
Climate Change During the Holocene (Past 12,000 Years)

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Irena Borzenkova, Eduardo Zorita, Olga Borisova, Laimdota Kalniņa,
Dalia Kisielienė, Tiiu Koff, Denis Kuznetsov, Geoffrey Lemdahl,
Tatyana Sapelko, Migle Stančikaitė, and Dimitry Subetto

Abstract

This chapter summarises the climatic and environmental information that can be inferred from proxy archives over the past 12,000 years. The proxy archives from continental and lake sediments include pollen, insect remnants and isotopic data. Over the Holocene, the Baltic Sea area underwent major changes due to two interrelated factors—melting of the Fennoscandian ice sheet (causing interplay between global sea-level rise due to the meltwater and regional isostatic rebound of the earth's crust causing a drop in relative sea level) and changes in the orbital configuration of the Earth (triggering the glacial to interglacial transition and affecting incoming solar radiation and so controlling the regional energy balance). The Holocene climate history showed three stages of natural climate oscillations in the Baltic Sea region: short-term cold episodes related to deglaciation during a stable positive temperature trend (11,000–8000 cal year BP); a warm and stable climate with air temperature 1.0–3.5 °C above modern levels (8000–4500 cal year BP), a decreasing temperature trend; and increased climatic instability (last 5000–4500 years). The climatic variation during the Lateglacial and Holocene is reflected in the changing lake levels and vegetation, and in the formation of a complex hydrographical network that set the stage for the Medieval Warm Period and the Little Ice Age of the past millennium.

I. Borzenkova (✉)
Climate Change Department, State Hydrological Institute,
St. Petersburg, Russia
e-mail: irena_borzen@mail.ru

E. Zorita
Institute of Coastal Research, Helmholtz-Zentrum Geesthacht,
Geesthacht, Germany
e-mail: eduardo.zorita@hzg.de

O. Borisova
Institute of Geography of the Russian Academy of Sciences,
Moscow, Russia
e-mail: olgakborisova@gmail.com

L. Kalniņa
Faculty of Geography and Earth Sciences, University of Latvia,
Riga, Latvia

D. Kisielienė · M. Stančikaitė
Department of Quaternary Research, Nature Research Centre,
Vilnius, Lithuania

T. Koff
Institute of Ecology, Tallinn University, Tallinn, Estonia

D. Kuznetsov · T. Sapelko
Institute of Limnology, Russian Academy of Sciences,
St. Petersburg, Russia

2.1 Introduction

The evolution of the coastline in the Baltic Sea area since the end of the last deglaciation has been the object of study for more than one hundred years. Despite this, some questions remain concerning both the chronologies of the transgression–regression phases of the prehistoric Baltic Sea basins and their spatial characteristics. Nevertheless, the long-term change in environmental conditions does provide information about the magnitude of natural climate and environmental variability, both that resulting from external climate drivers and that internally generated. This knowledge is important not only for understanding the mechanisms driving variability and the trend in climate change over centennial timescales,

G. Lemdahl
Department of Biology and Environmental Science, Linnaeus
University, Kalmar, Sweden

D. Subetto
Northern Water Problems Institute Karelian Academy of Science,
Russian Academy of Sciences, Petrozavodsk, Russia

but also to estimate the extent to which future climate could deviate from the monotonic long-term global trend caused by increasing concentrations of atmospheric greenhouse gases. At regional scales, deviations from the global average can be substantial and should be accounted for when designing regional policy for adaptation to climate change.

There are four main stages to the Lateglacial and Holocene history of the Baltic Sea basin:

- *Baltic Ice Lake stage*. This covers the deglaciation to ca. 11,550 cal year BP (calendar years before present)
- *Yoldia Sea stage*. This covers ca. 11,700–10,700 cal year BP (a brackish water basin in the first part of this stage and freshwater basin during the second; some studies place the end of the Yoldia Sea stage at 11,100 cal year BP)
- *Ancylus Lake stage*. A freshwater basin ca. 10,700–9500 cal year BP
- *Littorina Sea stage*. A brackish water basin, ca. 9500 cal year BP to present (Hyvärinen et al. 1988; Björck 1995, 1999; Andrén 2003; Andrén et al. 2002; Heinsalu and Veski 2007; Zillén et al. 2008). From colonisation by freshwater molluscs, the Limnea Sea has been dated at 4400 cal year BP and located in northern Estonia (Saarse and Vassiljev 2010).

The Baltic Sea basin and the Atlantic Ocean have exchanged water masses over almost their entire history. The exchange has been modulated both by glacio-isostatic land uplift and by eustatic (water volume) changes in sea level. Approximately 250 years after the final drainage of the Baltic Ice Lake, seawater flowed into the Baltic Sea basin through the Närke Strait in Billingen following a rapid rise in sea level resulting from the melting of the Scandinavian ice sheet (Yu 2003). This caused the Baltic Sea basin to become a brackish basin between 11,700 and 10,700 cal year BP (Yoldia Sea stage). Subsequent climate warming caused rapid melting of the continental ice sheets and pronounced isostatic uplift led to the isolation of the Baltic Sea basin from the Atlantic Ocean, turning it into a large freshwater lake (Ancylus Lake). The culmination of the transgression phase of this lake is dated to ca. 10,700 cal year BP (Yu 2003). The Ancylus Lake stage lasted until approximately ca. 9500 cal year BP. The modern Baltic Sea basin is part of the Littorina stage during which sea level and salinity have varied considerably (Miettinen et al. 2007).

Climate change in the Baltic Sea basin during the Holocene has been the result of various external and internal factors: changes in incoming seasonal solar radiation due to slow changes in the Earth's orbit, variations in the concentration of stratospheric aerosol caused by volcanic activity, change in the greenhouse gas content of the atmosphere due to natural factors, change in surface albedo of the sea-lake itself and in the surrounding land vegetation, and change in the intensity and type of circulation due to changes in basin salinity. The widely varying lake levels and vegetation

changes and the formation of a complex hydrographical network together indicate a complex pattern of climatic change in the Baltic Sea region through the Lateglacial and Holocene. These environmental changes also affected the stages of human migration in this territory during this period.

This chapter summarises the climatic and environmental information that can be inferred from proxy archives of the Baltic Sea basin. These cover approximately the past 12,000 years and include different types of proxy data, mostly from continental and lake sediments, insect remnants, and isotopic data. There is also a brief discussion on the sources and mechanisms of externally driven and internally generated climate variability at timescales relevant for the Holocene.

2.2 Causes of Climate Variability During the Holocene

Climate variability in the Baltic Sea basin over the past 12,000 years has been caused by changes in external climate drivers, or internally generated by nonlinear dynamics and interactions among the different components of the climate system. During the deglaciation that began in the Last Glacial Maximum and later in the Holocene, the main external climate drivers were the modulation of the orbital parameters of the Earth, change in the solar irradiance, volcanic activity, change in the properties of land cover (see Chap. 25), and the concentration of greenhouse gases in the atmosphere. Distinguishing between external and internal drivers is a matter of perspective. For instance, the effect of greenhouse gases and changes in the land surface are usually considered external climate forcings. However, if changes in the biosphere and the dynamics of the carbon cycle are included as interactive components of the climate system, these would constitute a source of additional internal variability. This apparent contradiction can be illustrated using the example of large-scale circulation patterns. From a regional perspective, they may be considered external climate forcings, whereas changes in the circulation patterns may in fact be due to changes in the external radiative forcing or simply the result of internal climate variability, partly also due to processes originating within the Baltic Sea region itself.

2.2.1 External Climate Forcing

According to present knowledge, the externally forced climate variability in the Baltic Sea basin is most likely to be due to orbital forcing at millennial timescales, to changes in solar irradiance at multi-decadal or centennial timescales, and to volcanic activity at annual to multi-decadal timescales. The multi-decadal climate response to volcanic forcing arises because, although the climate effect of a single

volcanic eruption may just last a few years, there exist multi-decadal periods where the frequency of eruptions has been considerably greater than average, for reasons yet unknown. A series of eruptions can then tip the climate system to a colder state giving rise to a longer-lasting climate response (Borzenkova 2012; Miller et al. 2012).

2.2.1.1 Astronomical Conditions

The only source of external climate forcing that can be accurately calculated is the Earth's orbital forcing (see Fig. 2.1 for an illustration of the Late Holocene trends). For longer periods, the evolution of solar insolation deviates too strongly from linearity to be represented by linear trends.

Variations in the position of the point of the orbit closest to the sun (perihelion), the obliquity of the Earth's axis and the eccentricity of the orbital ellipse, redistribute the incoming solar energy through the seasons and across latitudes. Although it is acknowledged that orbital variations are the main cause of the recurrence of glacial and interglacial periods, orbitally induced temperature variations can be reinforced by other factors, such as natural variations in atmospheric concentrations of greenhouse gases. The precise mechanisms that result in the interglacial successions, and thus caused the last deglaciation that extended from 20,000 to 10,000 cal year BP, are still not completely understood, and climate models are not yet able to reproduce the millennial-scale evolution of the rise in global sea level since the Last Glacial Maximum as reconstructed from proxy records (Brovkin et al. 2012). Since obliquity and eccentricity vary over longer timescales, the most important orbital factor during the relatively short Holocene period was the shift in the perihelion, from July 10,000 years ago to its current position at the beginning of January. Thus, northern high-latitude summers have received diminishing amounts

of solar insolation over the past few millennia, with a linear trend more negative than -5 W m^{-2} per thousand years at the latitudes of the Baltic Sea region (about 60°N). In contrast, winter, spring, and autumn have received increasing levels of insolation over the Holocene. Since most proxy records reflect summer mean temperature or the temperature in the biological growing season, the millennial trends or the changes between mid-Holocene and present reflected in the proxy records should be interpreted based on biological knowledge about that particular proxy.

2.2.1.2 Solar Activity

Solar irradiance, the energy of the sun reaching the upper layers of the atmosphere (the solar 'constant'), also varies over all timescales due to internal solar dynamics. Past solar irradiance can be approximately reconstructed and dated by analysing the concentrations of cosmogenic isotopes, beryllium-10 (^{10}Be) in polar ice cores and carbon-14 (^{14}C) in tree rings, and over the past 400 years from the reported number of sun spots (see for instance, Crowley 2000). Although the general shape of the time evolution for solar irradiance is generally agreed upon, the magnitude of its variations at centennial timescales is still contended. Some authors suggest values of the order of 0.5 % of the total solar constant (Shapiro et al. 2011), while others interpret the isotopic record to indicate typical changes of the order of 0.1 % (Schmidt et al. 2011). The recent reconstruction by Shapiro et al. (2011), displaying amplitude of centennial variations of the order of 0.5 %, has been critically assessed by the climate research community.

Figure 2.2 illustrates the wide range of uncertainty between two multi-millennial reconstructions of total solar irradiance by displaying two extreme estimates, both very recent. Thus, it is still unclear whether cooling or warming

Fig. 2.1 Linear trends in solar insolation in the boreal mid- and high latitudes as a function of season and latitude over the past 4000 years, calculated from data by Laskar et al. (2004)

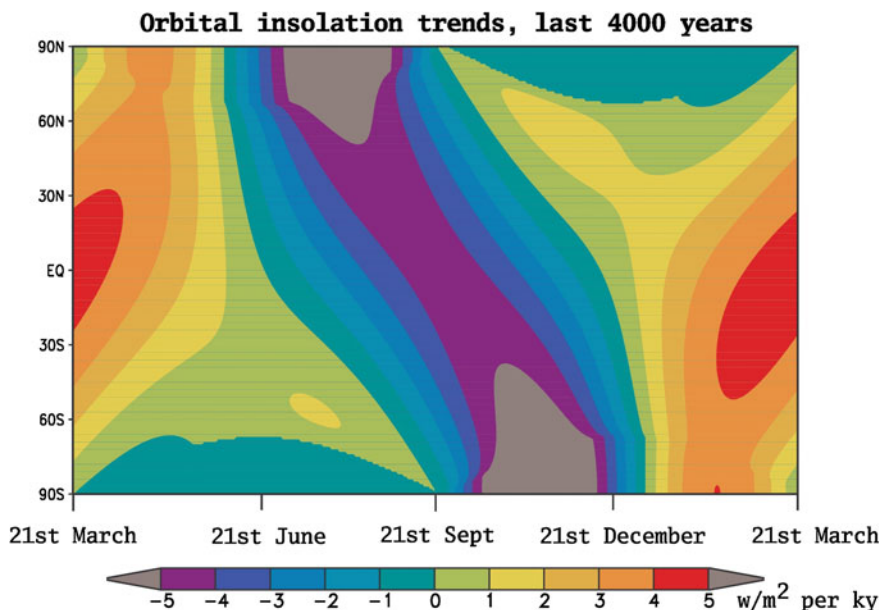
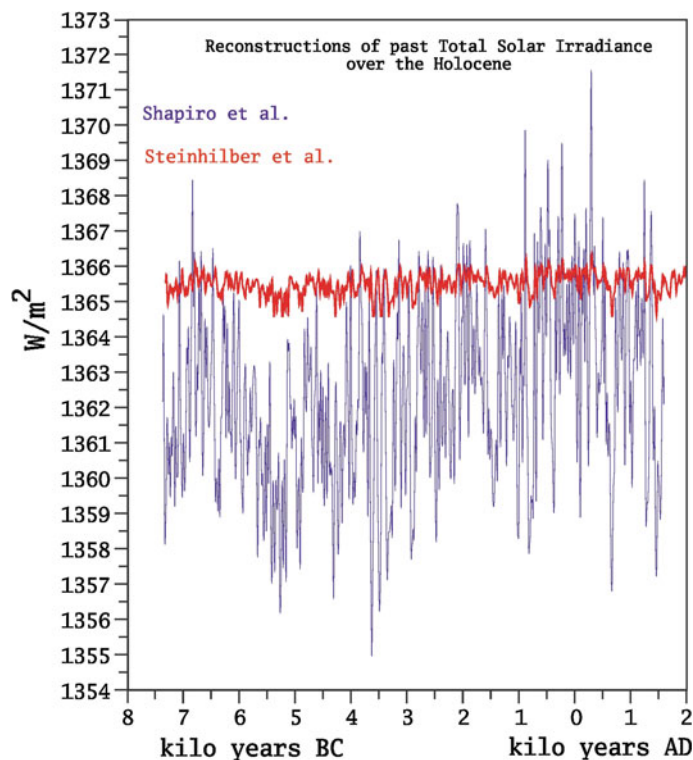


Fig. 2.2 Reconstructions of past total solar irradiance based on ^{10}Be concentrations in polar ice cores and different assumptions about solar physics. Adapted from Steinhilber et al. (2009) and Shapiro et al. (2011)



events can be confidently attributed to changes in solar irradiance alone, even when they are coincidental with periods of markedly different solar irradiance, or whether reinforcing mechanisms must be invoked (Shindell et al. 2001). Over the past millennium, for which more reliable reconstructions of volcanic activity exist than for previous periods, this situation is compounded by coincidences between solar minima and clustering of volcanic eruptions, as for instance during the Late Maunder Minimum and the Dalton Minimum. It is not known whether this coincidence also occurred prior to the past millennium.

2.2.1.3 Volcanic Eruptions

Past volcanic forcing can be reconstructed for recent centuries and, but with greater uncertainty, for the past few millennia by analysing the acidity of ice layers in polar ice cores (see Schmidt et al. 2011 for a thorough discussion). Volcanic eruptions produce vast amounts of sulphate aerosols which are transported through the stratosphere and deposited on snow and ice. The intensity, location, and seasonality of the eruptions (all important factors for estimate their climate effect) can only be indirectly inferred, which increases the uncertainty of estimating past volcanic forcing. Over the pre-industrial period, volcanic forcing is likely to have been the major factor driving external climate variability at multi-decadal and centennial timescales (Hegerl et al. 2003; Borzenkova et al. 2011; Borzenkova 2012; Miller et al. 2012). For periods further back in time, the lack of data precludes a robust inference.

2.2.1.4 Greenhouse Gases

Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)—greenhouse gases—have varied strongly since the Last Glacial Maximum and, albeit in a more subtle way, during the Holocene. Atmospheric CO_2 levels rose from 180 to 280 ppm between the glacial state and the start of the Holocene 10,000 cal year BP (Borzenkova 1992, 2003; Blunier and Brook 2001; Flückiger et al. 2002). Since then, there has been a slight, and intriguing, positive trend, the causes of which are unclear (Ruddiman et al. 2011).

Several factors, such as reforestation, coral growth and ocean geochemistry (carbonate compensation), are likely to be contributed to the changes in Holocene CO_2 concentrations (Joos et al. 2004). However, this small trend in rising Holocene CO_2 levels could only have had a very small effect on climate, if any at all. (Only from about the year 1750, the point at which atmospheric greenhouse gas concentrations rose sharply, could they have made a significant contribution to climate change.)

2.2.2 Climate Modelling of the Holocene in the Baltic Sea Basin

Ideally, the external forcing mechanisms described in this chapter could be used to drive a global climate model that would simulate the Earth's climate over the Holocene.

To date, this has only been possible using simplified climate models, since the computing requirements needed to reconstruct a period of several thousand years are considerable. These ‘models of intermediate complexity’ cannot adequately represent the Baltic Sea basin. Although the first simulations with comprehensive ocean–atmosphere global models covering the past 7000 years have recently been completed (Hünicke et al. 2010), the resolution of these models is still insufficient for a realistic representation of the Baltic Sea. For example, in these models the North Sea–Baltic Sea gateway is either closed or is 700 km wide. To properly simulate the climate of the Baltic Sea area, regional atmosphere–ocean models with a high spatial resolution are required (see Chap. 10). Such models, however, have not yet been applied for the long timescales of the Holocene. This is a task that could be envisaged for the coming decade, as it is not presently feasible. However, some ongoing projects will soon be able to simulate particular time slices (e.g. a few hundred years), of the Baltic Sea climate in the Holocene. A regional simulation of the past millennium was recently performed at the Swedish Meteorological and Hydrological Institute (Schimanke et al. 2012, see Chap. 3); this time span will hopefully be expanded back into the past.

In addition to the external climate drivers, nonlinear mechanisms within the different components of the climate system give rise to internal climate variability over all timescales. At the timescales relevant for the Holocene as a whole, multi-centennial and millennial, interaction between the hydrosphere and ocean dynamics are believed to have been the main factors modulating the climate variability superimposed on the millennial trends caused by the orbital forcing. Perhaps the best known episode of multi-centennial climate variability in the Holocene is the ‘8.2 ka cold event’; a sudden cooling that lasted for about 200–300 years, and that has left its imprint on many proxy records around the North Atlantic basin including northern Europe, as reported in several comprehensive reviews (Alley and Ágústsdóttir 2005; Rohling and Pälike 2005). A series of modelling studies (Renssen et al. 2001) supported the idea that the 8.2 ka cold event was caused by a sudden slowdown of the North Atlantic Meridional Overturning Circulation (AMOC), itself caused by a sudden release of melt water from the remnants of the Laurentide Ice Sheet into the North Atlantic Ocean. However, a large uncertainty concerning the volume of melt water which may have been discharged, its timing and the discharge rate still remains. According to this mechanism, freshening of the surface waters in the North Atlantic Ocean hindered oceanic convection and the deep-water formation that is typical of the present climate, thus reducing the amount of heat flux from the ocean to the atmosphere and also slowing the northward heat advection by the North Atlantic currents. Oceanic convection would have resumed once the anomalously fresher seawater in the

high-latitude North Atlantic Ocean had been re-distributed through the world ocean, which would have required a period of a few hundred years (Clark 2001; Clark et al. 2002; Clarke et al. 2004).

2.3 Palaeoclimatic Reconstructions Over the Holocene

2.3.1 Sources of Palaeoclimatic Data

Pollen records from mire deposits, lake sediments and sea sediments have been used to reconstruct climate variability during the Late Glacial and the Holocene periods. New quantitative information has been obtained from pollen and chironomid data over the past few years due to more detailed analysis and ^{14}C dating of sediments. The new insights are based on calibration of the modern pollen, diatom and beetle fauna data to climate parameters (annual and seasonal air temperature and annual precipitation) using different types of transfer functions (Birks 2003). However, the results from earlier investigations are still relevant.

The most recent and carefully investigated sediment sequences used for climate reconstruction stem from the following lakes: Svētiņū (Veski et al. 2012), Kurjanovas (Heikkilä et al. 2009), Busnieks (Grudzinska et al. 2010; Ozola et al. 2010), mires: Cena (Kalniņa 2007, 2008), Eipurs, Dzelve (Kuške et al. 2010a), Rozhu (Kuške et al. 2010b) and from archaeological sites at Lubans (Kalniņa et al. 2004), Sarnate (Kalniņa et al. 2011) and Priedaine (Cerina et al. 2010) (see Table 2.1). Some of the pollen records have been re-interpreted using the model REVEALS. This model estimates the relative species composition in a region from the pollen counts found in lake sediments layers, describing the dispersal and deposition of pollen and taking into account inter-species differences in pollen productivity (Sugita 2007; Ozola and Ratniece 2012).

2.3.2 Methodology for Palaeoclimatic Reconstructions

There are three established ways of using palaeobotanical data for palaeoclimatic reconstructions. All three involve the use of plant species (or sometimes genera) as climate indicators together with statistical methods to infer climate by mapping vegetation composition on climatic zones. Because these methods all extrapolate the ecological requirements of modern plants back into the past, this necessarily introduces a certain degree of uncertainty.

The first method was published by Iversen (1944), who examined the modern distributions of *Ilex aquifolium* (holly), *Hedera helix* (ivy), and *Viscum album* (mistletoe) in

Table 2.1 Location of sites dated by ^{14}C used in this study

Site No.	Location	Lat (N)	Lon (E)	Source
1	Toskaljavi, Finland	69°12	21°28	Seppä et al. (2002a)
2	Tsuolbmajavi, Finland	68°41	22°05	Kornola et al. (2000), Seppä and Birks (2001)
3	Tibetanus, Sweden	68°20	18°42	Hammarlund et al. (2002)
4	L. Späime, Sweden	63°07	12°19	Velle et al. (2005)
5	Nautajärvi, Finland	61°48	24°41	Ojala et al. (2008)
6	Klotjärnen, Sweden	61°49	16°32	Giesecke (2005), Giesecke et al. (2008)
7	Laihalampi, Finland	61°29	26°04	Heikkilä and Seppä (2003)
8	Mentilampi, Russia	61°22	29°15	Davydova et al. (1998)
9	Holtjärnen, Sweden	6°39	15°56	Giesecke (2005)
10	Medvedevskoye, Russia	60°13	29°54	Subetto et al. (2002)
11	Pastorskoye, Russia	60°13	30°02	Subetto et al. (2002)
12	Arapisto, Finland	60°35	24°05	Sarmaja-Korjonen and Seppä (2007)
13	L. Gilltjärnen, Sweden	60°05	15°50	Antonsson et al. (2006)
14	Vääna Lagoon, Estonia	59°22	24°25	Saarse and Vassiljev (2010)
15	Flarken, Sweden	58°33	13°44	Seppä et al. (2005)
16	Trehörningen, Sweden	58°33	11°36	Antonsson and Seppä (2007)
17	Igelsjön, Sweden	58°28	1°44	Hammarlund et al. (2003, 2005)
18	Lake Vättern, Sweden	58°48	14°36	Björck et al. (2001)
19	Pulli, Estonia	58°26	24°35	Veski et al. (2005)
20	Löpe, Estonia	58°26	24°35	Veski et al. (2005)
21	Cena Mire, Latvia	57°69	22°49	Kalniņa (2008)
22	Sarnate site, Latvia	57°10	21°47	Kalniņa et al. (2011)
23	Busnieks Lake, Latvia	57°23	24°51	Grudzinska et al. (2010)
24	Bazhi Mire, Latvia	57°69	22°48	Pakalne and Kalniņa (2005)
25	Engure Lake, Latvia	57°18	23°15	Kalniņa et al. (2012)
26	Dzelve Mire, Latvia	57°23	24°51	Kuške et al. (2010a)
27	Eipurs Mire, Latvia	57°24	24°62	Kuške et al. (2010a)
28	Roûge, Estonia	57°44	26°54	Veski et al. (2004)
29	Rozhu Mire, Latvia	56°86	26°88	Kuške et al. (2010b)
30	Svētiņū Lake, Latvia	56°45	27°09	Veski et al. (2012)
31	Priedaine site, Latvia	56°97	23°91	Cerina et al. (2010)
32	Eini site, Latvia	56°86	26°88	Kalniņa et al. (2004)
33	Viki Mire, Latvia	56°52	22°91	Kuške et al. (2010b)
34	Petrašiūnai, NE Lithuania	55°51	25°25	Stančikaitė et al. (2009)
35	Kašučiai Lake, western Lithuania	55°59	21°18	Stančikaitė et al. (2008)
36	Juodonys, Lithuania	55°44	25°26	Stančikaitė et al. (2009)
37	Hańcza, NE Poland	54°16	22°49	Lauterbach et al. (2011)
38	Pamerkiai, SE Lithuania	54°18	24°44	Stančikaitė et al. (2008)
39	L. Sumenko, northern Poland	54°11	17°48	Tylmann et al. (2011)
40	Biebrza Upper Basin, NE Poland	53°44	23°23	de Klerk et al. (2007)
41	Kurjanovas, Latvia	56°31	27°59	Heikkilä and Seppä (2010)
42	Zabieniec bog, central Poland	51°51	19°47	Plóciennik et al. (2011)
43	L. Perespilno, Poland	51°26	23°33	Goslar et al. (1999)
44	L. Słone, SE Poland	51°18	22°03	Kulesza et al. (2011)

(continued)

Table 2.1 (continued)

Site No.	Location	Lat (N)	Lon (E)	Source
45	No. 554, Gulf of Riga, water depth, 38.0 m; length of analysed sediments, 7.0 m	57°16	24°06	Kalniņa et al. (2012, 2003, 2012)
46	No. 556, Gulf of Riga, water depth, 32.4 m, length of analysed sediments, 3.55 m	57°06	23°29	Kalniņa et al. (2003)
47	No. 15, Gulf of Riga, water depth, 37.0 m; length of analysed sediments, 21.4 m	57°31	23°04	Kalniņa et al. (1999, 2003)
48	No. 989, Gulf of Riga, water depth, 49.5 m; length of analysed sediments, 5.1 m	57°47	23°26	Kalniņa et al. (1999, 2003)

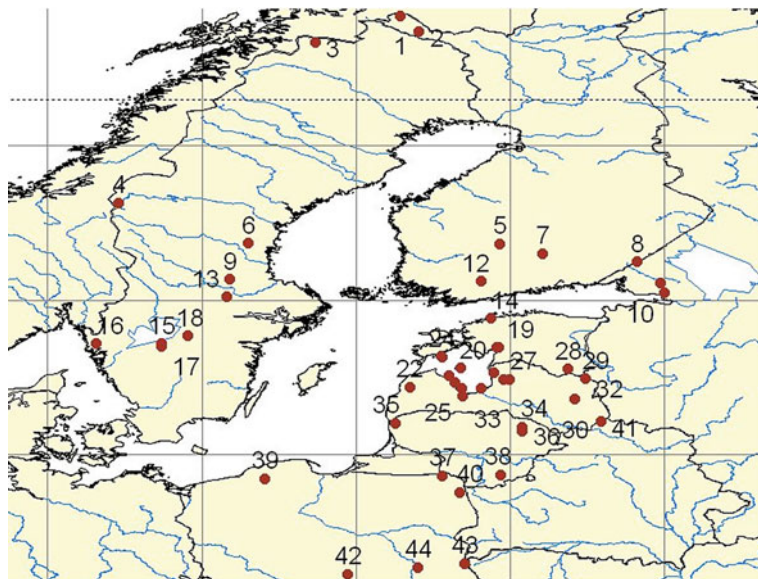
northern Europe and established a relationship between their occurrence and mean summer and winter temperatures. This approach is still applied to quantitative palaeoclimatic reconstructions (e.g. Zagwijn 1994). The second method, developed by V.P. Grichuk from Iversen's method, is known as the mutual climatic range method (Grichuk et al. 1984). This consists of determining the modern ranges of climatic factors that permit the existence of all the species of plants identified in the composition of a given fossil flora, either from pollen or plant macrofossil data. For each plant species, the modern climate ranges are determined and the intersection of all climate ranges of all species present in a given fossil flora determines the climatic conditions that allowed the existence of all species identified in a given sample.

The third method was also developed by V.P. Grichuk. It consists of reconstructing the main climatic indices from fossil plant data using a concept developed by Szafer (1946). This author proposed to locate a modern analogue of a palaeoflora by comparing present-day ranges of plants. This method has been widely used to reconstruct the Lateglacial and Holocene climate in the Russian territory (e.g. Borisova 1990, 1997). The accuracy of this method for determining mean summer and winter temperatures has been estimated at about ± 1 °C. For annual precipitation, the estimated accuracy is about ± 50 mm (Grichuk et al. 1984), assuming no change in plant physiology. Other methods for climate reconstructions using pollen data have recently been developed. These are based on multi-variate statistical techniques. A number of different mathematical techniques, ranging from multiple regressions to correlation analysis, can be used to design transfer functions. The calibration of a statistical transfer function for pollen data requires a collection of modern surface pollen samples that are mathematically correlated to modern climate parameters. Transfer functions have been developed for different parts of the Baltic Sea basin and can be applied to climate reconstructions in the Lateglacial–Holocene period (Seppä 1996; Seppä and Birks 2002; Seppä et al. 2002a, b, 2004a, b, 2005, 2008; Birks 2003; Heikkilä and Seppä 2003, 2010; Antonsson 2006; Antonsson et al. 2006, 2008; Antonsson and Seppä 2007;

Birks and Seppä 2010). A calibrated pollen–climate model has been recently developed to quantitatively reconstruct the Holocene annual mean, summer and winter air temperatures in northern Europe and in the Baltic Sea region. The model is based on modern pollen data sets from Finland, Estonia, and southern and central Sweden.

Common climatic fields and information-statistical methods have been successfully used to process fossil insect data (Coleoptera and Chironomidae) (Lemdahl 1991, 1997, 1998; Coope and Lemdahl 1995; Coope et al. 1998; Laroque et al. 2001; Walker 2001; Velle et al. 2005; Luoto 2009a, b; Olsson and Lemdahl 2009, 2010). Mean temperature estimates for the Lateglacial–Holocene transition were reconstructed based on coleopteran data from a number of sites in southern Sweden, central Poland and southern Finland (Lemdahl 1997; Coope et al. 1998; Lemdahl and Coope 2007). Continuous beetle records, covering almost the entire Holocene, have been obtained from sites in the uplands of southern Sweden (Olsson and Lemdahl 2009; Olsson et al. 2010) and at three alpine sites in the Abisko area, northern Sweden (Buckland et al. 2011). Fossil Coleoptera (beetles) can serve as a good proxy indicator of Lateglacial and Holocene climate changes in the Baltic Sea basin (Walker 2001). Many palaeoclimatic studies have been carried out in this region showing the presence of Coleoptera assemblages during interstadials (short warmer periods embedded in the glacial periods) that are more thermophilous than modern temperate, boreal or polar assemblages of beetle species. Beetle populations react rapidly to climate change and thus are indicative of contemporary climatic conditions. Coleoptera fauna have been widely employed to generate both temperature estimates and thermal gradients during the Lateglacial period in northern Europe. Chironomids (non-biting midges) are of special interest in palaeoclimatology because their larval head capsules remain well preserved in lake deposits. By using inference models that link present distribution and abundance of chironomids to contemporary climate, the past climate can be quantified from fossil assemblages. Chironomid populations respond rapidly to climate change and occur in a wide variety of modern environmental conditions (Brooks and Birks 2000, 2001;

Fig. 2.3 Location of sites discussed in this study. Numbers refer to site numbers in Table 2.1



Larocque et al. 2001; Velle et al. 2005; Antonsson 2006; Luoto 2009a, b). Statistical comparison between modern chironomid assemblages and July temperature enables the calibration of statistical models and this provides a basis for quantitative estimates of summer temperature during the Lateglacial period (Velle et al. 2005; Antonsson 2006). Finally, by comparing pollen-inferred temperatures with independent proxy records (e.g. chironomids and oxygen isotopes), it is possible to create a more comprehensive picture of past climatic patterns in the Baltic Sea basin (Rosén et al. 2001).

Dendroclimatological data are more successfully used to reconstruct climate in those sites where climate is a limiting factor (such as at the latitudinal or altitudinal boundary of the forest). Various dendrochronological records are used as indicators of climate change and have been used to reconstruct temperature and humidity during the warm season. These comprise tree ring width, wood density, distribution of frost-damaged rings (Briffa et al. 2001), and stable isotopes of hydrogen, oxygen and carbon stored in cellulose. Analysis of radiocarbon (^{14}C) from tree rings has been used to establish high-resolution radiocarbon chronologies. The density of wood in tree rings determined by X-ray densitometry is a much more informative characteristic of past climate compared to the conventional data on tree ring width. In recent times, this technique has been widely accepted, and data on tree ring density of coniferous (predominantly pine and black spruce) and oak trees have been used to reconstruct the summer air temperature over the past millennia (Grudd 2008; Esper et al. 2012). Long Holocene chronologies consist of oak and pine tree ring data from the southern part of Germany and cover large portions of the Lateglacial period, extending into the Younger Dryas back

to about 12,000 years ago (Friedrich et al. 1999), see also Chap. 3, Sect. 3.3.

The oxygen-isotopic palaeothermometry method is being widely applied not only to organic carbonates of marine origin but also to freshwater lake sediments (algae, lake marl), inorganic carbonate in caves (stalactites and stalagmites), and continental glaciers (mountain glaciers, polar ice sheets) (Mörner 1980; Seppä and Hammarlund 2000; Baldini et al. 2002; Hammarlund et al. 2002, 2003, 2005; Rasmussen et al. 2006; Kobashi et al. 2007, 2008).

Among other indications of past climate change in wide use is the diatomic analysis of lake sediments, data on varve width—which may depend on summer water temperature—and archaeological artefacts. Such artefacts (tools, land cultivation traces, ceramics) are primarily indicative of improved climatic conditions in the Baltic Sea basin, in particular increased summer and winter air temperatures and humidity (Pazdur 2004; Poska et al. 2004, 2008; Dolukhanov et al. 2009a, b, 2010).

To reconstruct past landscapes and climate, the entire set of available proxy evidence is used. This should render these reconstructions more robust. Table 2.1; Fig. 2.3 show key sections of the data used in this review.

2.4 Climate Variability During the Holocene Relevant for the Baltic Sea Basin

The modern Greenland Ice Core chronology (GRIP, NGRIP, and Dye-3) places the Younger Dryas /Holocene boundary at about 11,653 ice years ago (Alley 2000; Rasmussen et al. 2006; Walker et al. 2009). By analysing the ^{14}C isotope

content in tree rings, this boundary has been dated to 11,573 cal year BP and by tree ring chronology at ~11,590 cal year BP (Kobashi et al. 2008). This boundary almost coincides with the final drainage of the Baltic Ice Lake at in the Billingen area (central Sweden).

2.4.1 Climate at the Boundary of the Younger Dryas/Holocene

Two rapid warming events dated ~14,700 and ~11,500 cal year BP were clearly greater than background climate variability (Mangerud 1987; Björck et al. 2001; Hoek 2001; Hoek and Bohncke 2001; Hoek and Bos 2007; Hoek et al. 2008; Lowe et al. 2008). Between these intervals, the climate varied between alternating centennial warm and cool phases. During a warm episode around ~14,700 cal year BP, air temperatures in ice-free regions of the Baltic Sea basin increased to values close to modern values. This can be inferred from data of changing vegetation (Hoek 2001) and is consistent with modelling results obtained by Renssen and Isarin (2001) with the general circulation model ECHAM4. In their study, ECHAM4 was driven by different reconstructions of sea surface temperature available at the time of publication, by changed orbital configuration and by reconstructions of vegetation cover. Summer air temperatures in ice-free regions reached 13–15 °C as indicated by pollen of *Hippophaë rhamnoides* (sea buckthorn) and *Typha latifolia* (cat's tail). The latest results show that during the Bølling warming 14,500 cal year BP (GI-1e), a treeless tundra community comprising the shrubs *Betula nana* (dwarf birch), *Dryas octopetala* (mountain avens) and *Salix polaris* (polar willow) thrived in the eastern Baltic Sea area (Veski et al. 2012). This warming was interrupted by a series of cold episodes: the Oldest Dryas (GS-2a), the Older Dryas (GI-1d) and the Younger Dryas (GS-1). During the latter period, the cooling lasted for 700–1000 years and the expansion of arboreal vegetation that had started during the Bølling (GI-1e) and Allerød (GI-1a-c) warming was interrupted. The vegetation cover was again replaced by tundra–steppe vegetation typical of the glacial period. During the warmest period of the GI-1a (Allerød) at 13,000–12,700 cal year BP, a pine forest mixed with deciduous trees of the species *Betula pendula* (silver birch) and *Populus tremula* (common aspen) developed in the eastern Baltic region (Veski et al. 2012).

During the Younger Dryas, the ice sheet still covered a considerable part of Fennoscandia, and sea level was 60–70 m lower than at present. The Baltic Sea basin was filled with freshwater and comprised the Baltic Ice Lake with a dry area where the modern Danish–Swedish straits are located and a land strip 50–80 km wide along the modern coast of the north German and Pomeranian lowlands. The coasts of

the Gulfs of Riga and Finland and the Ladoga Lake basin, being subject to a strong glacio-isostatic depression, were submerged (Björck 1995; Mangerud et al. 2007). The cooling at that time has been correlated with the phases of glacial advance that resulted in the formation Salpausselkä I and II ice marginal formation, dated to 12,250 and 11,600 cal year BP, respectively (Rainio et al. 1995; Subetto et al. 2002; Rinterknecht et al. 2004, 2006; Subetto 2009). During the formation of the Salpausselkä marginal formation, the northern lowland part of the Karelian Isthmus formed the bottom of the Baltic Ice Lake, filling with its waters the Baltic and Ladoga basins (Subetto 2009).

The sediments of the periglacial lakes and the Baltic Ice Lake in the Gulf of Riga contain the lowest concentration of pollen and spores. At that time, the periglacial vegetation type emerged on weakly developed soils formed under conditions of severe Arctic-like climate. On the Karelian Isthmus, cold and dry climatic conditions and grass–bush (tundra–steppe) associations dominated until 11,000 cal year BP (Miettinen et al. 2007). The Younger Dryas (GS-1) cool phase strongly affected the floral composition of the vegetation. The pine forest collapsed within 100 years in eastern Latvia (Veski et al. 2012). The landscape again became treeless tundra as indicated by pollen spectra dominated by *Betula* sect. *albae*, *B. nana*, *Pinus*, *Salix*, *Artemisia*, *Poaceae*, *Cyperaceae*, *Chenopodiaceae* and *Dryas* (Ozola et al. 2010).

On the shores of the Baltic Ice Lake in the territories of modern Lithuania, Latvia and Estonia open tundra landscapes became widespread. Reconstructions based on the transfer function between modern climate and vegetation assemblage indicate that the mean annual temperature during the coldest period of the Younger Dryas (about 10,500–10,700 ¹⁴C year BP) was approximately 6 ± 1 °C lower than the present mean annual temperature (Arslanov et al. 2001).

Analysis of relic cryogenic forms indicates that permafrost developed in an ice-free territory of the Baltic Sea basin in the Younger Dryas (Mangerud 1987; Isarin et al. 1997). In addition, there is also evidence of activation of aeolian processes (Isarin et al. 1997; Isarin and Bohncke 1999; Kasse 2002), changes in river channel morphology (Starkel 1999) and lake levels and composition of lake sediments (Subetto 2009).

Air temperature has been estimated by applying the method of arealograms based on palaeofloristic data (pollen and plant macrofossil data) (Borisova 1990, 1997). The results show that during the coldest phase of the Younger Dryas, deviations of the mean January temperature from the modern value were greatest in north-western Europe, that is, in the Baltic Sea basin. The January temperature there attained values 10–13 °C below the modern level. As at present, mean temperature decreased from west to east, from approximately –14 °C at the Jutland Peninsula to –20 °C on the coasts of the Gulf of Finland. Temperature deviations for the warmest month (July) from modern values were much

smaller, about -2 °C on the southern coast of the Baltic Ice Lake. For most of this region, the July temperature in the Younger Dryas was about 13 – 14 °C (Borisova 1997).

In northern Germany, July temperatures were about 12 °C and in central Germany and Poland about 13 °C (Borisova 1990). In Finnish Karelia, they were 7 – 10 °C, in southern Sweden about 10 °C and in western Poland about 12 °C. In Poland, mean January temperatures were never above -20 °C (Walker 1995).

Analyses of the stable isotope content of Lake Gościąż sediments from the middle part of the Vistula River basin suggest that the July temperature was about 10 – 13 °C in the Younger Dryas (Starkel 2002). An independent reconstruction based on insect fauna composition (Chironomidae) indicates that the July temperature in south-western Norway near the south-western border of the Scandinavian ice sheet (Velle et al. 2005) was 5 – 6 °C compared to 11 °C at present. In south-eastern Karelia east of the Onega Lake (beyond the limits of the Baltic Sea basin), the minimum July temperature in the Younger Dryas has been estimated at 4 °C by pollen and macrofossils of *B. nana* versus a modern July temperature of 14 °C (Wohlfarth 1996; Wastegård et al. 2002; Wohlfarth et al. 2002, 2007).

Mörner (1980) was the first to quantitatively estimate air temperature changes at the Younger Dryas/Holocene boundary by oxygen isotope analysis of lake carbonates from southern Sweden. This data set showed a rise in air temperature of about 9 °C at the Younger Dryas/Holocene boundary. Independent estimates of the $^{29}\text{N}/^{28}\text{N}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ ratio in Greenland ice cores showed a temperature increase at the Younger Dryas/Holocene boundary of 10 ± 4 °C and that this occurred within less than 50 years (Grachev and Severinghaus 2005).

The first warming in marine sediment (in the Gulf of Riga) is reflected by the dominance of *Pinus* pollen, the presence of *B. nana*-type pollen up to 20 %, and pollen and spores of the periglacial plants *D. octopetala*, *H. rhamnoides* and *Selaginella selaginoides* (Kalniņa et al. 1999).

The end of the Younger Dryas (11,700 cal year BP) is marked by the rise of *Betula pubescens/pendula* species and *Pinus* pollen curves, accompanied by the abundance of their macrofossils and by a decline of *B. nana*, *Artemisia*, *Chenopodiaceae* and *Juniperus* (core No. 554, No. 989 and No. 15 in the Gulf of Riga, Eini Lake, Svētiņu Lake) (see Table 2.1) Within grass pollen, concentrations of *Poaceae* and *Cyperaceae* pollen also increased at this time (Kalniņa et al. 1999, 2011, 2012).

2.4.2 Early Holocene Oscillations

In the Early Holocene, a cold and relatively dry climate became suddenly warmer and more humid. The summer

temperature in north-western Russia increased from 4 to 10 – 12 °C (Wohlfarth et al. 2007). In the very first warm phase of the Preboreal around 11,530–11,500 cal year BP, the arboreal vegetation began spreading rapidly in ice-free regions as a result of an abrupt warming (within 50 years or less) and tundra–steppe vegetation dominated by shrubs and grass typical of the Younger Dryas was replaced by open forest associations (Bos et al. 2007). In the earliest warm phase of the Preboreal period, birch and pine started to spread, the former more vigorously than the latter. Periglacial vegetation still occupied large areas in some parts of the Baltic Sea basin. During the initial phase of this warming, the broad-leaved trees appeared in ice-free regions, where *Tilia*, *Ulmus*, *Corylus* and *Fraxinus* pollen was first found.

A shift from clastic–detrital deposition to an autochthonous sedimentation dominated by biochemical calcite precipitation was identified in the Early Holocene by accelerator mass spectrometer (AMS) ^{14}C dating $\sim 11,600$ cal year BP of Lake Hańcza (north-eastern Poland) sediments (Lauterbach et al. 2011). The accumulation of silt and clay was replaced by organic-rich gyttja at 11,650 cal year BP also in eastern Latvia (Veski et al. 2012).

Within the territory of the present Lithuania, a gradual amelioration of environmental conditions started at about 11,500 cal BP. However, there (Stančikaitė et al. 2004, 2008) and in north-western Russia (Wohlfarth et al. 2007) the change was less pronounced than that recorded in the North Atlantic region (Björck et al. 1996). The early expansion of *Picea* within the local vegetation, even before 11,500 cal BP, is worth noting. Despite a prolonged discussion involving pollen data, macrofossil finds and modern genetic information, the Lateglacial and Early Holocene history of *Picea* in this part of Europe is still under debate (Giesecke and Bennett 2004; Latałowa and van der Knaap 2006). Identification of *Picea* pollen and macrofossil finds suggests the local presence of this tree species during the earliest stages of the Holocene in the north-eastern and northern Lithuania (Kabailienė 1993; Kabailienė et al. 2009; Stančikaitė et al. 2009; Gaidamavičius et al. 2011). Recent evidence of stomata, needles and wood suggests that spruce populations expanded into Latvia during the Younger Dryas (Koff and Terasmaa 2011; Veski et al. 2012).

Moreover, the presence of *Picea abies* suggests a relatively warm climate in this region, with warm summers (~ 10 – 13 °C) and moist soil conditions (Giesecke and Bennett 2004) shortly before 11,500 cal year BP. However, changes in the vegetation composition point to the presence of at least two short cold climate episodes between 11,500 and 11,100 cal year BP in north-eastern Lithuania (Stančikaitė et al. 2009).

In Latvia, the earliest warm phase of the Preboreal period is marked by the rise of birch and pine curves in pollen diagrams. However, in several diagrams, especially those

from the Gulf of Riga (No. 989, No. 15), pollen and spores of periglacial plant (*B. nana*, *D. octopetala*) types are still present, albeit more rarely. Their values fluctuate strongly and display a marked spatial variability. Such fluctuations may suggest some climate instability. The pollen spectra characteristic of the Preboreal (PB) can be subdivided into two parts: those corresponding to the Early Preboreal (PB1), characterised by a small increase in *Betula* along with some increase in different grass pollen; and those spectra, mostly found in the second part of the Preboreal (PB2), where the typical Preboreal pollen is much reduced or completely missing. This can be explained by erosion of the sediment or by much reduced sedimentation rates during the Yoldia Sea stage (core No. 15, see Table 2.1).

The warming at the Holocene boundary, at about 11,530 and 11,500 cal year BP was interrupted by a short cold Preboreal oscillation dated using ice core data to 11,430–11,270 cal year BP (Rasmussen et al. 2006; Kobashi et al. 2008). A relatively short cooling phase (about 200–250 years long) occurred approximately 250 years after the final drainage of the Baltic Ice Lake, when seawater flowed into the Baltic Sea basin through the Närke Strait in Billingen due to a rapid rise in sea level resulting from the melting of the Scandinavian ice sheet (see Fig. 2.4). Brackish water entered the Yoldia Sea along the southern coast of the Gulf of Finland and freshwater flowed southwards from the melting ice sheet (Yu 2003).

The coldest part of the Preboreal oscillation is dated to ~11,430–11,350 cal year BP. The Preboreal cool oscillation



Fig. 2.4 The configuration of the Yoldia Sea stage at the end of the brackish phase at 11,100 cal year BP (Andrén et al. 2011)

almost coincides with the short brackish phase of the Yoldia Sea whose end has been dated to 11,200 cal year BP (Heinsalu and Veski 2007), which corresponds to the age 11,190 year BP in the GRIP ice core (Björck 1999).

At the start of the Preboreal cooling phase, sea level was approximately 50 m lower than at present. Subsequent melting of the continental ice sheets (Laurentide and Scandinavian) caused an increase in ocean volume and sea level rose.

Pollen stratigraphy clearly suggests some climate instability in the Early Holocene. During its coldest phase, forest tundra and open forest landscapes were established over the greater part of the Baltic Sea basin. This vegetation type remained in some regions until 10,700–10,600 cal year BP. Pazdur (2004) characterised the Preboreal climatic conditions in Poland as cold and dry. At this time, birch expansion that had started during the warming at the beginning of the Early Holocene was interrupted by a dry continental phase characterised by open grassland vegetation (Rammelbeek Phase) (Bos et al. 2007).

Within the territory of the present Lithuania, the most prominent climate cooling recorded shortly before 11,100 cal year BP may be correlated with the climate event termed the Preboreal Oscillation (PBO) ca. 11,300–11,150 cal BP, described as a humid and cool interval in north-western and central Europe. Only after 11,100 cal year BP does ongoing forestation of the territory by open forest dominated by birch and pine suggest a climatic improvement that could be interpreted as a delayed Pleistocene/Holocene warming.

At the beginning of the Late Preboreal time, between 11,270 and 11,210 cal year BP, there was a sudden shift to a warmer and more humid climate, and forest vegetation expanded once more. Expansion of pine occurred in the later part of the Late Preboreal. This can also be inferred from the increase in organic matter in lake sediments from central Latvia after 11,200 cal year BP, likely to be due to the reduced inflow of minerogenic matter in a denser forest (Puusepp and Kangur 2010).

As indicated by the Greenland ice core GISP2 isotope data, at the Preboreal/Boreal (PB/BO) boundary air temperatures increased by 4 ± 1.5 °C (Grachev and Severinghaus 2005). At this boundary between 10,770 and 10,700 cal year BP, dense pine woodland started to expand in the southern part of the Baltic Sea basin (Bos et al. 2007). In north-western Russia, boreal forest comprising *Pinus*, *Picea*, *Betula*, *Alnus incana* was present at lower altitudes (Subetto et al. 2002).

At that time, open landscapes typical of the Preboreal cooling changed to poplar–pine–birch closed vegetation in southern Finland. From 11,000 cal year BP onwards, the glacial boundary retreated fast in the south of the modern boreal belt in Finland, and at about 10,700 cal year BP the



Fig. 2.5 The configuration of the Ancylus Lake stage during the maximum transgression at ca. 10.5 cal year BP (Andrén et al. 2011)

region was free of ice, although the ice boundary was still very close. According to estimates made by (Heikkilä and Seppä 2003), between 10,700 and 10,500 cal year BP, the mean annual temperatures were about -3.0 to 0 °C. These temperatures correspond to the modern temperature at 70°N .

This climate warming caused the rapid melting of the continental ice sheets. The subsequent isostatic uplift cut-off the Baltic Sea basin from the Atlantic Ocean and lead to its conversion into a large freshwater basin (Ancylus Lake). The culmination of the transgression phase of this lake is dated to about 10,700 cal year BP (Yu 2003). The Ancylus Lake stage lasted until approximately 9500 cal year BP. The

contemporary Baltic Sea basin is part of the last Littorina Stage when significant water level and salinity variations took place (see Fig. 2.5).

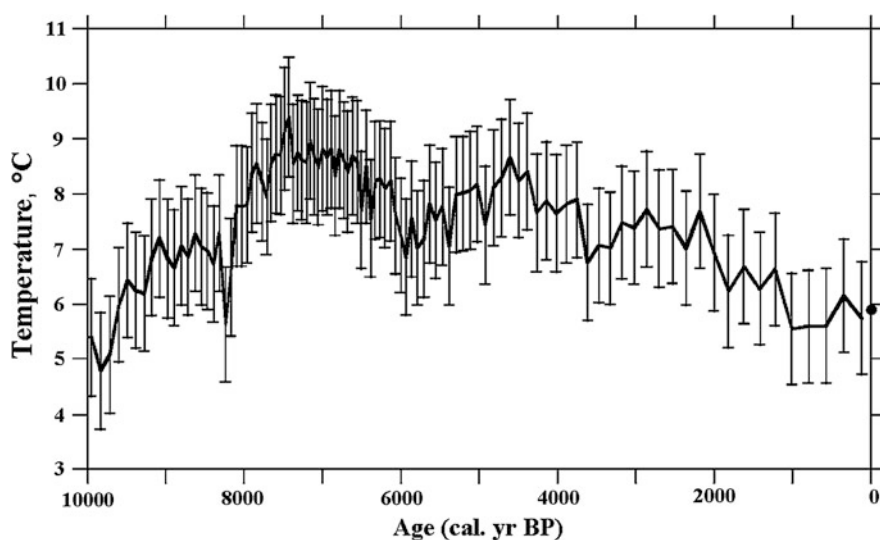
Beetle data from southern Sweden dated to between ca. 11,000 and 9000 cal year BP (Olsson and Lemdahl 2010; Olsson et al. 2010) suggest temperatures of the warmest month similar to present values. The relatively low numbers of aquatic species imply relatively dry and continental conditions. Reconstructed temperatures based on coleopteran data from Abisko are also similar to present temperatures (Buckland et al. 2011).

A temperature rise started after 10,000 cal year BP and lasted until the beginning of the cold event at 8200 cal year BP. Over the greater part of southern Sweden, Estonia, Latvia and Lithuania, open boreal woodlands and sparse birch vegetation were established. Summer air temperatures rose by 7 – 10 °C above the level attained during the Younger Dryas. However, major environmental changes in the area had begun already in 10,300–10,200 cal year BP, when deciduous trees including thermophilous species spread into the region.

According to data from Lake Hańcza in north-eastern Poland (11,600 cal year BP), the shrub pollen content of lake sediments decreased and a shift from clastic–detrital lake deposits to autochthonous sediments dominated by biochemical calcite occurred at the beginning of the Holocene. Warmer conditions ensued, and between 10,000 and 9000 cal year BP pollen spectra showed an increased content of pollen from broad-leaved trees. The organic content of the lake sediments also increased (Lauterbach et al. 2011). Figure 2.6 shows the reconstructed annual mean air temperature for south-central Sweden based on pollen data from Lake Flarken (Seppä et al. 2005).

The transition from the Ancylus Lake to the Littorina Sea in the Baltic Sea basin is marked by evidence of a weak

Fig. 2.6 Mean annual temperature reconstructed from pollen data from Lake Flarken (south-central Sweden) during the past 10,000 years (black line). Present-day mean annual temperature (5.9 °C) is marked by the point, modified from Seppä et al. (2005)



brackish phase between 9800 and 8500 cal year BP, called the Early Littorina Sea (Andr en et al. 2011). The ensuing brackish–marine stage is defined by evidence of significantly increased seawater influx (Hyv arinen et al. 1988) and an opening of the  resund Strait, an event dated to around 8500 cal year BP (Bj rck 1995; Yu 2003).

Between 11,000 and 9500 cal year BP, air temperatures in the Baltic Sea basin slowly raised reaching values of ~ 0.5 °C lower than at present. A prominent warming started about 9000 cal year BP and lasted until the Holocene thermal maximum (HTM) about 8000–4500 cal year BP, with summer air temperatures 2.5–3.5 °C above modern levels. Davis et al. (2003) reconstructed quantitative characteristics of the climate for the past 12,000 years in western Europe based on analyses of pollen data from more than 500 sections. In northern Scandinavia, summer air temperatures close to the modern levels have been inferred from pollen data (Sepp  and Birks 2001) and independent estimates based on chironomid and diatom assemblages (Ros en et al. 2001).

The temperature estimates based on macrofossils (for example, tree-line position) indicate a rapid and stable warming after 10,000 cal year BP across the entire northern Scandinavia (Sepp  and Birks 2001). Climate reconstructions for central Sweden using pollen spectra from Lake Giltj rnen sediments show a rapid increase in summer temperatures from 10.0 to 12.0 °C between 10,700 and 9000 cal year BP. This stable positive trend remained until the sudden cooling at about 8200 cal year BP (Antonsson et al. 2006).

2.4.3 The ‘8.2 ka Cold Event’

The ‘8.2 ka cold event’ was first identified from changes in oxygen isotope composition in ice cores from the Summit site in Greenland. The decrease in air temperature during this event has been estimated at 6 ± 2 °C in central Greenland (Allen et al. 2007; Alley et al. 1997; Muscheler et al. 2004; Alley and  g ustsd ttir 2005; Rohling and P like 2005; Thomas et al. 2007). An independent method to estimate both air temperature change and the duration of this cold phase, based on the concentrations of $\delta^{15}\text{N}$ in nitrogen (N_2) in ice cores (Leuenberger et al. 1999; Kobashi et al. 2007; Thomas et al. 2007). Kobashi et al. (2007) from the GISP2 ice core data, with a time resolution of ~ 10 year, showed a complex time evolution of this event.

The duration of the entire cold event was about 160.5 ± 5.5 years, the coldest phase occurring at 69 ± 2 years (Thomas et al. 2007). A drop in air temperature of 3 ± 1.1 °C occurred within less than 20 years. Independent estimates of changes in air temperature during this cooling event have been obtained from isotope data from four Greenland ice

cores: NGRIP, GRIP, GISP2, and Dye-3 (Thomas et al. 2007). According to the GRIP core data, the event has been dated to ca. 8190 ice years ago. The data from the GISP2 core revealed two milder cool stages: ca. 8220 and ca. 8160 ice years ago. The initial stage of cooling is more explicitly recorded in the NGRIP core data.

Independent empirical data, such as marine sediment cores with high resolution, lake sediments, clay varves, speleothem isotope data, and pollen diagrams among others, indicate that the cooling was widespread throughout the entire Baltic Sea basin, except for the most northern regions north of 70°N. The high-altitude glaciation intensified across all regions. In central and southern Norway, the snow line (equilibrium line altitude) lowered by 200 m (Nesje and Dahl 2001; Nesje 2009). The altitude of the upper boundary of arboreal vegetation also lowered (Sepp  and Birks 2001; Sepp  et al. 2007, 2008).

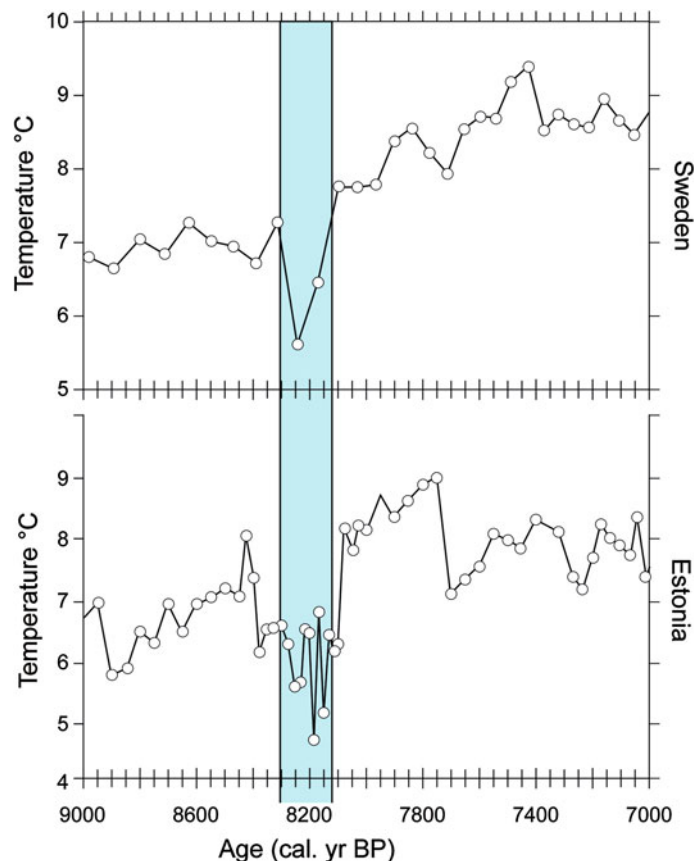
Pollen diagrams from lake and continental sediments provide independent evidence of this cooling. Davis et al. (2003) clearly identified the 8.2 ka cold event across the whole of western Europe, with the lowest air temperatures in areas adjacent to the North Atlantic Ocean (Sepp  et al. 2008; Rasmussen et al. 2009).

Pollen data from Estonia and southern Fennoscandia indicate a 1 °C air temperature drop (Fig. 2.7). At Lake R uge in Estonia, air temperature decreased by 1.8 °C (Veski et al. 2004), which agrees with estimates from pollen data from lakes in different part of Sweden (Lakes Giltj rnen, Flarken and Treh rningen) (see Fig. 2.8).

Lake sediments from four sites—Lake R uge (Estonia), Lake Flarken (Sweden), Lake Arapisto (Finland) and Lake Laihalampi (Finland), all located south of 61° N—indicate that the pollen percentage for the thermophilous deciduous tree taxa *Corylus* and *Ulmus*, decreased from 10 to 5 % in the Early Holocene to 5 % between 8250 and 8050 cal year BP (Sepp  et al. 2007). This implies a temperature drop of 0.5–1.5 °C at all these sites. Here, the cold event lasted 200–300 years and ended by a sudden temperature rise. In Estonia, the cold event lasted longer as indicated by a longer period of vegetation re-establishment after a decrease in annual air temperature of at least 1.5–2.0 °C (Sepp  and Poska 2004; Veski et al. 2004).

The 8.2 ka cold event has been identified in pollen diagrams from lake sediments from eastern Latvia (Eini, Malmuta) and the Gulf of Riga displaying a decrease in *Alnus*, *Corylus* and also *Ulmus*, and some increase in grass pollen. According to Heikkil  and Sepp  (2010), a relatively warm and stable climate was interrupted by cooling at about 8350–8150 cal year BP when mean annual air temperatures dropped by 0.9–1.8 °C. This was reflected in a change in vegetation composition, characterised by a decrease in broad-leaved tree productivity and an increase in the pollen of boreal species (Heikkil  and Sepp  2010). The limit of

Fig. 2.7 Two climate reconstructions for the cold event about 8200 cal year BP: annual air temperature reconstructed from pollen data from Lake Rõuge, Estonia (Veski et al. 2004) and pollen data from Lake Flarken, Sweden. The blue bar highlights the timing of the ‘8.2 ka cold event’ (adapted from Seppä et al. 2005)



detection for *Ulmus* and *Tilia* pollen is reached in the second part of the Boreal period when their pollen almost disappears before its contribution to the pollen assemblages starts rising again at beginning of the Holocene Thermal Maximum.

Re-establishment of *Picea* in the eastern Baltic Sea region (within the territory of the present Lithuania) is dated to 8600–8000 cal year BP. This short climatic deterioration may have limited the expansion of deciduous trees, providing more space for the expansion of spruce. The expansion of spruce may have been a response to a wet and cool climate with colder and snowier winters (Seppä and Poska 2004).

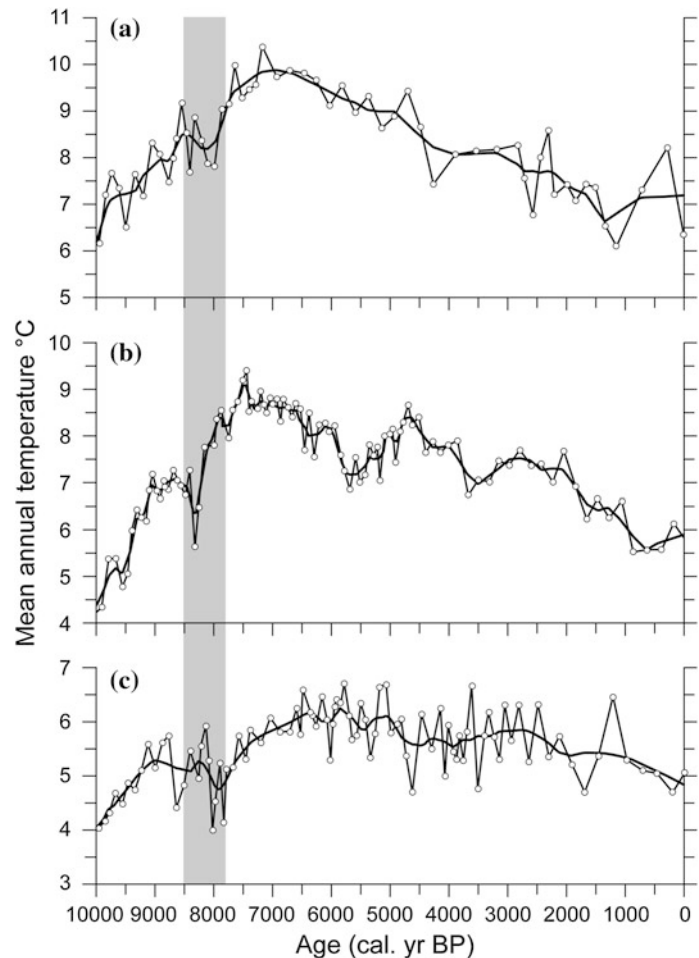
A section containing about 400 layers of varved sediments in west-central Sweden, supported by radiocarbon dating and by dendrochronological data, provides a detailed account of environmental development in this region, identifying an analogue of the 8.2 ka cold event between 8066 ± 25 cal year BP and 7920 ± 25 cal year BP. Snow precipitation increased during this cold period. The estimated duration of the 8.2 ka cold event has been estimated at 150 years (Snowball et al. 2002, 2010; Zillén et al. 2008; Zillén and Snowball 2009). There are no clear changes in the beetle assemblages from southern or northern Sweden that would indicate a cold spell during this time. This may be due to the insufficient time resolution of the data to identify this change.

In Germany, changes in the isotope composition of ostracod valve carbonate suggest this cold event lasts for about 200 years (von Grafenstein et al. 1998). Almost all data indicate that the decrease in air temperature was significantly greater in winter than in summer. This promoted an earlier freezing and later thawing of sea and lake surfaces.

The causes of the cooling during the 8.2 ka cold event and other cold episodes in the Lateglacial/Early Holocene drew the early interest of researchers (Alley et al. 1997; Barber et al. 1999; Leuenberger et al. 1999; Marotzke 2000; Clark 2001; Clark et al. 2002; Clarke et al. 2004; Alley and Ágústsdóttir 2005; Denton et al. 2005; Kobashi et al. 2007; Thomas et al. 2007; Yu et al. 2010). Although some scientists attribute the 8.2 ka cold event to changes in incoming solar radiation (Bos et al. 2007), most studies relate this cooling and other cooling events in the past 13,000 years to changes in the circulation of surface and deep water in the North Atlantic Ocean driven by melt water from the continental ice sheets.

Clark (2001) and Clark et al. (2002) assumed that freshening of the sea surface layer of the North Atlantic Ocean not only disturbed the circulation in the surface layer but also hindered the formation of deep water, thus affecting the intensity and position of the Atlantic ‘conveyor belt’ itself. Drainage of glacial lakes Agassiz and Ojibway due to

Fig. 2.8 Quantitative reconstructions of mean annual air temperature from pollen data for three lakes (C-Gilltjärnen, B-Flarken, A-Trehörningen). The grey bar highlights the timing of the ‘8.2 ka cold event’ (adapted from Antonsson and Seppä 2007)



the melting of the Laurentide Ice Sheet ca. 8470 cal year BP (~ 7700 ^{14}C year BP), during which about 2×10^{14} m^3 fresh lake water could have been released within less than 100 years, could have exerted a serious impact on the formation of sea ice, and thus significantly changing the timing of its formation in autumn and melting in spring. Sea ice has a higher albedo than open water, and a longer period of sea ice would cause an additional cooling (Barber et al. 1999; Clark 2001; Ganopolski and Rahmstorf, 2001; Fisher et al. 2002; Clarke et al. 2004; Wiersma and Renssen 2006; Widerlund and Andersson 2011).

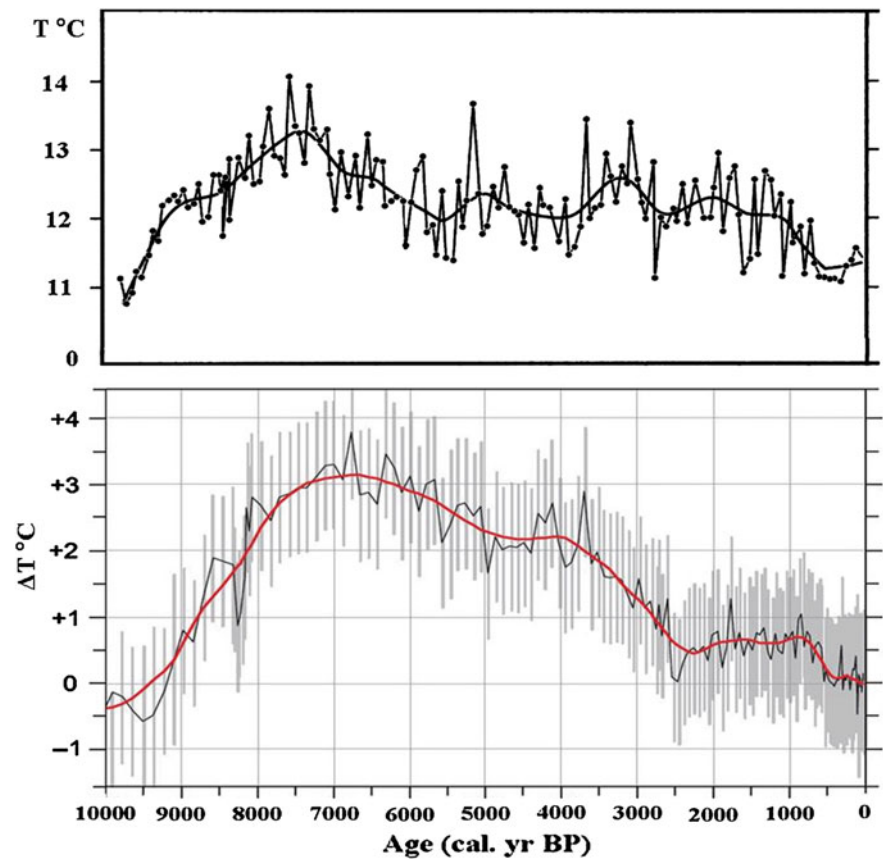
2.4.4 The Holocene Thermal Maximum

Pollen and chironomid records show that the period between 7500 and 5500 cal year BP was the warmest for the entire Baltic Sea basin area, although temperatures peaked at different times in different parts of the Baltic Sea basin, with amplitude varying from 0.8 to 1.5 °C and higher. The cold event at about 8.2 ka BP was followed by a warm period with air temperature and annual precipitation higher than

present. At that time, forest vegetation with thermophilous species flourished. In northern Finland, the warmest climate of the Holocene occurred between 8200 and 5700 cal year BP, with a temperature maximum at ca. 7950–6750 cal year BP. Pollen diagrams of Lake Tsuolbmajavri, northern Finland, suggest July temperatures around 13 °C. They dropped by 1 °C only after about 5750 cal year BP (see Fig. 2.9). According to the increasing *Pinus sylvestris* pollen percentages and by the decrease of lycopod and fern spore values, the mean annual sum of precipitation must have rapidly fallen to below 500 mm year^{-1} ca. 6650–5700 cal year BP (Seppä and Birks 2001), due to still unknown causes.

In the north-western part of Russia, forest vegetation with spruce and deciduous trees predominated (*Ulmus*, *Tilia*, *Quercus*). Between 8000 and 4500 cal year BP, summer temperatures were 2.0–2.5 °C and precipitation was 100–150 mm year^{-1} higher than present (Arslanov et al. 1999, 2001). On the Kola Peninsula, the warm period occurred between ca. 8000 and 4200 cal year BP with summer temperatures peaking around 6000–5000 cal year BP when July temperature was 13.6 °C (Solovieva et al. 2005).

Fig. 2.9 Reconstructed summer temperature in the northern and southern parts of the Baltic Sea basin. *Upper panel* The mean summer (July) air temperature reconstructed from pollen data from Lake Tsuolbmajavri, northern Finland 68° 41'N; *Lower panel* Reconstructed summer temperature anomalies shown as deviations from the modern reconstructed value. Lake Kurjanovas, south-eastern Latvia, 56° 31'N (adapted from Seppä and Birks 2001 and Heikkilä and Seppä 2010)



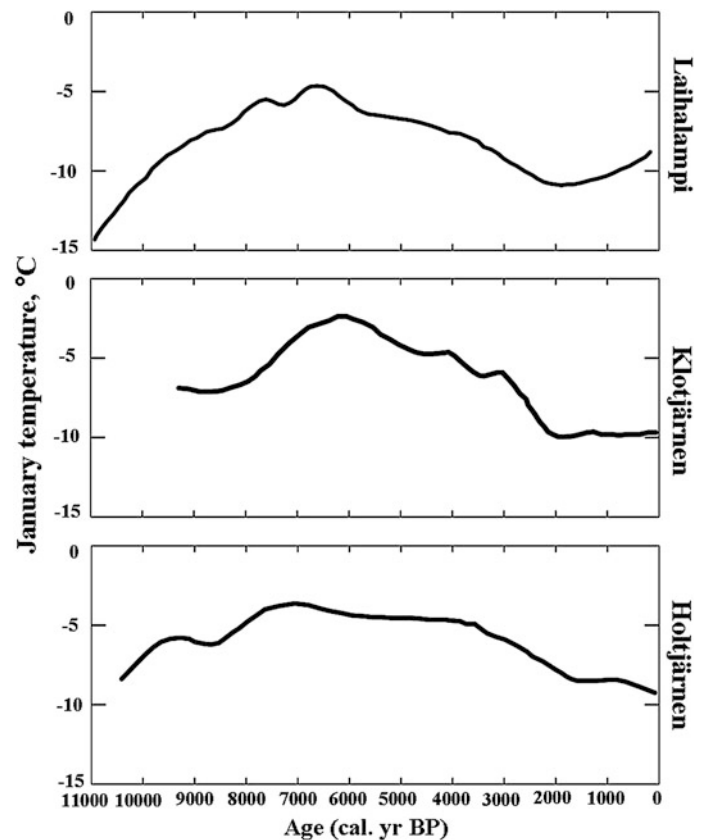
Giesecke et al. (2008) reconstructed winter (January) temperatures for the past 11,000 years using pollen data from three lakes (two in central and western Sweden and one in southern Finland) (Fig. 2.10). The highest winter temperatures were found to have occurred between 7000 and 6000 cal year BP. Quantitative reconstructions indicate that the climate in Fennoscandia has become increasingly continental over the past 7000 years, and mostly reflecting winter cooling. These reconstructions suggest that the Early Holocene in Fennoscandia was the most oceanic period, but probably with higher temperature variability. Millennial reconstructions of the North Atlantic Oscillation Index since the Holocene Thermal Maximum until present based on Greenland ice core data suggest a long-term negative trend, and thus increased continentality (Olsen et al. 2012). This is supported by a simulation with the coupled atmosphere–ocean model ECHO-G driven by changes in orbital configuration (Hünicke et al. 2010).

Reconstructions of mean annual air temperature by pollen data from Lake Trehörningen in south-western Sweden show that the maximum temperatures 2.5–3.0 °C above the modern values occurred between 7000 and 4000 cal year BP. In northern and eastern Scandinavia, mid-Holocene temperatures were somewhat lower, about 1.5–2.5 °C above present-day values (Antonsson and Seppä 2007). The

presence of a number of beetle species during the Mid-Holocene that today are found in central Europe suggests higher temperatures than present in southern Sweden during that period. The mutual climate range (MCR) reconstructions based on stenothermic beetles from Abisko (Buckland et al. 2011) indicate a climatic optimum between 7500 and 6000 cal year BP, with mean summer temperatures about 3 °C higher than at present.

In central Sweden, thermophilous vegetation (oak and linden) expanded after 7000 cal year BP. This type of vegetation requires high summer temperatures and is relatively resistant to low winter temperatures. During the warmest period in the Holocene (between 7000 and 4000 cal year BP), the range of *Tilia* advanced 300 km north compared to its modern position. Over that period, precipitation decreased and lake levels dropped. Near Lake Giltjärnen (60°N), a maximum mean annual temperature of 6.0–7.0 °C occurred at about 6500 cal year BP, compared to 5.0 °C at present (Antonsson et al. 2006). Reconstructions of summer air temperature in central Sweden using fossil Chironomidae composition show that these temperatures varied within wide limits, from –0.8 to +0.8 °C of its modern values (Brooks and Birks 2000, 2001; Velle et al. 2005). In Estonia, *Ulmus* and *Tilia* spread most widely between 7000 and 5000 cal year BP, which coincides with the maximum in

Fig. 2.10 The winter (January) air temperature in parts of the Baltic Sea basin over the past 11,000 years, obtained by pollen from three lakes: Laihalampi 61°29N (southern Finland), Klotjärnen 61°49N (Sweden), Holtjärnen, 60°39N (Sweden) (adapted from Giesecke et al. 2008)



summer air temperature. At that time, these species occupied about 40 % of the Estonian territory compared to 1 % at present (Saarse and Veski 2001).

Reconstructions based on sediment data from lakes Holzmaar and Meerfelder in the Westeifel Volcanic Field (Germany) show that temperatures were 1 °C higher than at present and declined after 5000 cal year BP (Litt et al. 2009).

In Latvia, the warmest climate of the Holocene occurred between about 8200 and 5700 cal year BP with temperatures more than ~2.5–3.5 °C above modern values and a peak warming of about 3.0–3.7 °C at ca. 7950–6750 cal year BP (Heikkilä and Seppä 2010). Temperatures subsequently declined towards present-day values (Figs. 2.8 and 2.9). Deciduous forest appeared here later than in Estonia. *Ulmus* started to spread in the first half of the boreal period and *Tilia* at about 7000–5000 cal year BP (Heikkilä and Seppä 2010). With the beginning of the Atlantic warming, mixed deciduous forest composed of *Ulmus*, *Tilia*, *Alnus*, *Corylus*, and *Picea* expanded (Mürniece et al. 1999; Ozola et al. 2010). The maximum values of *Ulmus* and *Tilia* pollen are found in the deposits formed in the first part of the Atlantic warming, but the maxima of the *Quercus* pollen occur in the later period. A short climate deterioration in the central part of the Holocene Thermal Maximum has been identified in pollen diagrams from Eini Lake, Malmuta River mouth (Segliņš et al. 1999) and the Gulf of Riga. The Atlantic

warming is clearly identified in pollen diagrams from lagoon sediments. During the second part of the Atlantic period, water level in the lagoon basins gradually decreased. The lagoons gradually filled up and lake sediments record the presence of fen peat with a dominance of *Carex* species, such as *Carex elata*, *C. lasiocarpa*, *C. teretiuscula*, *C. aproximate* and *Hypnum* (Cerina et al. 2010).

In Lithuania, the major environmental changes started after 10,300–10,200 cal year BP when deciduous trees, including thermophilous species, spread in this region. In eastern Lithuania, the expanding deciduous taxa, such as *Corylus* (ca. 10,200–10,000 cal year BP), *Alnus* (8200–8000 cal year BP), and broad-leaved species such as *Ulmus* (ca. 10,000 cal year BP), *Tilia* (7700–7400 cal year BP) and *Quercus* (5200 cal year BP), formed a dense mixed forest. *Picea* reappeared at 7300–6800 cal year BP (Gaidamavičius et al. 2011). In north-western Lithuania, immigration of *Corylus* was dated back to 7600–7200 cal year BP, *Alnus*—back to 7300–6900 cal year BP, and *Ulmus*—back to 8100–7500 cal year BP (Stančikaitė et al. 2006). After about 9800–9900 cal year BP, the expansion of deciduous species was accompanied by the spread of *Cladium mariscus* (L.) Pohl, suggesting that minimum mean July temperature increased up to +15.5 °C even in the northern part of the country. Development of deciduous forest requires moist and fertile soil and high humidity. Therefore, its expansion confirmed

that such ecological conditions pre-existed there. The Holocene Thermal Maximum, ca. 8000–4500 cal year BP, with dryer and warmer summers reflecting stronger continentality (Seppä and Poska 2004), was generally responsible for expansion of deciduous trees to the eastern Baltic Sea region. These taxa continued to flourish there between about 7500 and 4200 cal year BP (Stančikaitė et al. 2003, 2004, 2006, 2008, 2009; Giesecke and Bennett 2004; Giesecke et al. 2008; Gaidamavičius et al. 2011).

In central Poland, *Tilia* and *Quercus* appeared about 9300 cal year BP. However, they did not become widespread until 8000–7000 cal year BP. At the same time, *Alnus*—and in mountainous regions, *Picea*—spread widely. Then, at about 5000 cal year BP, the climate became wetter and colder (Pazdur 2004; Lauterbach et al. 2011). It should be noted that the first signs of anthropogenic deforestation are recorded at 6500 cal year BP in this region.

For northern Europe as a whole, Davis et al. (2003) dated the well-defined thermal maximum of the Holocene at ca. 6000 cal year BP. For the Baltic Sea region, the highest temperatures occurred around 6500 cal year BP and were 1.5–2.5 °C above present-day values in the north-west area and 1.0–1.5 °C in the north-east.

2.4.5 Late Holocene Cooling

As is clear from Figs. 2.7, 2.8 and 2.9, climate has been relatively unstable across the Baltic Sea basin over the past 4500 years, with alternating warm and cold periods superimposed on a general cooling trend.

Different proxy data indicate a two-stage air temperature decrease in the Late Holocene. The first occurred between 5000 and 4500 cal year BP and the second between 4300 and 3300 cal year BP. During each of these periods, the

temperature drop was at least 1 °C. A warming at ca. 3200 and cooling at ca. 2800 cal year BP are revealed by detailed palaeoclimatic reconstructions (Zubakov and Borzenkova 1990; Arslanov et al. 2001; Bjune et al. 2009). Although the general trend of the Late Holocene cooling is probably related to decreased summer solar radiation due to astronomical factors, the causes of the superimposed oscillations are still unclear.

Climate cooling in north-western and northern Russia and other regions of the Baltic Sea basin started at about 4500 cal year BP. A warmer period at about 3500 cal year BP and a colder period at about 2500 cal year BP are apparent, superimposed on the general cooling trend (Arslanov et al. 2001; Subetto et al. 2006).

Analyses of Lake Igelsjön sediments in southern Sweden suggest that relatively warm conditions remained until 4700 cal year BP, followed by an abrupt hydrological shift to cooler and/or wetter conditions by around 4000 cal year BP (Jessen et al. 2005). A cooling trend thereafter, up to pre-industrial times, was punctuated by a series of short rapid warm fluctuations. Pollen diagrams show changes in vegetation composition and a distinct decrease in thermophilous species (primarily *Corylus*). About 2000 cal year BP, the temperatures were already close to modern values (Jessen et al. 2005).

Proxy data reconstructions show that a trend towards cooler and wetter conditions prevailed across Fennoscandia during the past 2000–1500 years (Bjune et al. 2009; Esper et al. 2012). These climate trends are shown by, for example, $\delta^{18}\text{O}$ records from lake sediments (Hammarlund et al. 2003; Rosqvist et al. 2007), tree ring-inferred summer temperature and pollen data. The mean July temperature reconstructions based on these data obtained from 11 lakes located in the different landscape zones in the northern parts of Norway, Sweden, Finland, and north-western Russia are shown in Fig. 2.11.

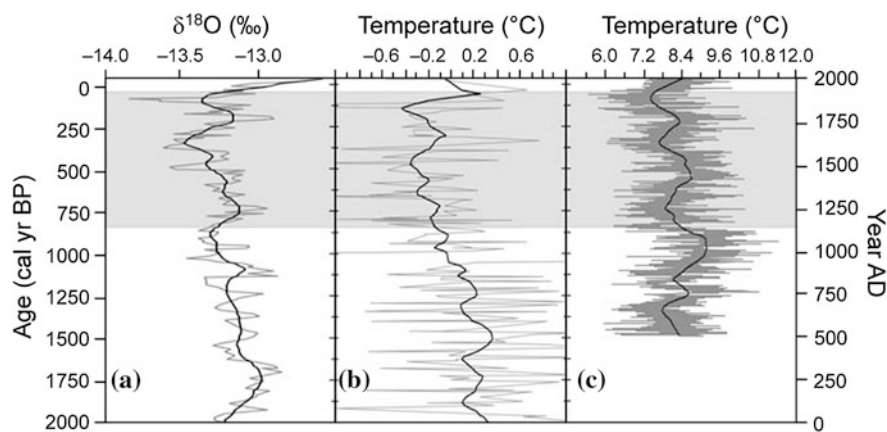


Fig. 2.11 Three proxy climate records covering the past 2000 years from northern Fennoscandia: **a** $\delta^{18}\text{O}$ from calcareous lacustrine sediments from Abisko, Sweden (Rosqvist et al. 2007); **b** pollen-

inferred mean July temperature deviations from 11 lakes. **c** tree ring-inferred summer (April–August) temperature from the Torneträsk region, Sweden (Grudd 2008), (Bjune et al. 2009)

In Poland, analyses of lake sediments of the Late Holocene, including pollen spectra, indicate that lake levels rose and peat mires developed at this time. Between 5000 and 4200 cal year BP, the climate was relatively warm and dry, but by the end of this period became more humid. The dominant species in forest associations changed slightly. In the mountains, spruce expanded and *Carpinus* and *Fagus* migrated from the south-east into this region. At about 3500 cal year BP, *Abies* spread from the south-west and became a forest-forming species in southern Poland (Kulesza et al. 2011). *Picea* spread to the north-east of Poland and *Fagus* penetrated this region from the west. Pazdur (2004) showed that the Subatlantic period started about 2800 cal year BP.

According to Heikkilä and Seppä (2010), summer air temperature dropped by $\sim 3^{\circ}\text{C}$ in Latvia during the Late Holocene. Pollen diagrams show changes in vegetation; a significant decrease and almost disappearance of the thermophilous broad-leaved species and *Corylus*. The dominant tree species over the past 3000 years was *Pinus* and *Betula* (Mürniece et al. 1999; Kalniņa 2008; Kuške et al. 2010b), except in the central part of the Subatlantic period when the *Picea* pollen curve, and to a lesser extent *Alnus* and *Quercus*, rose again. Dwarf shrub (mainly Ericales) and grass pollen (Poaceae, Cyperaceae) concentrations increased during the past 1000 years, reflecting a decrease in forest cover, which resulted from both climatic and human impacts (Ozola et al. 2010; Kalniņa et al. 2012).

Analyses of isotopic strontium concentrations in molluscs can give information about past salinity in the Baltic Sea (Widerlund and Andersson 2011). Data suggest that the difference in surface salinity in the various Baltic Sea basins has been much less in the past than now and that the general trend over the past two millennia is towards freshening, with this trend strongest in the Bothnian Bay. These results would be consistent with a decrease in summer evaporation caused by increasingly colder summers, or with an annual increase in precipitation. Since the seasonality of the orbital forcing is quite different from that which is likely for a GHG-forced future climate, an extrapolation of these trends is not justified.

2.5 Conclusion

Over the Holocene, the Baltic Sea area has undergone major changes due to two interrelated factors. First, the demise of the Fennoscandian ice sheet that had previously accumulated as part of the 100-thousand-year-long glacial cycle. This demise started around 18,000 years ago, but due to the long timescales involved in land-ice dynamics and the slow crustal readjustment to the disappearance of the weight of an ice sheet 3 km deep, its effects are felt throughout most of the Holocene. The most important effect of the melting of

the ice sheets is an interplay between global sea-level rise due to the increase in the ocean volume and a regional isostatic rebound (uplift) of the earth's crust. This interplay led to a series of transitions of the Baltic Sea basin as a brackish sea or freshwater lake, with periods of isolation and periods of interchange with the North Sea. The modern configuration of the Baltic Sea as a brackish Mediterranean or inland sea was established around 4500 years ago. Second, changes in the orbital configuration of the Earth. This is thought to be the major trigger for glacial to interglacial transition, but also modulated solar insolation to the high northern latitudes during the Holocene and thus strongly influenced the energy balance of the Baltic Sea area. Summer solar insolation modulated by these changes peaked around 7000–6000 years ago. Its effects were recorded in a phase of warm temperatures, extended vegetation cover and a progressive millennial cooling thereafter.

The instruments used to reconstruct the climate of the Baltic Sea area during the Holocene are multifaceted. Palaeobiological and geochemical records that, at least partly, reflect past environmental conditions can be used to reconstruct past temperature and/or precipitation in some seasons. Among these, the more widely used are pollen and spore assemblages derived from dated lake sediments, tree ring data, and fossil remains that may be indicative of the spatial spread of thermophilous or halophilous species and thus may give information about past temperatures or salinity.

The Baltic Sea area underwent a series of climatic phases during the Holocene. The Younger Dryas occurred in a transitional period between the Last Ice Age and the Holocene and ended around 11,500 years ago. Temperatures then rose, land ice partially disappeared, and the earth's crust rose causing a drop in relative sea level, giving rise to a large freshwater lake (Ancylus Lake). As temperatures and sea level continued to rise (due to the melting of the northern hemisphere ice sheets), a connection was established between the North Atlantic Ocean and Ancylus Lake forming the brackish Littorina Sea. The rise in temperature was interrupted by another climatic cold event, however, about 8200 years ago which is thought to have been caused by freshwater drainage from the North American ice sheet into the North Atlantic Ocean. This event was shorter and less intense than the Younger Dryas, with a drop in temperature of about 2°C lasting for about 200 years. This event was the last cooling episode of the Early Holocene and was followed by a stable and relatively warm period with summer temperatures $1.0\text{--}3.5^{\circ}\text{C}$ higher than at present. The period between 7500 and 5500 years ago was the warmest in the Baltic Sea basin area as a whole, although the timing of maximum temperatures was not synchronous in different parts of the region. Thereafter, a trend of northern hemisphere cooling and increased climatic instability began, typical of the Late Holocene interval. Temperatures in the

Baltic Sea region started to drop around 5000–4500 cal year BP coincident with decreased summer solar insolation due to the quasi-cyclical changes in the Earth's orbit. The climatic variation during the Lateglacial and Holocene is reflected in the changing lake levels and vegetation and in the formation of a complex hydrographical network that set the stage for the Medieval Warm Period and the Little Ice Age of the past millennium.

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References

- Allen JRM, Long AJ, Ottley CJ, Pearson DG, Huntley B (2007) Holocene climate variability in northernmost Europe. *Quaternary Sci Rev* 26:1432-1453
- Alley RB (2000) The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Sci Rev* 19:213-226
- Alley RB, Ágústadóttir AM (2005) The 8 ka event: cause and consequences of a major Holocene abrupt climate change. *Quaternary Sci Rev* 24:1123-1149
- Alley RB, Mayewski PA, Sowers T, Stuiver M, Taylor KC, Clark PU (1997) Holocene climatic instability: a prominent, widespread event 8200 yr ago. *Geology* 25:483-486
- Andrén T (2003) Ancylyussön – fortfarande ett mysterium. (The Ancylyus Sea – still a mystery) *Havsutsikt* 3:8-9 (in Swedish)
- Andrén T, Lindeberg G, Andrén E (2002) Evidence of final drainage of the Baltic Ice Lake and the brackish phase of the Yoldia Sea in glacial varves from the Baltic Sea. *Boreas* 31:226-238
- Andrén T, Björck S, Andrén E, Conley D, Zillén L, Anjar J (2011) The development of the Baltic Sea Basin during the last 130 ka. In: Harff J, Björck S, Hoth P (eds) *The Baltic Sea Basin, Central and Eastern European 75. Development Studies (CEEDES)*, Springer-Verlag Berlin Heidelberg
- Antonsson K (2006) Holocene climate in central and southern Sweden. Quantitative records from fossil data. *Acta Universitatis Upsalien-sis*, Uppsala, Sweden
- Antonsson K, Seppä H (2007) Holocene temperatures in Bohuslän, southwest Sweden: a quantitative reconstruction from fossil pollen data. *Boreas* 36:400-410
- Antonsson K, Brooks SJ, Seppä H, Telford RJ, Birks HJB (2006) Quantitative palaeotemperature records inferred from fossil pollen and chironomid assemblages from Lake Giltjärnen, northern central Sweden. *J Quaternary Sci* 21:831-841
- Antonsson K, Chen D, Seppä H (2008) Anticyclonic atmospheric circulation as an analogue for the warm and dry mid-Holocene summer climate in central Scandinavia. *Clim Past* 4:215-224
- Arslanov KH, Saveljeva LA, Gey NA, Klimanov VA, Chernov SB, Chernova GM, Kuzmin GF, Tertychnaya TV, Subetto DA, Denisikov VP (1999) Chronology of vegetation and paleoclimatic stages of northwest Russia during the Late Glacial and Holocene. *Radiocarbon* 41:25-45
- Arslanov KH, Savelieva LA, Klimanov VA, Chernov SB, Tertychnaya TV, Subetto DA (2001) New data on chronology of landscape-paleoclimatic stages in northwestern Russia during the Late Glacial and Holocene. *Radiocarbon* 43:581-594
- Baldini JUL, McDermott F, Fairchild IJ (2002) Structure of the 8200 yr cold event revealed by a speleothem trace element record. *Science* 296:2203-2206
- Barber DC, Dyke A, Hillaire-Marcel C, Jennings AE, Andrews JT, Kerwin MW, Bilodeau G, McNeely R, Southon J, Morehead MD, Gagnon JM (1999) Forcing of the cold event 8200 yr ago by catastrophic drainage of Laurentide lakes. *Nature* 400:344-348
- Birks HJB (2003) Quantitative palaeoenvironmental reconstruction from Holocene biological data. In: Mackay A, Battarbee R, Birks HJB (eds) *Global Change in the Holocene*, Arnold, London, p 109-123
- Birks HJB, Seppä H (2010) Late-Quaternary palaeoclimatic research in Fennoscandia – A historical review. *Boreas* 39:655-673
- Björck S (1995) A review of the history of the Baltic Sea, 13.0-8.0 ka BP. *Quatern Int* 27:19-40
- Björck S (1999) Event stratigraphy for the Last Glacial-Holocene transition in eastern middle Sweden. *Quaternaria* A:1-48
- Björck S, Kromer B, Johnsen S, Bennike O, Hammarland D, Lemdahl G, Possnert G, Rasmussen TL, Wohlfarth B, Hammer CU, Spurk M (1996) Synchronized terrestrial-atmospheric deglacial records around the North Atlantic. *Science* 274:1155-1160
- Björck J, Possnert G, Schoning K (2001) Early Holocene deglaciation chronology in Västergötland and Närke, southern Sweden - biostratigraphy, clay varve, ¹⁴C and calendar year chronology. *Quaternary Sci Rev* 20:1309-1326
- Bjune AE, Seppä H, Birks HJB (2009) Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. *J Paleolimnol* 41:43-56
- Blunier T, Brook E (2001) Timing of millennial-scale climate change in Antarctica and Greenland during the Last glacial period. *Science* 291:109-112
- Borisova OK (1990) The Younger Dryas climate event in the high and middle latitudes of the Northern Hemisphere. *Izv Acad Nauk of the USSR Ser Geogr* 3:66-74 (in Russian)
- Borisova OK (1997) Younger Dryas landscape and climate in Northern Eurasia and North America. *Quaternary Int* 41/42:103-109
- Borzenkova II (1992) The Changing Climate during the Cenozoic. *Gidrometeoizdat*, St. Petersburg (in Russian)
- Borzenkova II (2003) Determination of global climate sensitivity to the gas composition of the atmosphere from the paleoclimatic data. Translated from Russian to English from "Izvestiya RAN, Ser. "Atmospheric and Ocean Physics", 39:197-202
- Borzenkova II (2012) Volcanic eruptions and climate of the Earth: Volcanism as an analogue of geoengineering. In: proceedings of the international conference on problems of adaptation to climate change, Moscow, 7–9 November 2011, p 122-129
- Borzenkova II, Zhiltsova EL, Lobanov VA (2011) Climate variations in the extratropics of the northern hemisphere over the past 1000 years: analysis of data and possible causes. In: *Problems of the Ecological Monitoring and Modeling of the ecosystem, Planeta*, Moscow, p 131-152 (in Russian)
- Bos JAA, van Geel B, van der Plicht J, Bohncke SJP (2007) Preboreal climate oscillations in Europe: Wiggle-match dating and synthesis of Dutch high-resolution multi-proxy records. *Quaternary Sci Rev* 26:1927-1950
- Briffa KR, Osborn TJ, Schweingruber FH, Harris IC, Jones PD, Shiyatov SG, Vaganov EA (2001) Low-frequency temperature variations from a northern tree ring density. *J Geophys Res* 106:2929-2941
- Brooks SJ, Birks HJB (2000) Chironomid-inferred Late-glacial and early Holocene mean July air temperatures for Kråkenes Lake, western Norway. *J Paleolimnol* 23:77-89

- Brooks SJ, Birks HJB (2001) Chironomid-inferred air temperatures from Lateglacial and Holocene sites in north-west Europe: progress and problems. *Quaternary Sci Rev* 20:1723-1741
- Buckland PI, Lemdahl G, Olsson F (2011) Holocene insect record from three alpine lakes in the Abisko area, N Sweden: implications on climate and ecosystem change. XVIII INQUA Congress, Bern, Switzerland, 21-27 July
- Brovkin V, Ganopolski A, Archer D, Munhoven G (2012) Glacial CO₂ cycle as a succession of key physical and biogeochemical processes. *Clim Past* 8:251-264
- Cerina A, Apsite L, Berzins V, Kalniņa L, Ozola I (2010) Vegetation change and human impact, as reflected in Littorina sea lagoonal deposits near the Priedaine archaeological site at the head of the Gulf of Riga (plant macroremains, pollen and wooden artefacts). In: Bittmann F (ed), proceedings of the international conference of the international work group for palaeoethnobotany, TERRA NOSTRA – Schriften der GeoUnion Alfred-Wegener-Stiftung, Vol. 2010/2, p121, www.nihk.de/downloads/261/15thiwgp_programme_abstracts.pdf
- Clark PU (2001) Freshwater forcing of abrupt climate change during the last glaciation. *Science* 293:283-287
- Clark PU, Pisias NG, Stocker TF, Weaver AJ (2002) Role of the thermohaline circulation in abrupt climate change. *Nature* 415:863-869
- Clarke GKC, Leverington DW, Teller JT, Dyke AS (2004) Paleohydrodynamics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event. *Quaternary Sci Rev* 23:389-407
- Coope GR, Lemdahl G (1995) Regional differences in the Lateglacial climate of northern Europe based on coleopteran analysis. *J Quaternary Sci* 10:391-395
- Coope GR, Lemdahl G, Lowe JJ, Walkling A (1998) Temperature gradients in northern Europe during the last glacial-Holocene transition (14-9 ¹⁴C kyr BP) interpreted from coleopteran assemblages. *J Quaternary Sci* 13:419-433
- Crowley TJ (2000) Causes of climate change over the past 1000 years. *Science* 289:270-277
- Davis BAS, Brewer S, Stevenson AC, Guiot J, Data Contributors (2003) The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Sci Rev* 22:1701-1716
- Davydova N, Subetto O, Khomutova V (1998) Palaeohydrological and palaeoclimatic changes recorded at lakes Krasnoye and Mentilampi, Karelian Isthmus, Russia. *Paleoclimate Res* 25:19-35
- de Klerk P, Couwenberg J, Joosten H (2007) Short-lived vegetational and environmental change during the Preboreal in the Biebrza Upper Basin (NE Poland). *Quaternary Sci Rev* 26:1975-1988
- Denton GH, Alley RB, Comer GC, Broecker WS (2005) The role of seasonality in abrupt climate change. *Quaternary Sci Rev* 24:1159-1182
- Dolukhanov PM, Subetto DA, Arslanov KHA, Davydova NN, Zaitseva GI, Djindiridze EN, Kuznetsov DD, Ludikova AV, Sapelko TV, Savelieva LA (2009a) The Baltic Sea and Ladoga Lake transgressions and early human migrations in North-western Russia. *Quaternary Int* 203:33-51
- Dolukhanov PM, Shukurov A, Davison K, Sarson G, Gerasimenko NP, Pashkevich GA, Vybornov AA, Kovalyukh NN, Skripkin VV, Zaitseva GI, Sapelko TV (2009b) The spread of the Neolithic in the south east European plain: radiocarbon chronology, subsistence and environment. *Radiocarbon* 51:783-794
- Dolukhanov PM, Subetto DA, Arslanov KHA, Davydova NN, Zaitseva GI, Kuznetsov DD, Ludikova AV, Sapelko TV, Savelieva LA (2010) Holocene oscillations of the Baltic Sea and Lake Ladoga levels and early human movements. *Quaternary Int* 220:102-111
- Esper J, Frank DC, Timonen M, Zorita E, Wilson RJS, Luterbacher J, Holzkämper S, Fischer N, Wagner S, Nievergelt D, Verstege A, Büntgen U (2012) Orbital forcing of tree-ring data. *Nat Clim Change* 2:862-866
- Fisher TG, Smith DG, Andrews JT (2002) Preboreal oscillation caused by a glacial Lake Agassiz flood. *Quaternary Sci Rev* 21:873-878
- Flückiger J, Monnin E, Stauffer B, Schwander J, Stocker TF, Chappellaz J, Raynaud D, Barnola J-M (2002) High resolution Holocene N₂O ice core record and relationship with CH₄ and CO₂. *Global Biogeochem Cy* 16(1):1010, doi:10.1029/2001CB001417
- Friedrich M, Kromer B, Spurk M, Hofmann J, Kaiser KF (1999) Paleo-environment and radiocarbon calibration as derived from Lateglacial/Early Holocene tree-ring chronologies. *Quaternary Int* 61:27-39
- Gaidamavičius A, Stančikaitė M, Kisieliene D, Mažeika J, Gryguc G (2011) Post-glacial vegetation and environment of the Labanoras region, East Lithuania: implications for regional history. *Geol Q* 55:269-284
- Ganopolski A, Rahmstorf S (2001) Rapid changes of glacial climate simulated in a coupled climate model. *Nature* 409:153-158
- Giesecke T (2005) Holocene dynamics of the southern boreal forest in Sweden. *The Holocene* 15:858-872
- Giesecke T, Bennett KD (2004) The Holocene spread of *Picea abies* (L.) Karst. in Fennoscandia and adjacent areas. *J Biogeogr* 31:1523-1548
- Giesecke T, Bjune AE, Chiverrell RC, Seppä H, Ojala AEK, Birks HJB (2008) Exploring Holocene continentality changes in Fennoscandia using present and past tree distributions. *Quaternary Sci Rev* 27:1296-1308
- Goslar T, Balaga K, Arnold M, Tisnerat N, Starnwska E, Kuźniarski M, Chrost L, Walanus A, Więckowski K (1999) Climate-related variations in the composition of the Lateglacial and Early Holocene sediments of Lake Perespiłno (Eastern Poland). *Quaternary Sci Rev* 18:899-911
- Grachev AM, Severinghaus JP (2005) A revised +10 ± 4°C magnitude of the abrupt change in Greenland temperature at the Younger Dryas termination using published GISP2 gas isotope data and air thermal diffusion constants. *Quaternary Sci Rev* 24:513-519
- Grichuk VP, Gurtovaya YeYe, Zelikson EM, Borisova OK (1984) Methods and results of Late Pleistocene paleoclimatic reconstructions. In: Velichko AA (ed) Late Quaternary Environments of the Soviet Union. Univ. Minnesota Press, Minneapolis, p 251-261
- 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. *Clim Dynam* 31:843-857
- Grudzinska I, Kalniņa L, Saulīte A (2010) Development of Būšnieks Lake and changes of environmental conditions during the Holocene. *Papers of University of Latvia. Earth Env Sci* 752:64-74 (in Latvian)
- Hammarlund D, Barnekow L, Birks HJB, Buchardt B, Edwards TWD (2002) Holocene changes in atmospheric circulation recorded in the oxygen-isotope stratigraphy of lacustrine carbonates from northern Sweden. *The Holocene* 12:339-351
- Hammarlund D, Björck S, Buchardt B, Israelson C, Thomsen CT (2003) Rapid hydrological changes during the Holocene revealed by stable isotope records of lacustrine carbonates from Lake Igelsjön, southern Sweden. *Quaternary Sci Rev* 22:353-370
- Hammarlund D, Björck S, Buchardt B, Thomsen CT (2005) Limnic responses to increased effective humidity during the 8200 cal. yr BP cooling event in southern Sweden. *J Paleolimnol* 34:471-480
- Hegerl G, Crowley TC, Baum SK, Kim KY, Hyde W (2003) Detection of solar, volcanic and greenhouse gas signals in paleo-reconstructions of Northern Hemisphere temperature. *Geophys Res Lett* 30:1242. doi:10.1029/2002GL016635
- Heikkilä M, Seppä H (2003) A 11,000 yr palaeotemperature reconstruction from the southern boreal zone in Finland. *Quaternary Sci Rev* 22:541-554

- Heikkilä M, Seppä H (2010) Holocene climate dynamics in Latvia, eastern Baltic region: a pollen based summer temperature reconstruction and regional comparison. *Boreas* 39:705-719
- Heikkilä M, Fontana SL, Seppä H (2009) Rapid Lateglacial tree population dynamics and ecosystem changes in the eastern Baltic region. *J Quaternary Sci* 24:802-815
- Heinsalu A, Veski S (2007) The history of the Yoldia Sea in Northern Estonia: palaeoenvironmental conditions and climatic oscillations. *Geol Q* 51:295-306
- Hoek WZ (2001) Vegetation response to the ~ 14.7 and ~ 11.5 ka cal. BP climate transitions: is vegetation lagging climate? *Global Planet Change* 30:103-115
- Hoek WZ, Bohncke SJP (2001) Oxygen-isotope wiggle matching as a tool for correlation of ice-core and terrestrial records over Termination I. *Quaternary Sci Rev* 20:85-98
- Hoek WZ, Bos JAA (eds) (2007) Early Holocene climate oscillations - causes and consequences. *Quaternary Sci Rev* 26:1901-2030
- Hoek WZ, Yu ZC, Lowe JJ (2008) INTegration of Ice-core, MARine, and TERrestrial records (INTIMATE): refining the record of the Last Glacial-Interglacial transition. *Quaternary Sci Rev* 27:1-5
- Hünicke B, Zorita E, Haeseler S (2010) Baltic Holocene climate and regional sea-level change: A statistical analysis of observations, reconstructions and simulations within present and past as analogues for future changes. Reports of the GKSS-Forschungszentrum Geesthacht, Geesthacht, p 64
- Hyvärinen H, Donner J, Kessel H, Raukas A (1988) The Littorina Sea and Limnea Sea in the northern and central Baltic. *Ann Acad Sci Fenn A III* 148:25-35
- Isarin RFB, Bohncke SJP (1999) Mean July temperatures during the Younger Dryas in northwestern and central Europe as inferred from climate indicator plant species. *Quaternary Res* 51:158-173
- Isarin RFB, Renssen H, Koster EA (1997) Surface wind climate during the Younger Dryas in Europe as inferred from aeolian records and model simulations. *Palaeogr Palaeoecol* 134:127-148
- Iversen J (1944) *Viscum*, *Hedera*, *Ilex* as climate indicators. A contribution to the study of the post-glacial temperature climate. *Geol Foren Stock For* 66:463-483
- Jessen CA, Rundgren M, Björck S, Hammarlund D (2005) Abrupt climatic changes and an unstable transition into a late Holocene Thermal Decline: a multiproxy lacustrine record from southern Sweden. *J Quaternary Sci* 20:349-362
- Joos F, Gerber S, Prentice IC, Otto-Bliessner BL, Valdes PJ (2004) Transient simulations of Holocene atmospheric carbon dioxide and terrestrial carbon since the Last Glacial Maximum. *Global Biogeochem Cy* 18:GB2002, doi:10.1029/2003GB002156
- Kabailienė M (1993) The problems of stratigraphy and environmental history during Late-Glacial and Holocene in Lithuania. *Geologija* 14:208-222
- Kabailienė M, Vaikutienė G, Damušytė A, Rudnickaitė E (2009) Post-Glacial stratigraphy and palaeoenvironment of the northern part of the Curonian Spit, Western Lithuania. *Quaternary Int* 207:69-79
- Kalniņa L (2007) Diversity of mire origin and history in Latvia. *Peatlands International* 2:54-56
- Kalniņa L (2008) Origin and development of Cena Mire. In: Pakalne M (ed), Mire conservation and management in especially protected nature areas in Latvia. *Latvian Fund for Nature*, Riga p 30-33
- Kalniņa L, Juskevics V, Stiebrins O (1999) Palynostratigraphy and composition of Late Glacial and Holocene sediments from the Gulf of Riga, eastern Baltic Sea. In: Andrén Th (ed), Proceedings of the Conference The Baltic – past, present and future, 14-16 March 1994, Stockholm. *Quaternaria A* 7:55-62
- Kalniņa L, Sakson M, Miller U, Robertsson A-M (2003) Pollen and diatom records from the Gulf of Riga as indicator of climatic changes during Late Quaternary. Bäck S, Harjumkoski R, Koivu J, Toivanen R, Viitasalo I (eds) Abstract Publication. Baltic Sea Science Congress 2003, Helsinki, p 92-93
- Kalniņa L, Cerina A, Vasks A (2004) Pollen and plant macroremain analyses for the reconstruction of environmental changes in the Early Metal Period. In: Scott EM, Alekseev AY, Zaitseva G (eds), Impact of the Environment on Human Migration in Eurasia. NATO Science series, Kluwer Academic Publishers, p 275-289
- Kalniņa L, Ceriņa A, Ozola I, Apsīte L (2011) Paleobotanical records from the Raunīs site. In: Lukševičs E, Stinkulis G, Vasiļkova J (eds), Abstracts of the eighth Baltic stratigraphical conference, University of Latvia, p 32
- Kalniņa L, Cerina A, Ozola I, Grudzinska I, Pujate A, Kuske E (2012) Fen and raised bog development in the areas of the former Littorina Sea lagoons at the Coastal Lowland of Latvia. In: proceedings of the 14th International Peat Congress, Peatlands in Balance
- Kasse C (2002) Sandy aeolian deposits and environments and their relation to climate during the Last Glacial Maximum and Lateglacial in northwest and central Europe. *Progr Phys Geogr* 26:507-532
- Kobashi T, Severinghaus JP, Brook EJ, Barnola J-M, Grachev AM (2007) Precise timing and characterization of abrupt climate change 8200 years ago from air trapped in polar ice. *Quaternary Sci Rev* 26:1212-1222
- Kobashi T, Severinghaus JP, Barnola J-M (2008) $4 \pm 1.5^\circ\text{C}$ abrupt warming 11,270 yr ago identified from trapped air in Greenland ice. *Earth Planet Sci Lett* 268:397-407
- Koff T, Terasmaa J (2011) The sedimentary sequence from the L. Kūži outcrop, central Latvia: implications for late glacial stratigraphy. *Estonian J Earth Sci* 60:113-122
- Kornola A, Weckstöm J, Holmström L, Erästö P (2000) A quantitative Holocene climatic record from diatoms in Northern Fennoscandia. *Quaternary Res* 54:284-294
- Kulesza P, Suchora M, Pidek IA, Alexandrowicz WP (2011) Chronology and directions of Late Glacial palaeoenvironmental changes: A multi-proxy study on sediments of Lake Słone (SE Poland). *Quaternary Int* 238:89-106
- Kuške E, Silamikele I, Kalniņa L, Kļaviņš M (2010a) Peat formation conditions and peat properties: a study of two Ombrotrophic Bogs in Latvia. In: Kļaviņš M (ed), Mires and Peat, University of Latvia Press, p 56-70
- Kuške E, Strautnieks I, Kalniņa L, Ozola I, Silamikele I, Krumins J (2010b) Changes of palaeovegetation composition during the development of fens in Latvia. In: Abstracts of the 8th European palaeobotany-palynology conference, 6-10 July 2010 Budapest, Hungary, p 145-146
- Larocque I, Hall RI, Grahn E (2001) Chironomids as quantitative indicators of mean July air temperature: validation by comparison with century-long meteorological records from northern Sweden (Lapland). *J Paleolimnol* 26:307-322
- Laskar J, Robutel P, Joutel F, Gastineau M, Correia ACM, Levrard B (2004) A long-term numerical solution for the insolation quantities of the Earth. *Astron Astrophys* 428:261-285
- Latałowa M, van der Knaap WO (2006) Late Quaternary expansion of Norway spruce *Picea abies* (L.) Karst. *Quaternary Sci Rev* 25:2780-2805
- Lauterbach S, Brauer A, Andersen N, Danielopol DL, Dulski P, Hüls M, Milecka K, Namiotko T, Plessen B, von Grafenstein U, DecLakes participants (2011) (January) Multi-proxy evidence for early to mid- Holocene environmental and climatic changes in northeastern Poland. *Boreas* 40:57-72
- Lemdahl G (1991) A rapid climate change at the end of the Younger Dryas in south Sweden – palaeoclimatic and palaeoenvironmental reconstructions based on fossil insect assemblages. *Palaeogr Palaeoecol* 83:313-331

- Lemdahl G (1997) Late Weichselian and Early Holocene colonization of beetle faunas in S Sweden. *Quaternary Proc* 5:153-164
- Lemdahl G (1998) Późnoglacialne poziome owadów ze stanowiska w Imiolkach nad jeziorem Lednica w Wielkopolsce (Lateglacial insect assemblages from Imiolki, Lake Lednica, Great Poland). *Biblioteka Studiów Lednickich, Poznan. TOM IV*:55-59
- Lemdahl G, Coope GR (2007) Beetle records: Late Pleistocene of Europe. In Elias SA (ed), *Encyclopedia of Quaternary Science* 1:190-196
- Leuenberger MC, Lang C, Schwander J (1999) Delta ^{15}N measurements as a calibration tool for the paleothermometer and gas-ice age differences: a case study for the 8200 BP event on GRIP ice. *J Geophys Res* 104D: 22163-22170
- Lowe JJ, Rasmussen SO, Björck S, Hoek WZ, Steffensen JP, Walker MJC, Yu Z, INTIMATE group (2008) Synchronization of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Sci Rev* 27. doi:10.1016/j.quascirev.2007.09.016
- Luoto TP (2009a) Subfossil Chironomidae (Insecta: Diptera) along a latitudinal gradient in Finland: development of a new temperature inference model. *J Quaternary Sci* 24:150-158
- Luoto TP (2009b) A Finnish chironomid- and chaoborid-based inference model for reconstructing past lake levels. *Quaternary Sci Rev* 28:1481-1489
- Mangerud J (1987) The Allerød/Younger Dryas boundary. In: Berger WH, Labeyrie LD (eds), *Abrupt Climatic Change*, D. Reidel Publ, p 163-171
- Mangerud J, Lundqvist J, Ehlers J, Gibbard PL (2007) Late Glacial events in northwest Europe. In: *Encyclopedia of Quaternary Science*, Elsevier, Amsterdam, p 1116-1122
- Marotzke J (2000) Abrupt climate change and thermohaline circulation: mechanisms and predictability. *P Natl Acad Sci USA* 97:1347-1350
- Miettinen A, Savelieva L, Subetto D, Dzhinoridze R, Arslanov K, Hyvärinen H (2007) Palaeoenvironment of the Karelian Isthmus, the easternmost part of the Gulf of Finland, during the Litorina Sea stage of the Baltic Sea history. *Boreas* 36:1-18
- Miller GH, Geirsdottir A, Zhong Y, Larsen D, Otto-Bliesner BL, Holland MM, Bailey DA, Refsnider KA, Lehman SJ, Southon JR, Anderson C, Björnsson H, Thordarson T (2012) Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophys Res Lett* 39:L02708. doi:10.1029/2011GL050168
- Mörner N-A (1980) A 10,000 years temperature trend from Gotland Pleistocene/Holocene boundary events in Sweden. *Boreas* 9:283-287
- Mürniece S, Kalniņa L, Bērziņš V, Grasis N (1999) Environmental change and prehistoric human activity in west Kurzeme, Latvia. In: Miller U, Hackens T, Lang V, Raukas A, Hicks Sh (eds), *Environmental and cultural history of the Baltic Region*, PACT 57, Belgium, p 35-70
- Muscheler R, Beer J, Vermoos M (2004) Causes and timing of the 8200 yr BP event inferred from the comparison of the GRIP ^{10}Be and the tree ring $\Delta^{14}\text{C}$ record. *Quaternary Sci Rev* 23:2101-2111
- Nesje A (2009) Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia. *Quaternary Sci Rev* 28:2119-2136
- Nesje A, Dahl SO (2001) The Greenland 8200 cal. yr BP event detected in loss-on-ignition profiles in Norwegian lacustrine sediment sequences. *J Quaternary Sci* 16:155-166
- Ojala AEK, Heinsalu A, Kauppila T, Alenius T, Saarnisto M (2008) Characterizing changes in the sedimentary environment of a varved lake sediment record in southern central Finland around 8000 cal. yr BP. *Quaternary Res* 23:765-775
- Olsen J, Anderson NJ, Knudsen MF (2012) Variability of the North Atlantic Oscillation over the past 5200 years. *Nature Geo* 5:808-812
- Olsson F, Lemdahl G (2009) A continuous Holocene beetle record from the site Stavsåkra, southern Sweden: implications for the last 10,600 years of forest and landuse history. *J Quaternary Sci* 24:612-626
- Olsson F, Lemdahl G (2010) A forest history for the last 10,900 years at the site Storås, southern Sweden – implications from beetle assemblages. *J Quaternary Sci* 25:1211-1221
- Olsson F, Gaillard M-J, Lemdahl G, Greisman A, Lanos P, Marguerie D, Marcoux N, Skoglund P, Wäglind J (2010) A continuous record of fire covering the last 10,500 calendar years from southern Sweden – The role of climate and human activities. *Palaeogr Palaeocl* 291:128-141
- Ozola I, Ratniece V (2012) Vegetation reconstruction according REVEALS model results and pollen data from investigations of mire and lake sediments. In: proceedings of the 58th scientific conference on geography, geology, environmental sciences, University of Latvia, Riga, p 126-127 (in Latvian)
- Ozola I, Ceriņa A, Kalniņa L (2010) Reconstruction of palaeovegetation and sedimentation conditions in the area of ancient Lake Burtnieks, northern Latvia. *Estonian J Earth Sci* 59:164-179
- Pakalne M, Kalniņa L (2005) Mire ecosystems in Latvia. In: Steiner GM (ed), Moore - von Sibirien bis Feuerland / Mires - from Siberia to Tierra del Fuego. Linz : Biologiezentrum der Oberösterreichischen Landesmuseen, p 147-174
- Pazdur A (2004) Archaeological cultures on the background of climatic changes in the Holocene, Poland. In: Scott EM, Alekseev AY, Zaitseva G (eds), *Impact of the Environment on Human Migration in Eurasia*, NATO Science Series, IV. Earth and Environmental Sciences, Kluwer Academic Publ 42:309-321
- Plóciennik M, Self A, John H, Birks B, Brooks SJ (2011) Chironomidae (Insecta: Diptera) succession in Żabieniec bog and its palaeolake (central Poland) through the Late Weichselian and Holocene. *Palaeogeogr Palaeoclimatol Palaeoecol* 307:150-167
- Poska A, Saarse L, Veski S (2004) Reflections of pre- and early-agrarian human impact in the pollen diagrams of Estonia. *Palaeogr Palaeocl* 209:37-50
- Poska A, Sepp E, Veski S, Koppel K (2008) Using quantitative pollen-based land-cover estimations and a spatial CAMarkov model to reconstruct the development of cultural landscape at Rõuge, South Estonia. *Veget Hist Archaeobot* 17:527-541
- Puusepp L, Kangur M (2010) Linking diatom community dynamics to terrestrial vegetation changes: a paleolimnological case study of Lake Kūži, vidzeme Heights (Central Latvia). *Estonian J Ecol* 59:259-280
- Rainio H, Saarnisto M, Ekman I (1995) Younger Dryas end moraines in Finland and NW Russia. *Quaternary Int* 28:179-192
- Rasmussen SO, Andersen KK, Svensson AM, Steffensen JP, Vinther BM, Clausen HB, Siggaard-Andersen M-L, Johnsen SJ, Larsen LB, Dahl-Jensen D, Bigler M, Röthlisberger R, Fischer H, Goto-Azuma K, Hansson ME, Ruth U (2006) A new Greenland ice-core chronology for the last glacial termination. *J Geophys Res* 111: D06102. doi: 10.1029/2005JD006079
- Rasmussen P, Hede MU, Noe-Nygaard N, Clarke AL, Vinebrooke RD (2009) Environmental response to the cold climate event 8200 years ago as recorded at Højby So, Denmark. *Geol Surv Den Green* 15:57-60
- Renssen H, Isarin RFB (2001) The two major warming phases of the last deglaciation at 14.7 and 11.5 kyr cal BP in Europe: climate reconstructions and AGCM. *Global Planet Change* 30:117-153
- Renssen H, Goosse H, Fichefet T, Campin JM (2001) The 8.2 kyr BP event simulated by a global atmosphere–sea-ice–ocean model. *Geophys Res Lett* 28:1567-1570
- Rinterknecht VR, Clark PU, Raisbeck GM, Yiou F, Brook EJ, Tschudi S, Lunkka JP (2004) Cosmogenic ^{10}Be dating of the Salpausselkä I

- Moraine in southwestern Finland. *Quaternary Sci Rev* 23:2283-2289
- Rinterknecht VR, Clark PU, Raisbeck GM, Yiou F, Bitinas A, Brook EJ, Marks L, Zelšs V, Lunkka J-P, Pavlovskaya IE, Piotrowski JA, Raukas A (2006) The last deglaciation of the southeastern sector of the Scandinavian Ice Sheet. *Science* 311:1449-1452
- Rohling EJ, Pälike H (2005) Centennial-scale climate cooling with a sudden cold event around 8200 year ago. *Nature* 434:975-979
- Rosén P, Segerström U, Eriksson L, Renberg I, Birks HJB (2001) Holocene climatic change reconstructed from diatoms, chironomids, pollen and near-infrared spectroscopy at an alpine lake (Sjuodjläure) in northern Sweden. *The Holocene* 11:551-562
- Rosqvist GC, Leng MJ, Jonsson C (2007) North Atlantic region atmospheric circulation dynamics inferred from a late-Holocene lacustrine carbonate isotope record, northern Swedish Lapland. *The Holocene* 17:867-873
- Ruddiman WF, Kutzbach JE, Vavrus SJ (2011) Can natural or anthropogenic explanations of late-Holocene CO₂ and CH₄ increases be falsified? *The Holocene* 21:865-8879
- Saarse L, Vassiljev J (2010) Holocene shore displacement in the surroundings of Tallinn, North Estonia. *Estonian J Earth Sci* 59:207-215
- Saarse L, Veski S (2001) Spread of broad-leaved trees in Estonia. *Proc Estonian Acad Sci Geol* 50:51-65
- Sarmaja-Korjonen K, Seppä H (2007) Abrupt and consistent responses of aquatic and terrestrial ecosystems to the 8200 cal. yr cold event: a lacustrine record from Lake Arapisto, Finland. *The Holocene* 17:457-467
- Schimanke S, Meier HEM, Kjellström E, Strandberg G, Hordoir R (2012) The climate of the Baltic Sea region during the last millennium simulated with a regional climate model. *Clim Past* 8:1419-1433
- Schmidt G, Jungclauss JH, Ammann CM, Bard E, Braconnot P, Crowley TJ, Delaygue G, Joos F, Krivova NA, Muscheler R, Otto-Bliesner B, Pongratz J, Shindell DT, Solanki SK, Steinhilber F, Vieira LEA (2011) Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0) *Geosci Model Dev* 4:33-45
- Segliņš V, Kalniņa L, Lācis L (1999) The Lubans Plain, Latvia as reference area for long term studies of human impact on the environment. In: Miller U, Hackens T, Lang V, Raukas A, Hicks Sh (eds) *Environmental and cultural history of the Baltic Region*, PACT 57, Belgium, p 105-130
- Seppä H (1996) Post-glacial dynamics of vegetation and tree-lines in the far north of Fennoscandia. *Fennia* 174:1-96
- Seppä H, Birks HJB (2001) July mean temperature and annual precipitation trends during the Holocene in the Fennoscandian tree-line area: pollen-based reconstructions. *The Holocene* 11:527-539
- Seppä H, Birks HJB (2002) Holocene climate reconstructions from the Fennoscandian tree-line area based on pollen data from Toskaljavri. *Quaternary Res* 57:191-199
- Seppä H, Hammarlund D (2000) Pollen-stratigraphical evidence of Holocene hydrological change in northern Fennoscandia supported by independent isotopic data. *J Paleolimnol* 24:69-79
- Seppä H, Poska A (2004) Holocene annual mean temperature changes in Estonia and their relationship to solar insolation and atmospheric circulation patterns. *Quaternary Res* 61:22-31
- Seppä H, Nyman M, Korhola A, Weckstrom J (2002a) Changes of tree lines and alpine vegetation in relation to post-glacial climate dynamics in northern Fennoscandia based on pollen and chironomid records. *J Quaternary Sci* 17:287-301
- Seppä H, Birks HH, Birks HJB (2002b) Rapid climatic changes during the Greenland stadial 1 (Younger Dryas) to early Holocene transition on the Norwegian Barents Sea coast. *Boreas* 31:215-225
- Seppä H, Birks HJB, Odland A, Poska A, Veski S (2004a) A modern pollen-climate calibration set from northern Europe: developing and testing a tool for palaeoclimatological reconstructions. *J Biogeogr* 31:251-267
- Seppä H, Hannon G, Bradshaw RHW (2004b) Holocene history of alpine vegetation and forestline on Pyhäkero Mountain, Northern Finland. *Arctic Antarctic Alpine Res* 36:607-614
- Seppä H, Hammarlund D, 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 Dynam* 25:285-297
- Seppä H, Birks HJB, Giesecke T, Hammarlund D, Alenius T, Antonsson K, Bjune AE, Heikkilä M, MacDonald GM, Ojala AEK, Telford RJ, Veski S (2007) Spatial structure of the 8200 cal yr BP event in northern Europe. *Clim Past* 3:225-236
- Seppä H, MacDonald GM, Birks HJB, Gervais BR, Snyder JA (2008) Late-Quaternary summer temperature changes in the northern-European tree-line region. *Quaternary Res* 69:404-412
- Shapiro AI, Schmutz W, Rozanov E, Schoell M, Haberleiter M, Shapiro AV, Nyeki S (2011) A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing. *Astron Astrophys* 529 A 67
- Shindell DT, Schmidt GA, Mann ME, Rind D, Waple A (2001) Solar forcing of regional climate change during the Maunder Minimum. *Science* 294:2149-2152
- Snowball I, Zillén L, Gaillard MJ (2002) Rapid early-Holocene environmental changes in northern Sweden based on studies of two varved lake-sediment sequences. *The Holocene* 12:7-16
- Snowball I, Muscheler R, Zillén L, Sandgren P, Stanton T, Ljung K (2010) Radiocarbon wiggle matching of Swedish lake varves reveals asynchronous climate changes around the 8.2 kyr cold event. *Boreas* 39:20-733
- Solovieva N, Tarasov PE, MacDonald G (2005) Quantitative reconstruction of Holocene climate from the Chuna Lake pollen record, Kola Peninsula northwest Russia. *The Holocene* 15:141-148
- Stančikaitė M, Milkevičius M, Kisieliene D (2003) Palaeoenvironmental changes in the environs of Žadeikiai Bog, NW Lithuania, during the Late Glacial and Holocene according to palaeobotanical and ¹⁴C data. *Geologija* 43: 47-60
- Stančikaitė M, Kisieliene D, Simniškytė A (2004) Vegetation response to the climatic and human impact changes during the Late Glacial and Holocene: case study of the marginal area of Baltija Upland, NE Lithuania. *Baltica* 17:17-33
- Stančikaitė M, Baltrūnas V, Šinkūnas P, Kisieliene D, Ostrauskas T (2006) Human response to the Holocene environmental changes in the Biržulis Lake region, NW Lithuania. *Quaternary Int* 150:113-129
- Stančikaitė M, Šinkūnas P, Šeirienė V, Kisieliene D (2008) Patterns and chronology of the Lateglacial environmental development at Pamerkiai and Kašučiai, Lithuania. *Quaternary Sci Rev* 27:127-147
- Stančikaitė M, Kisieliene D, Moe D, Vaikutienė G (2009) Lateglacial and early Holocene environmental changes in northeastern Lithuania. *Quaternary Int* 207:80-92
- Starkel L (1999) 8500–8000 yrs BP humid phase – global or regional? *Sci Rep Res Tohoku Geography* 49:105-133
- Starkel L (2002) Younger Dryas–Preboreal transition documented in the fluvial environment of Polish rivers. *Global Plant Change* 35:157-167
- Steinhilber F, Beer J, Fröhlich C (2009) Total solar irradiance during the Holocene. *Geophys Res Lett* 36:L19704, doi:[10.1029/2009GL040142](https://doi.org/10.1029/2009GL040142)
- Subetto DA (2009) Lake sediments: Paleolimnological reconstructions. Herzen, St. Petersburg (in Russian)

- Subetto DA, Wohlfarth B, Davydova NN, Sapelko TV, Björkman L, Solovieva N, Wastegård S, Possnert G, Khomutova VI (2002) Climate and environment on the Karelian Isthmus, northwestern Russia, 13 000-9000 cal. yrs BP. *Boreas* 31:1-19
- Subetto D, Davydova N, Kuznetsov DD, Ludikova AV, Sapelko TV (2006) Climate and environment reconstructions of the Lake Ladoga area during the Late Holocene. In: European Large Lakes Symposium. Ecosystem changes and their ecological and socio-economic impacts. 11-15 September 2006. Tartu, Estonia
- Sugita S (2007) Theory of quantitative reconstruction of vegetation I: pollen from large site REVEALS regional vegetation composition. *The Holocene* 17:229-241
- Szafer W (1946) Flora pliocenska w Krosconku nad Dunajcem [The Pliocene flora of Krosconku in Poland]. *Polska Akad. Umiej. Rozpr Wydz., Mat.-prz. v. 72, Dz.B, N1-2*: Krakow
- Thomas ER, Wolff EW, Mulvaney R, Steffensen JP, Johnsen SJ, Arrowsmith C, White JWC, Vaughn B, Popp T (2007) The 8.2 ka event from Greenland ice cores. *Quaternary Sci Rev* 26:70-81
- Tylmann W, Szpakowska K, Ohlendorf C, Woszczyk M, Zolitschka B (2011) Conditions for deposition of annually laminated sediments in small meromictic lakes: a case study of Lake Suminko (northern Poland). *J Paleolimnol* 47:55-70
- Velle G, Brooks SJ, Birks HJB, Willassen E (2005) Chironomids as a tool for inferring Holocene climate: an assessment based on six sites in southern Scandinavia. *Quaternary Sci Rev* 24:1429-1462
- Veski S, Seppä H, Ojala AEK (2004) Cold event at 8200 yr BP recorded annually laminated lake sediments in eastern Europe. *Geology* 32:681-684
- Veski S, Koppel K, Poska A (2005) Integrated palaeoecological and historical data in the service of fine-resolution land use and ecological change assessment during the last 1000 years in Rouge, southern Estonia. *J Biogeogr* 32:1473-1488
- Veski S, Amon L, Heinsalu A, Reitalu T, Saarse L, Stivrins N, Vassiljev J (2012) Lateglacial vegetation dynamics in the eastern Baltic region between 14,500 and 11,400 cal yr BP: A complete record since the Bølling (GI-1e) to the Holocene. *Quaternary Sci Rev* 40:39-53
- von Grafenstein U, Erlenkeuser H, Muller J, Jouzel J, Johnsen SJ (1998) The cold event 8200 year ago documented in oxygen isotope records of precipitation in Europe and Greenland. *Clim Dynam* 14:73-81
- Walker MJC (1995) Climatic changes in Europe during the last glacial-interglacial transition. *Quaternary Int* 28:63-76
- Walker MJC (2001) Rapid climate change during the last glacial-interglacial transition; implications for stratigraphic subdivision, correlation and dating. *Global Planet Change* 30:59-72
- Walker M, Johnsen S, Rasmussen SO, Popp T, Steffensen J-P, Gibbard P, Hoek W, Lowe J, Andrews J, Björck S, Cwynar LC, Hughen K, Kershaw P, Kromer B, Litt T, Lowe DJ, Nakagawa T, Newnham R, Schwander J (2009) Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. *J Quaternary Sci* 24:3-17
- Wastegård S, Possnert G, Khomutova VI (2002) Climate and environment on the Karelian Isthmus, northwestern Russia, 13 000-9000 cal. yrs BP. *Boreas* 31:1-19
- Widerlund A, Andersson SA (2011) Late Holocene freshening of the Baltic Sea derived from high-resolution strontium isotope analyses of mollusk shells. *Geology* 39:187-190
- Wiersma AP, Renssen H, (2006) Model-data comparison for the 8.2 ka BP event: confirmation of a forcing mechanism by catastrophic drainage of Laurentide lakes. *Quaternary Sci Rev* 25:63-88
- Wohlfarth B (1996) The chronology of the last termination: A review of radiocarbon-dated, high-resolution terrestrial stratigraphies. *Quaternary Sci Rev* 15:267-284
- Wohlfarth B, Filimonova L, Bennike O, Björkman L, Brunnberg L, Lavrova N, Demidov I, Possnert G (2002) Late-Glacial and Early Holocene environmental and climatic change at Lake Tambichozero, southeastern Russian Karelia. *Quaternary Res* 58:261-272
- Wohlfarth B, Lacourse T, Bennike O, Subetto D, Filimonova L, Tarasov P, Sapelko T, Demidov I (2007) Review article: Climatic and environmental changes in NW Russia between 15,000 and 8000 cal yr BP. *Quaternary Sci Rev* 26:1871-1883
- Yu S-Y (2003) Centennial-scale cycles in middle Holocene sea level along the southeastern Swedish Baltic coast. *Bull Geol Soc Am* 115:1404-1409
- Yu S-Y, Colman SM, Lowell TV, Milne GA, Fisher TG, Breckenridge A, Boyd M, Teller JT (2010) Freshwater outburst from lake Superior as a trigger for the cold event 9300 years ago. *Science* 328:1262-1265
- Zagwijn WH (1994) Reconstruction of climate change during the Holocene in western and central Europe based on pollen records of indicator species. *Veget Hist Archaeobot* 3:65-88
- Zillén L, Snowball I (2009) Complexity of the 8 ka climate event in Sweden recorded by varved lake sediments. *Boreas* 38:493-503
- Zillén L, Conley DJ, Andrén T, Andrén E, Björck S (2008) Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact. *Earth Sci Rev* 91:77-92
- Zubakov VA, Borzenkova II (1990) Global paleoclimate of the Late Cenozoic. *Developments in Paleontology* 12. Elsevier