstructed summer temperature (ΔT) anomalies shown as deviations from the modern value, Lake Kurjanovas, Latvia (Heikkilä, Seppä, 2010).



During each period the temperature drop was at least 1°C. A warming c. 3,200 and cooling c. 2,800 cal yr BP are revealed by detailed palaeoclimatic reconstructions.

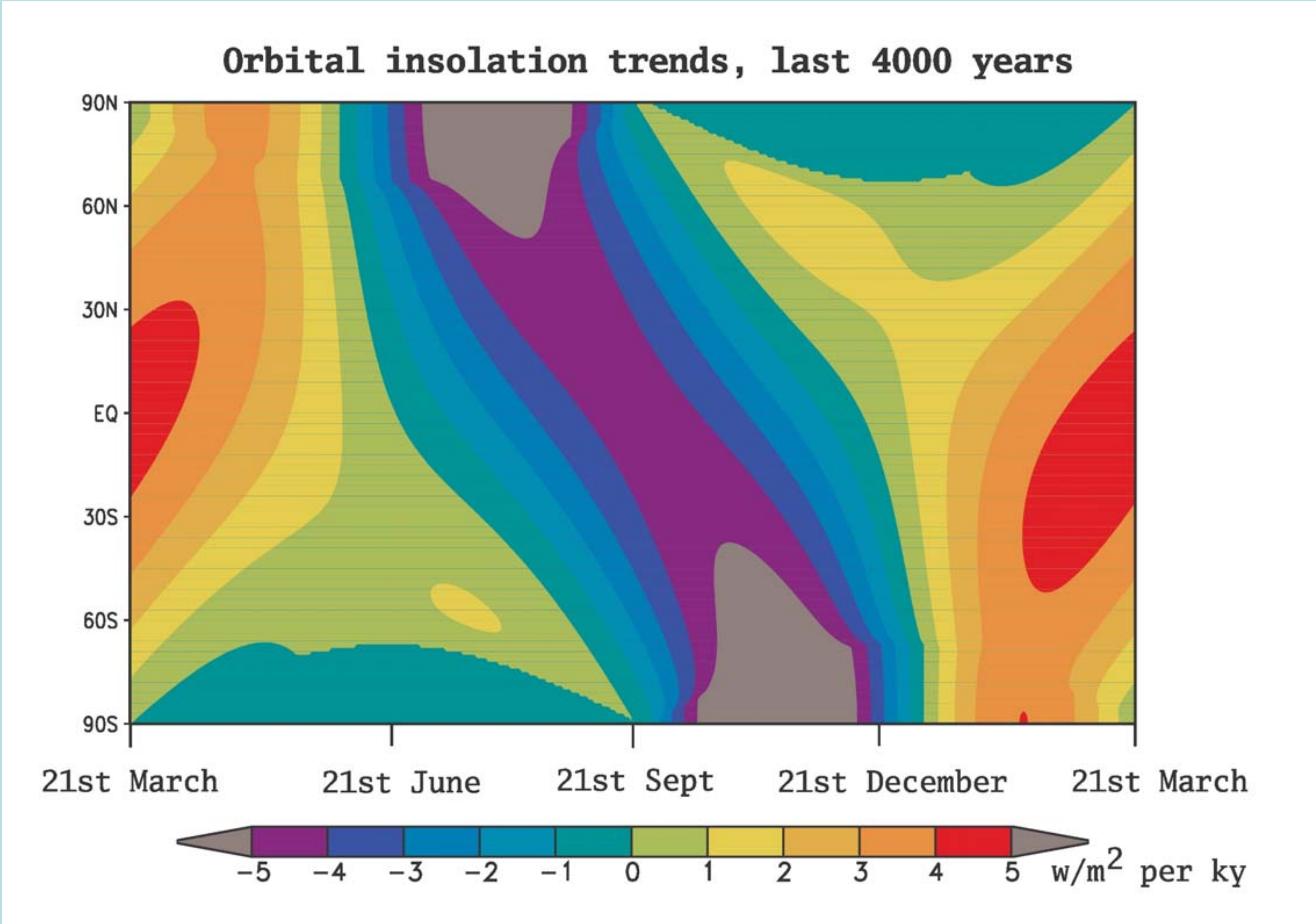
Although the general trend of the Late Holocene cooling is undoubtedly related to decreased summer solar radiation due to astronomical factors, the causes of these oscillations need further studies.

Causes of climate variability

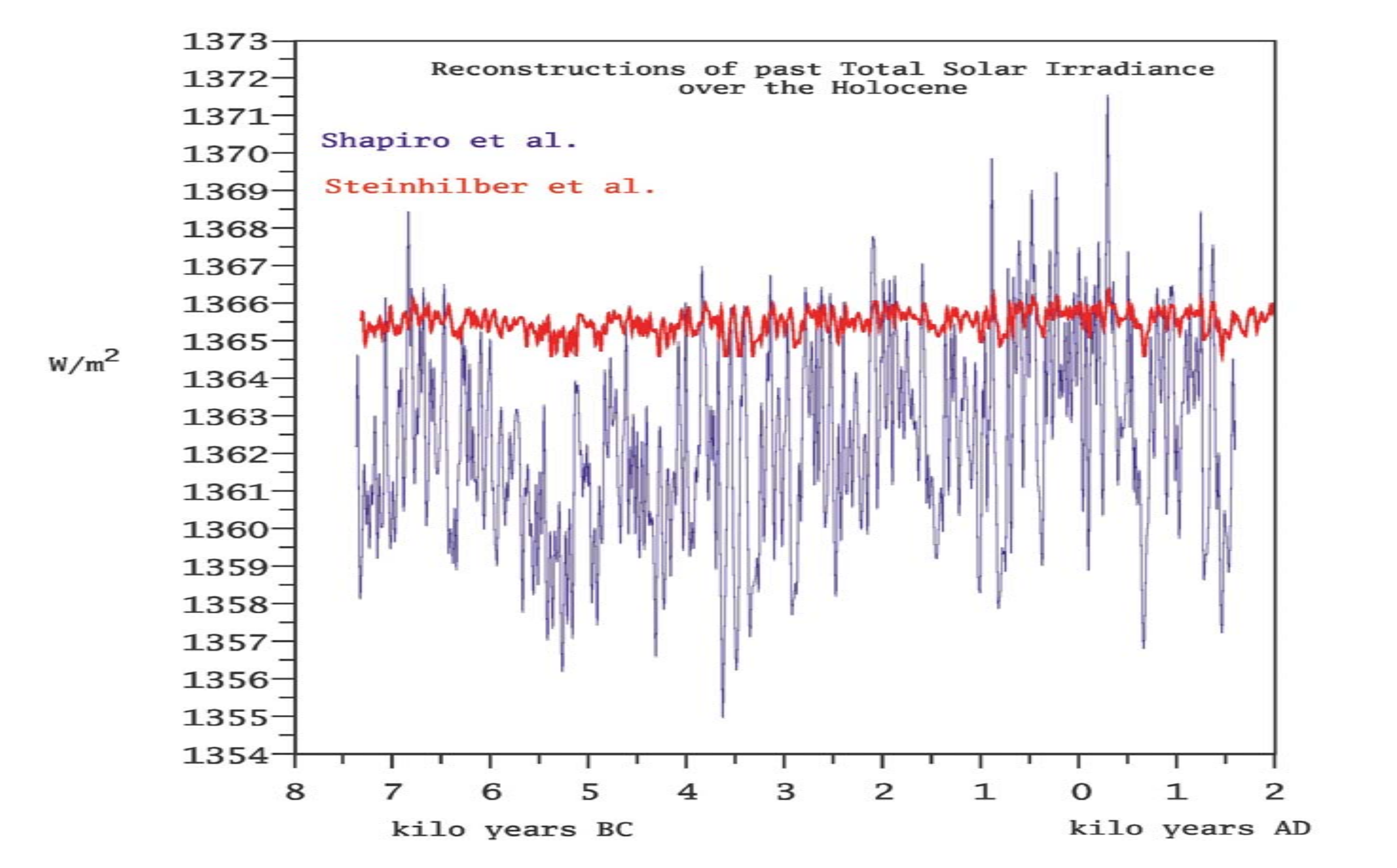
Climate variability in the Baltic Sea basin during the Late Glacial – Holocene was caused by changes in the external climate drivers, or internally generated by the non-linear dynamics and interactions among the different components of the climate system. The only external climate forcing that can be calculated accurately is orbital forcing.

The externally forced climate variability in the Baltic Sea basin is most likely attributed to orbital forcing at millennial time scales, to solar changes in solar irradiance centennial timescales, or to volcanic activity at multidecadal timescale.

Linear trends of solar insolation as a function of season and latitude over the last 4000 years (Laskar et al., 2004).



Two reconstructions of past Total Solar Irradiance based on ^{10}Be concentrations in polar ice cores and different assumptions about solar physics (Steinhilber et al., 2009; Shapiro et al., 2011).



In addition to the above factors that can be considered as an external forcing there are those (internal forcing) that lead to climate variability on multi-centennial timescales caused by extremely complicated and non-linear atmosphere-ocean interactions.

Proxy data from the areas adjoining North Atlantic shows rapid climatic cooling related to upper layer sea water freshening due to influx of large volumes of melt water from disintegrating continental ice sheets (Scandinavian and Laurentide). These can cause a weakening or even shutdown of the thermohaline circulation (THC).

What does climate changes during the last 10,000 years tell us about present and future climate variability in the Baltic Sea Basin?

Analyses of the different proxies records during the last 10,000 years show that relatively long-term past warm periods were followed by a shift to much colder weather, and, vice versa, cooling periods changed to rapid (of the order of a few decades) warming.

These abrupt climate changes are assumed to be related to nonlinear processes in the climate system. At some threshold values the climate system can transit "jump wise" from one stable mode to another one, within first few decades.

The mechanism of some of these abrupt climate events in the beginning of the Holocene is likely to depend on a massive influx of fresh glacial meltwater into the ocean and intensified hydrological cycle under global warming.

In high latitudes, abrupt climate changes are most noticeable, especially in the areas adjoining to the North Atlantic area.

In case the modern global warming due to the growth of greenhouse gases concentration lasts longer, the future consequence of this process might be the freshening of the sea surface layer.

The Baltic Sea Basin is the key region for studies on the effect on regional climate of refreshing of the upper layer of the Atlantic Ocean due to increased precipitation, melting mountain and sheet glaciers in the Northern Hemisphere.