Technical Report

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Climate in Sweden during the past millennium – Evidence from proxy data, instrumental data and model simulations

Anders Moberg, Department of Physical Geography and Quaternary Geology, Stockholm University
Department of Meteorology, Stockholm University

Isabelle Gouirand, Kristian Schoning, Barbara Wohlfarth
Department of Physical Geography and Quaternary Geology, Stockholm University

Erik Kjellström, Markku Rummukainen, Rossby Centre, SMHI

Rixt de Jong, Department of Quaternary Geology, Lund University

Hans Linderholm, Department of Earth Sciences, Göteborg University

Eduardo Zorita, GKSS Research Centre, Geesthacht, Germany

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Anders Moberg, Department of Physical Geography
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Lund University

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Summary

Knowledge about climatic variations is essential for SKB in its safety assessments of a geological repository for spent nuclear waste. There is therefore a need for information about possible future climatic variations under a range of possible climatic states. However, predictions of future climate in any deterministic sense are still beyond our reach. We can, nevertheless, try to estimate the magnitude of future climate variability and change due to natural forcing factors, by means of inferences drawn from natural climate variability in the past. Indeed, the climate of the future will be shaped by the sum of natural and anthropogenic climate forcing, as well as the internal climate variability.

The aim here is to review and analyse the knowledge about Swedish climate variability, essentially during the past millennium. Available climate proxy data and long instrumental records provide empirical information on past climatic changes. We also demonstrate how climate modelling can be used to extend such knowledge. We use output from a global climate model driven with reconstructed radiative forcings (solar, volcanic and greenhouse gas forcing), to provide boundary conditions for a regional climate model. The regional model provides more details of the climate than the global model, and we develop a simulated climate history for Sweden that is complete in time and space and physically consistent. We use output from a regional model simulation for long periods in the last millennium, to study annual mean temperature, precipitation and runoff for the northern and southern parts of Sweden. The simulated data are used to place corresponding instrumental records for the 20th century into a plausible historical perspective. We also use output from the regional model to study how the frequency distribution of the daily temperature, precipitation, runoff and evaporation at Forsmark and Oskarshamn could have varied between unusually warm and cold 30-year periods during the last millennium. Models, however, cannot be used to deduce the exact time evolution of climate variations, but they can provide relevant information in a statistical sense, for example by defining the limits within which climate naturally has varied. Uncertainties – and also advantages – of both empirical climate data and model simulations are discussed.

A main conclusion is that there have been both relatively warm and cold past periods, as well as some relatively wet and dry periods during the past 1,000 to 2,000 years. It appears that the last 70-year period in Sweden was the warmest period over at least the last 500 years. Exactly how unusual the past few decades were can, however, not yet be established due to limitations of the proxy data. There are also indications that significant past changes in precipitation, river runoff and storminess have occurred, although available proxy data do not yet allow accurate quantitative estimations.

The results of the present report will be used by SKB, along with other information, in the process of defining and describing future climate scenarios. They will also be used in evaluating the impact of climate on various processes related to repository safety, for example biosphere processes.

To increase knowledge of past climate variations in Sweden for the last millennium, it seems necessary to develop additional climate proxy records with annual or at least decadal resolution. Long simulations with climate models may also be used in this context.

Sammanfattning

Kunskap om klimatvariationer är avgörande för SKB:s säkerhetsanalyser avseende förvaringsplatser för utbränt kärnbränsle. Det finns därför behov av information om möjliga framtida klimavariationer under en rad tänkbara klimattillstånd. Tillförlitliga prognoser av framtida klimat ligger emellertid ännu utanför vår kunskapsram. Vi kan ändå försöka skatta möjliga storleksordningar av framtida klimatförändringar, baserat på kunskap om naturliga klimatvariationer i det förgångna. Framtida klimatet kommer att manifestera sig som summan av naturlig och antropogen klimatpåverkan samt intern klimatvariabilitet.

Målsättningen här är att analysera tillgänglig information om klimatvariationer i Sverige under i huvudsak det senaste millenniet. Klimatproxydata och långa instrumentella serier definierar den empiriska kunskapsbasen. Vi visar därtill hur klimatmodellering kan användas för att utöka kunskapen. Utdata från en global modellsimulering, driven med rekonstruerade variationer i yttre klimatpåverkan (solvariationer, vulkaniska aerosoler och växthusgaser), nyttjas för att ge randvillkor till en regional modellsimulering. Den regionala modellen ger finare rumslig upplösning än den globala modellen, och används här för att skapa en svensk klimathistoria som är komplett i tid och rum och som är fysikaliskt konsistent. Vi använder utdata från en regional klimatmodellsimulering, för långa perioder under senaste årtusendet, för att studera variationer hos årsmedeltemperatur, nederbörd och avrinning i norra och södra delen av Sverige. Simulerade data används för att sätta motsvarande instrumentella observationer från 1900-talet i ett tänkbart historiskt perspektiv. Vi nyttjar därtill modellutdata för att studera hur frekvensfördelningen av dygnsvärden av temperatur, nederbörd, avrinning och avdunstning vid Forsmark och Oskarshamn kan tänkas ha varierat mellan ovanligt varma och kalla 30-årsperioder under senaste millenniet. Modellsimuleringar kan emellertid inte visa den exakta tidsutvecklingen av klimatets variationer. De kan däremot ge relevant information i en statistisk bemärkelse, till exempel genom att definiera de gränser inom vilket klimatets naturliga variationer rimligen har skett. Osäkerheter – men också fördelar – hos såväl empiriska klimatdata som modellsimuleringar diskuteras här.

En huvudslutsats är att det har funnits både relativt varma och relativt kalla perioder, såväl som relativt torra och våta perioder under de senaste 1 000 till 2 000 åren. De senaste 70 åren i Sverige tycks ha varit den varmaste perioden under åtminstone 500 år. Exakt hur ovanliga de senaste decennierna var, kan emellertid ännu inte säkert avgöras på grund av stora osäkerheter i proxydata. Det finns också indikationer på att signifikanta variationer förekommit i nederbörd, avrinning och stormighet. Tillgängliga proxydata möjliggör dock inte noggranna kvantitativa skattningar av sådana aspekter.

SKB kommer att använda resultaten från denna rapport, tillsammans med annan information, i processen med att definiera och beskriva framtida klimatscenarier. Resultaten kommer också att nyttjas i utvärderingar av hur klimatet påverkar processer, i t ex biosfären, som är av betydelse för säkerheten vid förvaringsplatserna.

För att utöka kunskapen om klimatvariationer i Sverige under senaste millenniet, är det nödvändigt att utveckla många fler klimatproxyserier med årlig, eller åtminstone dekadal, tidsupplösning. Fler långa simuleringar med klimatmodeller kan också bidra till ökad kunskap i detta sammanhang.

Contents

1 Introduction

1.1 Context for the present study

The results of the present study will be used by SKB in safety assessments for a geological repository for spent nuclear waste. The safety assessments are based on various climate scenarios depicting possible future climate developments /cf SKB 2006a/. The safety functions of the repository should fulfil the requirements in all these climate cases. The results of the present report are used, along with other information, in the process of defining and describing the climate scenarios. For example, the SR-Can safety assessment /SKB 2006ab/ includes one variant of climate evolution where the long-term climate trend is assumed to be affected only by natural climate variations, and not by anthropogenically enhanced greenhouse warming. Therefore, for this variant, palaeoclimate data depicting natural climate variability and trends can be used to assess the climate during the initial 1,000 years after repository closure. In the SR-Can safety assessment, this variant of climate evolution is complemented with a variant describing a situation with an increased greenhouse warming /SKB 2006ab/. Finally, the results of the present study makes it possible to evaluating the impact of climate on various other processes related to repository safety, for example biosphere processes.

1.2 Background and objectives

A project called "A 2000-year climate reconstruction for Sweden" started in May 2004 with the purpose to address the questions posed above. The first project ideas arose from discussions within the first MUSCAD (MUlti-proxy Studies of Climate Anno Domini) meeting held at Stockholm University in November 2002. MUSCAD is a network for scientists interested in issues related to climate variations in Sweden during the past 2000 years. The project was conducted for SKB jointly by the Department of Physical Geography and Quaternary Geology at Stockholm University, the Department of Meteorology at Stockholm University and the Rossby Centre at the Swedish Meteorological and Hydrological Institute, and was finished in April 2006.

The main objectives of the project were; (i) to describe the climatic conditions in Sweden during the past 2,000 years for improved understanding of natural climate variability and its underlying mechanisms, and (ii) to evaluate how a combination of proxy data and climate modelling can be used to reconstruct past climate.

The original goal of reconstructing climate for the last 2,000 years could not be fully reached because the amount of detailed information of past climate decreases too rapidly back in time. Therefore, the title of this report, "Climate in Sweden during the past millennium – Evidence from proxy data, instrumental data and model simulations", better represents the material analysed and discussed.

1.2.1 Scientific background

Climate is changing naturally on time scales of 10 to more than 100,000 years, due to e.g. solar variability, volcanic eruptions, and insolation changes caused by variations in the earth's orbit. Recent climate changes, however, are also affected by increased atmospheric concentrations of greenhouse gases. The recent rise in greenhouse gases is certainly mainly due to human activities. Climate scenarios based on global and regional climate models indicate for the 21st century a substantial rise in temperatures, a considerable change in hydrological conditions and a rise in global sea level due to increased greenhouse gas levels /IPCC 2001/. The impact of these changes will likely exhibit distinct and important geographical differences. In addition to the change and variability attributable to causes external to the global climate system, internal variability is a characteristic of the system as well. The latter is often more pronounced on regional scales than in the global mean.

The future climate will be shaped by both anthropogenic and natural forcing, as well as by unforced internal variability. The necessary scenarios for the anthropogenic climate forcing rely on assumptions about future human activities as a result of societal choices, including future population changes and economic development. These scenarios for future anthropogenic climate forcing have then been used to force climate models, in order to develop scenarios for the future climate changes towards the end of the current century /IPCC 2001/. Inferences on the internal climate variability can be made both from past data and by means of climate modelling. Scenarios for the future natural climate forcing are, however, impossible to construct as the relevant mechanisms are not understood in any predictive sense. We can, nevertheless, try to estimate the possible magnitude of future natural change, based on inference drawn from natural climate changes in the past. Our ability to manage the impact of future changes, such as in the context of management of nuclear fuel repositories, will be shaped by the sum of natural and anthropogenic changes and internal climate variability.

Studies of *past climate* – based on natural climate archives that provide climate proxy data – offer the possibility to reconstruct a wider range of past climatic conditions compared to the recent information provided by instrumental observations that extend back a few centuries at best. In addition to shedding light on past climate conditions, these studies are useful for evaluating climate models that are used to project *future climate changes*.

The last millennium offers a unique opportunity to reconstruct natural climate variations and their underlying causes, due to its richness of different types of climate proxy data with different time resolutions /Mann et al. 1998, 1999, Briffa 2000, Jones et al. 2001, Luterbacher et al. 2002, 2004, Mann and Jones 2003, Jones and Mann 2004, Moberg et al. 2005a/, and consequently also as one test period for evaluating climate models. Europe – including Sweden has also an unusual potential for such investigations, being the only part of the world with widespread instrumental data series reaching back into the 18th century /Moberg and Bergström 1997, Camuffo and Jones 2002, Böhm et al. 2001/. The problem of reconstructing past climates is, however, a difficult one. This is illustrated in Figure 1-1, which shows two different attempts to reconstruct Northern Hemisphere annual mean temperatures for the last millennium, one by /Mann et al. 1999/ and one by /Moberg et al. 2005a/. Both reconstructions suggest that the hemispheric-scale warmth since the late 20th century is unprecedented in the last millennium, although the amplitude of past temperature changes clearly differ between the two records.

This report presents an overview of what proxy data can tell us about climate in Sweden during the last millennium, or in some cases even longer back in time. We have attempted a collection of many types of proxy data. This is important as they offer different advantages and they suffer from different problems. This report also provides more detailed climate information from Swedish instrumental data for the last 260 years. A tentative evolution of climate in Sweden for the last millennium as simulated by a climate model is also provided. Taken together, these three basic types of information are used to illustrate possible Swedish climate variations during the last millennium. It is impossible, however, to reconstruct exact details of the past climate.

MuscAD
Multi-proxy Studies of Climate Anno Domini

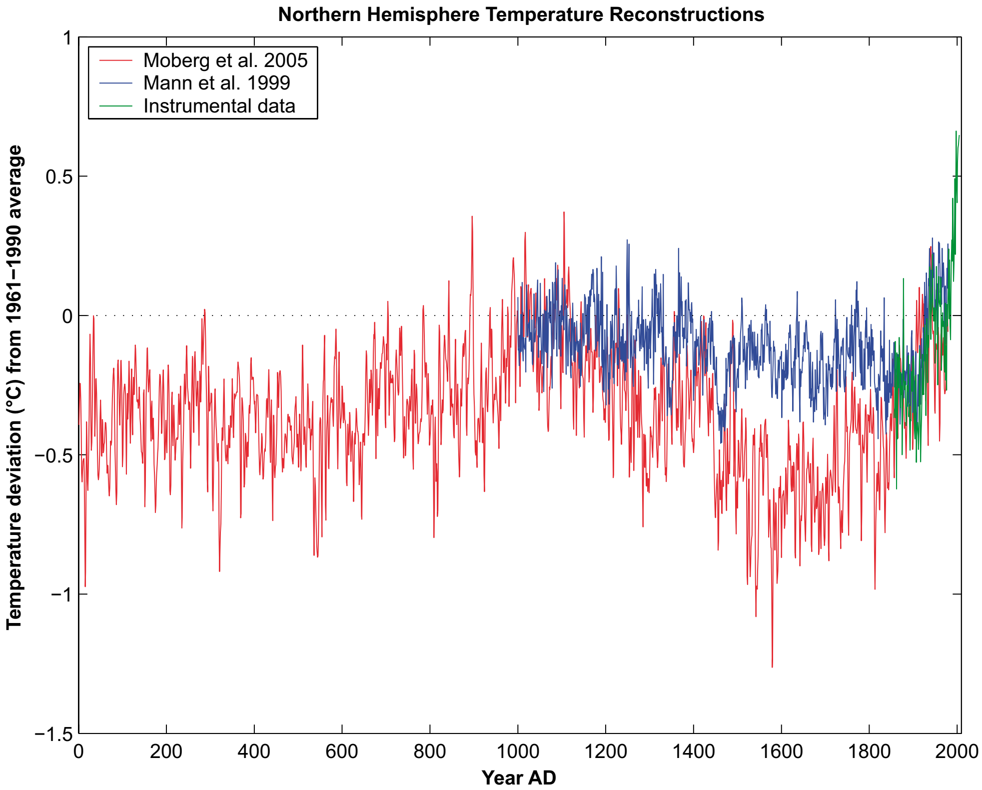

***Figure 1-1**. Northern Hemisphere annual mean temperature reconstructions from proxy data by /Mann et al. 1999/ and /Moberg et al. 2005a/. The instrumental record from the Climatic Research Unit, updated from /Jones and Moberg 2003/, is also shown.*

Nevertheless, this report provides a benchmark for the *likely range within which our regional climate has varied naturally during the last millennium*. An example of this is given in the very last analysis presented in the report. In this example, output from a regional climate model simulation is used to illustrate how daily temperature, precipitation, runoff and evaporation at Forsmark and Oskarshamn might have differed between unusually cold and warm 30-year periods during the last millennium.

2 Methodology

The basic methods and ideas utilized in this report are the following:

- We **review and analyse available climate proxy data** (mainly for the last 500 to 1,000 years, but some records reach longer back) and **long instrumental records** (for the last 260 years) for the Scandinavian region with focus on Sweden. This gives an **overview of the empirical evidence** for the evolution of climate in the region. However, only a few climate variables can be reconstructed from proxy data, often with rather poor spatial representation and with limited seasonal information. Moreover, each proxy series is associated with various individual technical problems. These difficulties are briefly discussed.
- We **demonstrate how climate modelling can be used** to facilitate the drawing of inferences about past regional climate variations in Sweden. We use output from a **global climate model** driven with reconstructed radiative forcings (solar, volcanic and greenhouse gas forcing), to provide boundary conditions for a **regional climate model**. The regional model provides more details of the climate than the global model. We develop a simulated climate history for the Swedish region that is complete in time and space and physically consistent for selected periods. The resulting simulated regional climate, however, is conditioned by the reliability of the global model and the forcing history used to drive the global model. Therefore, we **compare the Scandinavian climate as simulated with the global model with proxy data and instrumental data**, to obtain an understanding for how realistically the global model behaves over the region of interest. It should be understood that the simulated climate is only one realization out of numerous possible realizations given the same reconstructed forcing history. Especially under periods with uncertain or weak external forcing, even a "perfect" climate model should be expected to provide only a statistical match to the evolution of the real system, due to the nature of unforced internal variability. Past solar and volcanic forcings are also uncertain, whereas greenhouse gas changes are rather well known. Some discussion of these features is provided. Moreover, analyses of climate in Scandinavia simulated with the global model help to understand processes of importance for the regional climate variability in Sweden
- We use output from the regional model simulation for long periods during the last millennium, to study **annual mean temperature, precipitation and runoff for the northern and southern parts of Sweden**. These data are used to place corresponding instrumental records for the 20th century into a tentative historical perspective. We also use the output from the regional model to study how the frequency distribution of the **daily temperature, precipitation, runoff and evaporation at Forsmark and Oskarshamn could have varied between unusually warm and cold 30-year periods during the last millennium**.

3 Climate proxy data and long instrumental climate records

Climate proxies are physical, chemical, or biological variables which can be extracted from a variety of geological or biological archives to reconstruct past climatic and environmental changes. Climate proxies can also be obtained from historical documentary sources. Initially, climate reconstructions based on proxy evidence were mainly qualitative, i.e. indicating relative changes. With the more recent development of extensive transfer functions and statistical techniques, past climatic and environmental changes can now also be quantitatively assessed. The value of climate proxy data series has been more and more acknowledged during the past years, since instrumental climate data series, which often extend back only about 150 years, do not cover the full range of climate variability. Moreover, climate models should ideally be tested for a wider range of climatic conditions than those which occurred during the past ca 150 years of instrumental data. The only available data sets for such exercises are climate proxies.

Terrestrial climatic and environmental archives comprise, for example, lake sediment sequences, peat deposits, fluvial and glacial sediments, annual growth rings in wood, cave speleothems and aeolian deposits. Examples of marine archives are marine sediment sequences, corals and raised beaches. Moreover, ice cores have been obtained from large ice sheets and glaciers in different regions. Historical documentary evidence may provide a variety of climate information from regions where there has been a long tradition of writing and documenting human activities.

Climatic reconstructions based on proxy data are limited by a number of factors and these have to be carefully evaluated before attempts are made to use a certain proxy and/or archive for quantitative temperature and/or precipitation reconstructions:

(i) Geological and biological archives are not only influenced by climatic changes, but also by a variety of site-specific, local processes and feedbacks. These in turn will have an influence on the different proxy records.

(ii) Each specific proxy may respond to a number of climatic and environmental variables (e.g. lake water temperature, air temperature, summer temperature, humidity/precipitation, length of ice cover, salinity changes, etc).

(iii) Climatic/environmental changes and human impact may be difficult to differentiate.

(iv) Predators may change the floral and faunal assemblages in a lake system and this in turn may influence the lake ecosystem without any external climatic changes.

(v) Transfer functions, developed for specific proxies depend on the assumption that present-day climatic and environmental conditions can be extrapolated into the past.

(vi) Different types of transfer functions exist for different proxies and these are not directly comparable.

(vii) In the case of historical documentary archives a careful assessment and evaluation of the historical and societal background is necessary. The original reason for collecting the information was often related to some practical purpose, which can lead to subjective selection.

3.1 Lake sediment data

Lakes are important terrestrial archives, since their sediments preserve physical, chemical and biological information on climatic and environmental conditions which existed at a certain time in the past. If the sediments are annually laminated, annual layer counting may enable a very detailed chronological framework. If the sediments are massive, their chronology needs to be determined by ^{14}C, ^{210}Pb or ^{137}Cs dating techniques.

Due to rapid burial and anoxic conditions, biological remains are often well preserved. Pollen and plant macro remains from the surrounding vegetation give a picture of how the vegetation changed, and allow reconstructing summer and winter temperatures and precipitation. Algae (diatoms) and insect remains (chironomids) give information on lake status changes, on past summer temperatures and precipitation. Stable isotopes allow reconstructing moisture sources, precipitation and temperatures. Moreover, lake sediments are often an excellent source for tracing past volcanic eruptions, anthropogenic pollution, catchment erosion, agricultural activity and lake level changes (Figure 3-1).

Lake sediment records in southern Sweden contain climatic and environmental information for the past ca 16,000 years BP, while lake sediment records from central and northern Sweden, where the last deglaciation occurred considerably later, only extend back to the start of the Holocene, i.e. covering approximately the last 11,500 years.

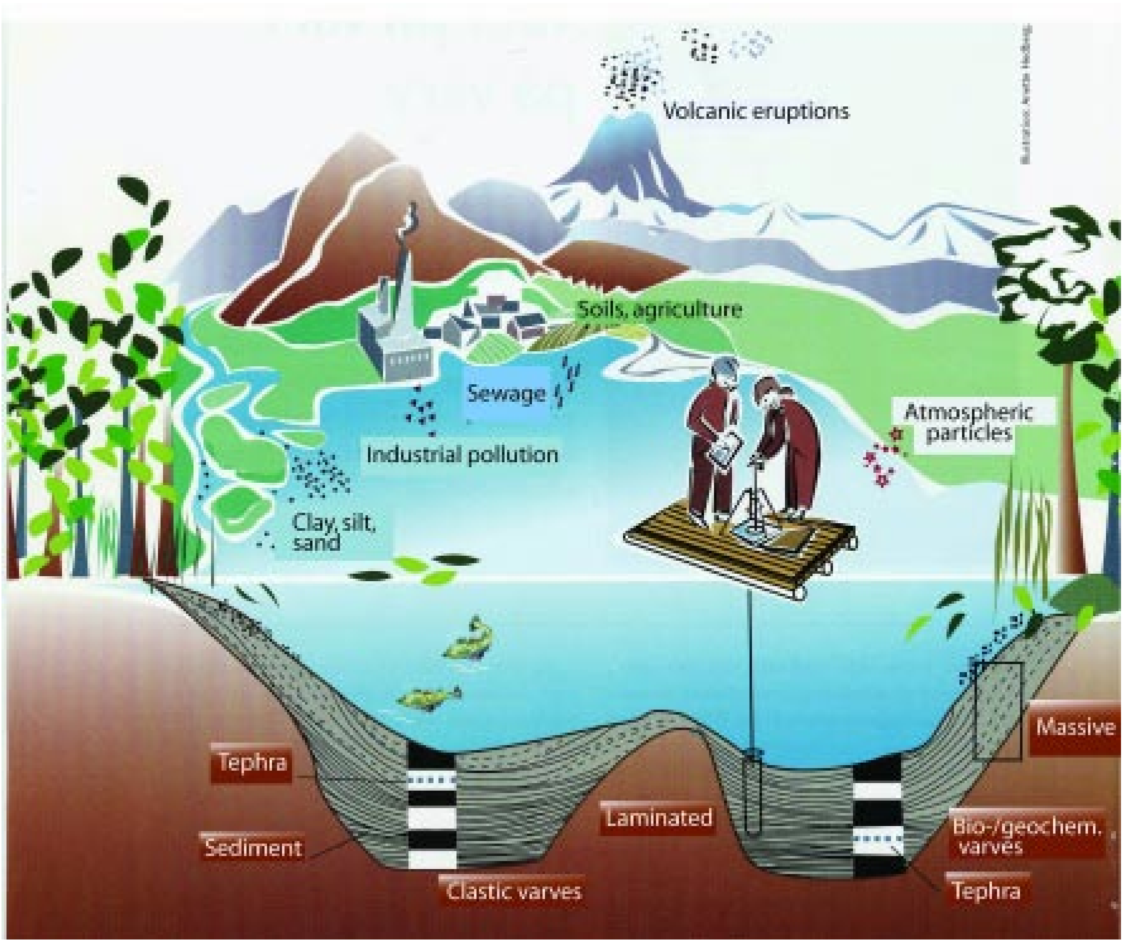

Figure 3-1. *Lake sediments as climatic and environmental archives. Lake sediments record catchment changes, such as industrial pollution, river input, vegetation changes, agricultural activity, temperature and precipitation changes through a variety of so-called climate and environmental proxies. From /Wohlfarth and Björck 2001 Figure 1/.*

While the general climatic and environmental development during the Holocene has been known for several decades, quantitative temperature and precipitation reconstructions, based on pollen, diatoms, chironomids and stable isotopes have only been made during the past ca 5–10 years /Seppä and Birks 2002, Bigler et al. 2003, Hammarlund et al. 2004, Larocque and Bigler 2004/. Broadly these reconstructions mirror the general trend of an early Holocene warm interval, followed by a gradual cooling from ca 6,000 years to the present. Examples from Lake Vuoskkujávri near Abisko in northern Sweden illustrate these general climatic trends (Figure 3-2). However, it has to be noted that the reliability of the climate reconstructions based on the different proxies is very limited between ca 10,000 and 8,000 years BP, because the calibration data is highly uncertain. During the mid-Holocene (8,000–5,500 years BP) temperature and humidity seem to have been higher, while the late Holocene (5,500 years to present) was generally cooler and drier. Comparisons of different types of climate proxies show that they do not agree well for the early part of the Holocene, where pollen data indicate cooler conditions and aquatic species warmer conditions. As shown in Figure 3-2, the error margin of these reconstructions is fairly large, at 1.5–2°C for temperature and at around 300–500 mm for precipitation.

Most of these lake sediment studies address the longer-term Holocene climatic changes and cover the last ca 10,000 years. For practical reasons, the sampling resolution is often only about 4–6 samples per 1,000 years /Hammarlund et al. 2004, Seppä and Birks 2002, Bigler et al. 2003, Larocque and Bigler 2004/. Thus, for the interval covering last 2,000 years only up to 13–14 samples were analyzed in several cases, which means a sampling resolution of around 150 years/sample (Figure 3-2). Since these types of studies are just commencing, there are still only few records with quantified climate parameters. Their strength is that they are from areas in central and northern Sweden, where human impact is assumed to have been minimal during the Holocene epoch.

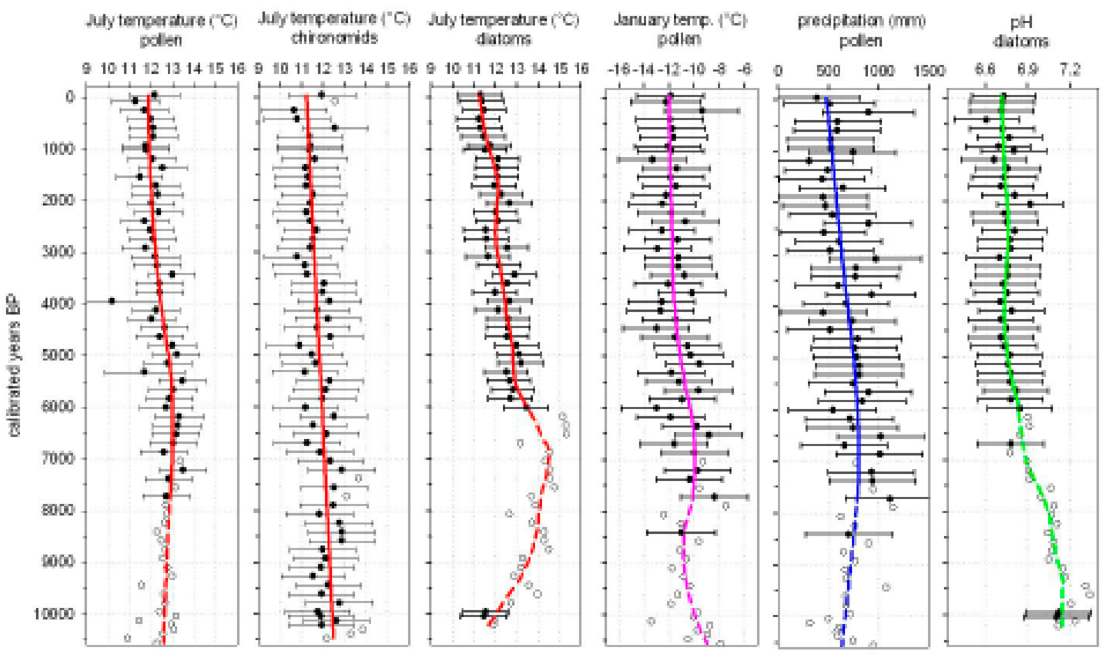

***Figure 3-2.** Lake sediment climate proxy data from Lake Vuoskkujávri (68°20'43 N, 19°06'00 E, 348 m.a.s.l.) near Abisko in northern Sweden (Lapland) for the last 10,500 years. Data from /Bigler et al. 2002/.*

3.1.1 Pollen

Pollen found in lake sediments mirror the surrounding vegetation at the time of sediment deposition. Small lake basins with a restricted catchment usually only receive pollen rain from the close surroundings, while larger lake basins with inflow and outflow incorporate pollen from distant sources, including reworked, older pollen.

Pollen-based climate reconstructions have been obtained by calibrating the pollen assemblage in each sample against a pollen calibration set, which has been established based on surface sediments from a large number (nearly 200) of lakes distributed over the whole of Norway and northern Sweden, covering broad gradients in temperature and precipitation. See /Bigler et al. 2002/ for details and further references.

The advantage of this calibration set, compared to other pollen-based temperature reconstructions, is that it is based on carefully evaluated lakes in close proximity to meteorological stations. The disadvantage is that each surface sample in the training set may correspond to anything between 5 and 30 years. The correlation to meteorological data series has thus to take into account that each sample contains an accumulative average of the pollen rain covering a time interval considerably longer than 1 year.

3.1.2 Diatoms and chironomids

Diatoms (algae) and chironomid (non-biting midges) in lake sediments respond to changes in water (and air) temperature, to lake-water salinity changes and to ecological changes in the lake's floral and faunal assemblages. As such, it is important to disentangle ecological from climatic driven changes.

Diatom and chironomid based climate reconstructions have been obtained by calibrating the respective assemblages in each sample against a calibration set for diatoms and chironomids from several lakes (about 100), which are distributed regionally over northernmost Sweden /Laroque et al. 2001, Bigler and Hall 2002/. See /Bigler et al. 2002/ for details and further references.

3.1.3 Reconstructed temperatures – results from multiple sites and proxies

Here, we have compiled information from 11 temperature reconstructions from eight lakes (Figure 3-3), based on chironomids, diatoms and pollen (Table 3-1), to make an average July temperature record for the past 2,000 years. Before averaging, each series was expressed as anomalies from its mean value. Moreover, linear interpolation between successive values was made in each individual series to obtain annual resolution. Then, an average series was created by taking the arithmetic average of all series in each year. Figure 3-4 shows this composite temperature record, together with all individual proxy data series, as temperature anomalies from the long-term average. The different proxy records show some similar trends but the amplitude and exact timing of the peaks show little coherency. Two periods with warm temperatures are recorded in the composite record for the period AD 150–350 and between AD 500 and 1,000. The composite record shows low temperatures between AD 400 and 500. From AD 1,000 to present temperatures are mainly below the long-term average, with a minimum between AD 1,650 and 1,800. From 1,800 onwards the composite record indicates increasing temperatures. The large spread among the individual proxy records, however, illustrates a large uncertainty in the trends of the composite series.

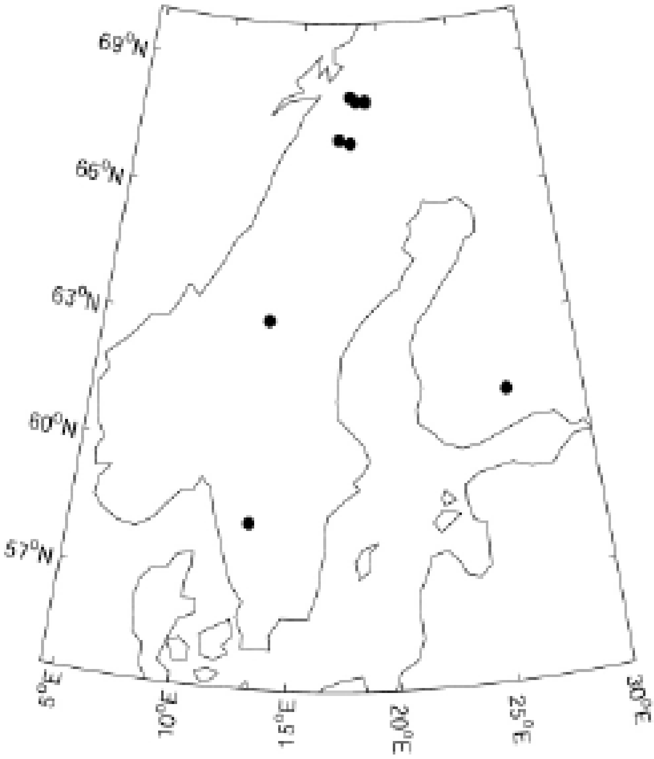

Figure 3-3. *Locations of the eight lakes presented in Table 3-1.*

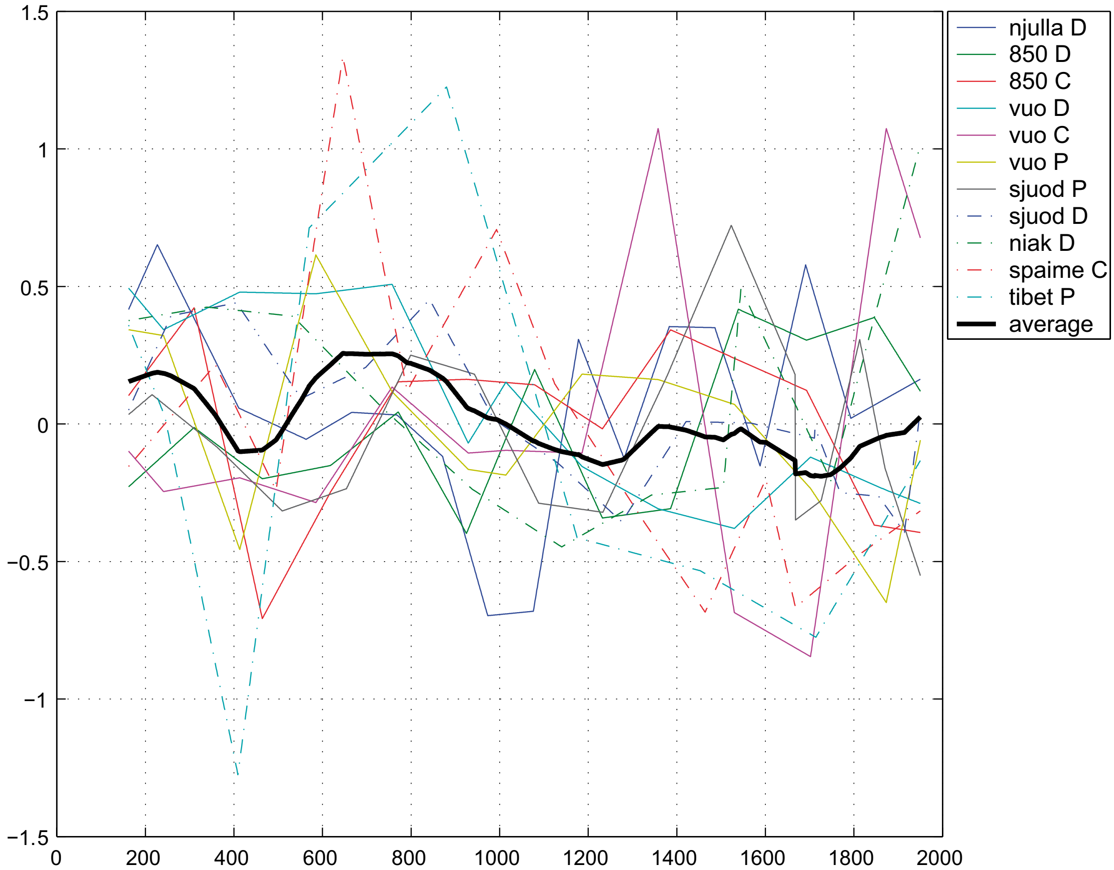

Figure 3-4. *Summer temperature reconstructions based on proxy data from sediments in the eight lakes presented in Table 3-1. The average of the 11 individual series is also shown. Temperature anomalies (°C) from the long-term average.*

Table 3-1. List of lakes from which climate proxy data have been retrieved and which are discussed in the context of the present study. The legend column refers to the legend in Figure 3-4.

Lake	Lat	Long	Proxy	Legend	Reference
Lake Njulla	68.30	18.07	Diatom	njulla D	/Bigler et al. 2003/
Lake 850	68.18	19.07	Diatoms	850 D	/Laroque and Bigler 2004/
Lake 850	68.18	19.07	Chironomids	850 C	/Laroque and Bigler 2004/
Lake Vuoskkujávri	68.20	19.06	Diatoms	vuo D	/Bigler et al. 2002/
Lake Vuoskkujávri	68.20	19.06	Chironomids	vuo C	/Bigler et al. 2002/
Lake Vuoskkujávri	68.20	19.06	Pollen	vuo P	/Bigler et al. 2002/
Sjuodjijaure	67.22	18.04	Pollen	sjuod P	/Rosén et al. 2003/
Sjuodjijaure	67.22	18.04	Diatoms	sjuod D	/Rosén et al. 2003/
Niak	67.30	17.31	Diatoms	niak D	/Rosén et al. 2003/
Spåime (A)	61.80	13.50	Chironomids	spaime C	/Hammarlund et al. 2004/
Lake Tibetanus	68.20	18.42	Pollen	tibet P	/Hammarlund et al. 2002/

3.2 River sediment data

Maximum annual discharge in the large Swedish rivers is related to snow melt, which occurs during a fairly short time interval during May and June. Variations in maximum annual river discharge produce a distinct, annually laminated sedimentation pattern in the sediments deposited in the rivers' estuaries.

Based on numerous sediment cores drilled in the estuary of River Ångermanälven, central Sweden (Figure 3-5), varve thickness records have been constructed, extending from the year 1978 more than 2,000 years back in time. The annual sediment thickness of the youngest varves (1909–1978) was compared to maximum annual river discharge data and was found to mirror year to year variations in maximum discharge /Sander et al. 2002/ (Figure 3-6). This relationship was then used to obtain a 2,000-year long reconstruction of maximum annual discharge.

Reconstructed maximum daily annual discharge (Figure 3-7) shows considerable variations during the past 2,000 years. High values are persistent for the periods AD 300–650 and 1750–1971 and lower values for the period before AD 300 and during 650–1750. These changes are likely related to climatic fluctuations, implying that climatic factors have influenced maximum daily annual discharge on longer time scales /Sander et al. 2002/.

3.3 Aeolian sand data

An important component of climate in NW Europe is the intensity and frequency of storms. Storminess is governed by atmospheric circulation, and therefore a reconstruction of storminess in the past can give information on changes in atmospheric circulation patterns. This is important since such changes have a major effect on all components of climate. However, storminess is not just interesting from a climatic viewpoint, but also from an economical perspective, which was clearly demonstrated by the damage caused by the storm Gudrun in January 2005.

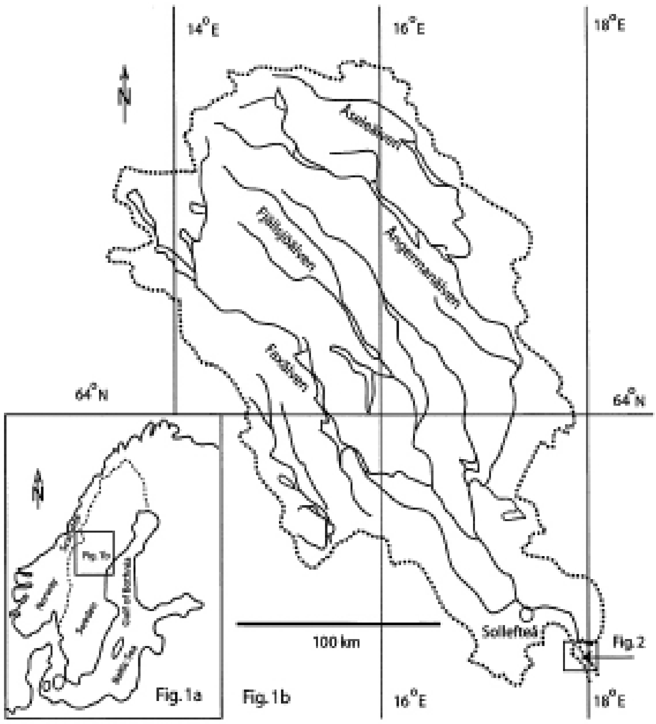

Figure 3-5. *Map of Scandinavia (a) and the catchment of River Ångermanälven (b). The stippled line in (b) shows the catchment boundary. From /Sander et al. 2002 Figure 1/.*

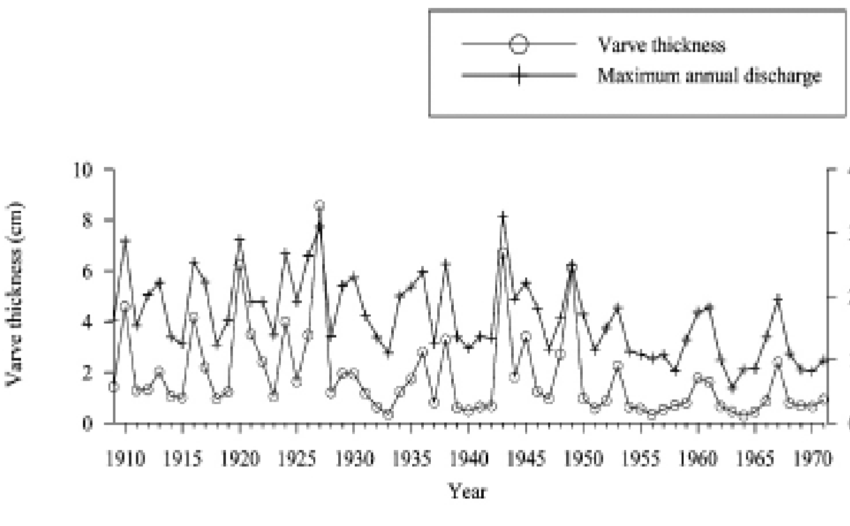

Figure 3-6. *Varve thickness (cm) (open circles) and Q_{max} (m^3s^{-1}) (crosses) variations for River Ångermanälven between 1909 and 1971 shown on a common time scale. From /Sander et al. 2002 Figure 3/.*

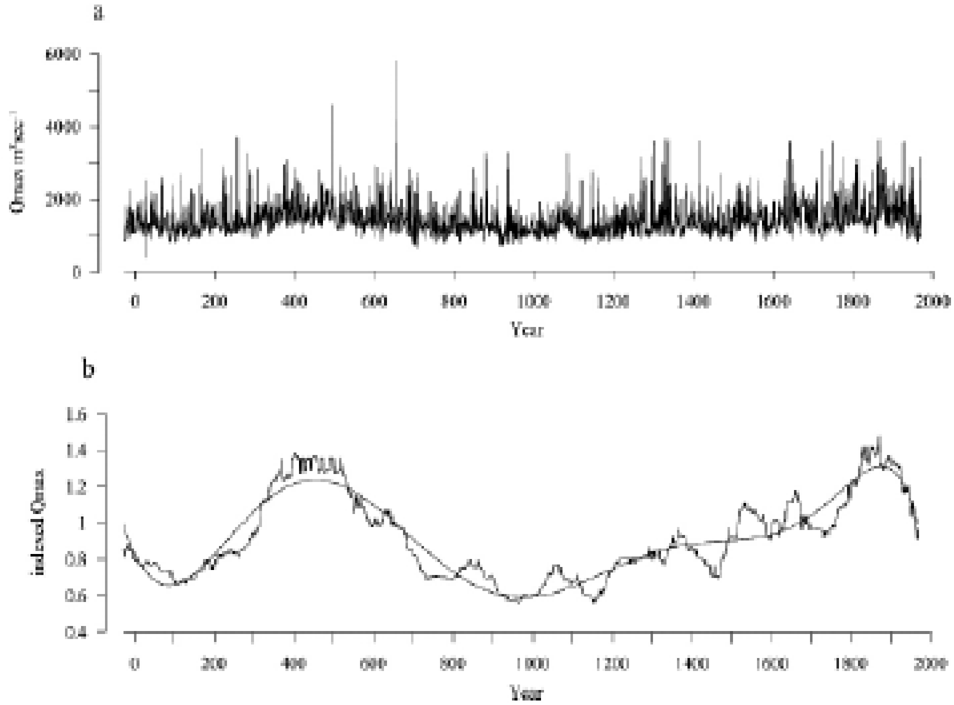

Figure 3-7. *Time-series of 2,000-year reconstructed maximum daily annual discharge (a). An indexed running median (100 years) is shown in black with an 8 degree polynomial fitted (b). From /Sander et al. 2002 Figure 8/.*

Aeolian sand influx (ASI) represents the amount of sand grains that has been deposited in a raised bog during a certain time interval. Since raised bog deposits are formed in situ, mineral particles present in the central part of these bogs must have been transported there by wind. Furthermore, sand grains > 200 µm are normally not transported in suspension but as bedload (saltation) /Tsoar and Pye 1987/. This implies not only strong winds, but also conditions that allow for saltation of mineral particles over the bog surface.

Sand grain particles measured in peat bogs in SW Sweden /Björck and Clemmensen 2004, De Jong et al. in press/ show that the maximum grainsize per sample frequently exceeds 400 µm, and that maxima reach values over 1,200 µm (Figure 3-8). Since it is unlikely that such large grains saltate on a wet, irregular bog surface, /Björck and Clemmensen 2004/ suggested that the transport of these large particles is associated with snow storms, thus niveo-aeolian conditions. This implies that the ASI record of the coarser grains can be used as a proxy for the frequency and intensity of winter storms. The ASI proxy is therefore, in principle, related to atmospheric circulation patterns during wintertime.

Sand influx is, however, also influenced by sediment availability, which is controlled mainly by the degree of vegetation cover and the moisture content of the sediment /Li et al. 2004, Wiggs et al. 2004/. Intense cultivation, overgrazing and forest disturbance make soils more prone to erosion, which can lead to increased sand transport even under stable wind conditions. Therefore it is necessary to know the extent and timing of human impact to correctly interpret the ASI proxy /de Jong et al. in press/.

In Figure 3-8 a, c and d the ASI values for sand grains > 200 µm are shown for the Undarsmosse, Boarps mosse and Hyltemossen bog sites. All three sites are situated on the coastal plain of Halland, SW Sweden (Figure 3-9). This area in particular is subjected to strong variations in storminess, since it lies in the region where storm tracks pass. The influx peaks (shaded areas) are based on influx values and maximum grainsize at the Undarsmosse site.

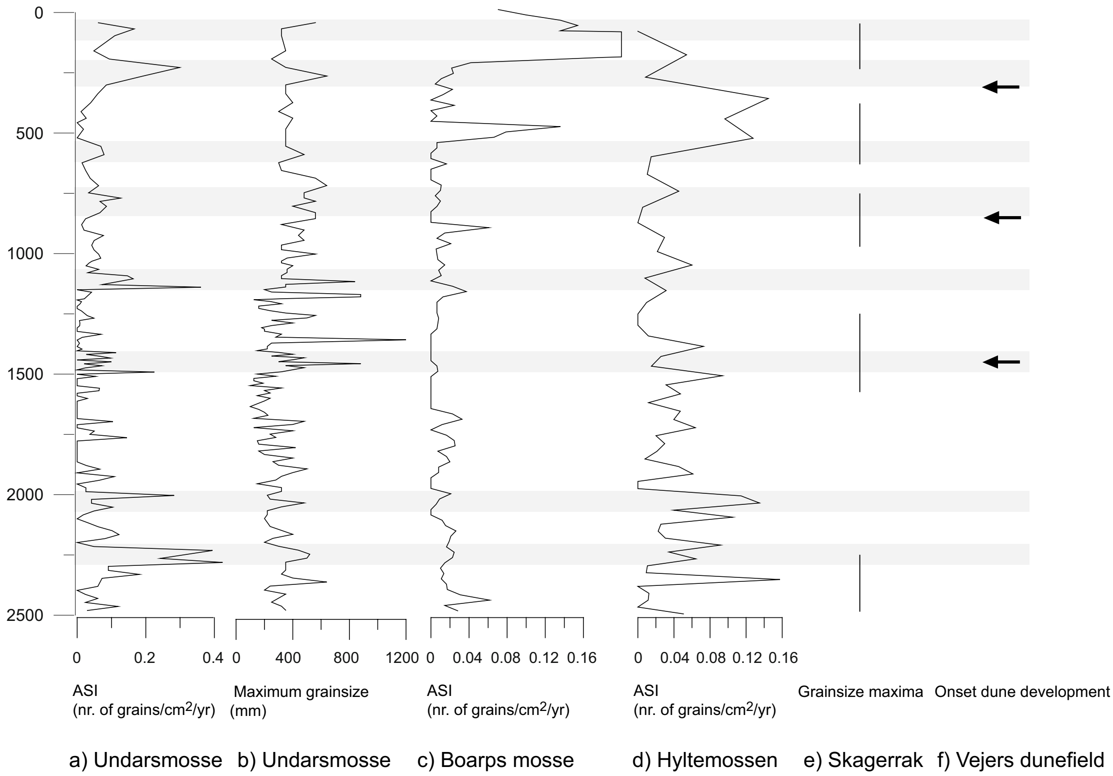

Figure 3-8. *Regional comparison of aeolian sand index (ASI) data from a) Undarsmosse /de Jong et al. in press/ c) Boarps mosse and d) Hyltemossen /Björck and Clemmensen 2004/ with e) grain-size maxima as recorded in the Skagerrak by /Hass 1996/, who interpreted these as reflecting stormy winter-like conditions and f) the onset or intensification of dune development at the Vejers dunefield /Clemmensen et al. 2001, Clemmensen et al. in press/. Also shown are the grain-size maxima for Undarsmosse (b). Adjusted from /de Jong et al. in press/.*

Figure 3-9. *Location map showing the location of Undarsmosse bog (U) /de Jong et al. in press/ , Boarps mosse (B) /Björck and Clemmensen 2004/; Hyltemossen (H) /Björck and Clemmensen 2004/ and Vejers dunefield (V) /Clemmensen et al. 2001; Clemmensen et al. in press/. Figure adjusted from /de Jong et al. in press/.*

Also shown are the results from a study of oxygen isotopes and grainsizes in marine sediments from the Skagerrak. Here large grainsize values and high sedimentation rates were interpreted as indicating severe stormy conditions, and the isotopic record indicates that these generally coincide with a cooling of the water column /Hass 1996/. Furthermore the timing of increased aeolian activity at the Vejers dunefield on the west coast of Jutland, Denmark, is shown /Clemmensen et al. 2001, Clemmensen et al. in press/. The onset or intensification of dune development is thought to be related to climatic factors as well as human impact.

The comparison of the different data sets is complicated by dating uncertainties, the use of different proxies, resolution differences within and between sites and site-specific factors. Therefore, a direct correlation in timing and peak amplitude between the different sites cannot be expected. Nevertheless, some similarities can be seen in the records for the last c 2,500 years. The peaks occurring around c 2,300, 1,450, 800 and after c 400 cal years BP are represented at all localities, indicating that these periods of increased storminess are of regional significance /de Jong et al. in press/. It thus seems that the ASI datasets from SW Sweden may reflect large scale alterations in atmospheric circulation patterns.

3.4 Tree-ring data

Tree-ring data is one of the most frequently used proxy for reconstructing past summer temperature variations. Tree-rings, i.e. the annual growth rings in wood, can give annually-resolved information on temperature, but also on precipitation or drought, mainly for the growth season. This information can be extracted by measuring either the width or the maximum latewood density of the growth rings /Briffa et al. 2002/. However, tree growth is dependent on the area where trees live. Therefore, attention has to be paid for the site-specific environmental and climatological location of the tree growth sites. To avoid stand-related biases, tree rings from a certain number of trees are measured at each locality and are then combined into a regional or local average series. Tree-ring based quantitative temperature reconstructions are fairly straightforward, while quantitative reconstructions of precipitation are limited due to the large spatial variability of this variable.

A common problem with tree-ring data is that tree growth is dependent on the age of the tree. The traditional way to handle this problem is to fit a curve to each individual tree-ring-width data series, and then use the ratio between the ring width series and the fitted curve to describe the temperature variations. A drawback with this method is that slow climate variations, with period lengths longer or similar to the life-length of the trees, are effectively removed. A number of data processing techniques have therefore been developed to cope with the latter problem in order to minimize its effect. One method is based on the idea that the growth curve should be fitted to a regional average chronology, rather than to each individual tree-ring record /Briffa et al. 1992/. Another method is based on the idea to build separate chronologies using tree-ring data that are of the same relative ages, and then to combine separate age-banded chronologies into a composite series /Briffa et al. 2001/. Neither of these methods, however, are able to cope with any possibly occurring slow adaptation of the tree growth rate to climate changes. Therefore, a strong correlation with warm-season temperatures does not itself guarantee that a tree-ring record correctly depicts climate variations on timescales longer than centuries. It is difficult, however, to quantify how serious this problem is.

In this section, we focus on warm-season temperature reconstructions from Sweden and neighbouring Scandinavian countries using tree-ring data. The full details of the analysis undertaken here are reported in a manuscript that has been submitted to a journal and which is, at the time of writing, provisionally accepted for publication. We refer to this article as /Gouirand et al. submitted manuscript/.

As stated by /Gouirand et al. submitted manuscript/, Scots pine (*Pinus sylvestris*) tree-ring data have been widely used as a proxy for summer temperatures in Swedish and Finnish Lapland /Lindholm et al. 1996, Grudd et al. 2002/, central Sweden /Gunnarson and Linderholm 2002/

and northern and central Norway /Kalela-Brundin 1999, Kirchhefer 2001/. Norway spruce (*Picea abies*) has been utilized in dendroclimatological studies to a lesser extent, but has also been proven to be useful climate indicator /Solberg et al. 2002/.

In a first step in /Gouirand et al. submitted manuscript/, existing tree-ring based temperature reconstructions are analysed to evaluate their climate representativity at a regional scale. Then an analysis is made how existing dendroclimatic reconstructions in this region can be improved. They also present a new summer temperature reconstruction back to AD 442, which is based on the maximum available number of useful individual chronologies. The number of available chronologies, however, decreases back in time – implying that the quality of the reconstruction is best in the most recent period and decreases back in time. The rest of the current section (3.4) is essentially a short version of /Gouirand et al. submitted manuscript/.

3.4.1 Available local and regional reconstructions

Four previously published summer temperature reconstructions for Fennoscandia were considered particularly interesting as they cover at least the past millennium. They have also been used by other investigators in large-scale temperature reconstructions. Two of these series are summer temperature reconstructions for the Torneträsk region /Briffa et al. 1992, Grudd et al. 2002/, one is from Finish Lapland /Helama et al. 2002/ and one is from Jämtland /Linderholm and Gunnarson 2005/. In addition, a large-scale regional warm-season temperature reconstruction representative for Northern Europe covering the last 400 years /Briffa et al. 2001/ is analysed. All five selected tree-ring records have been processed with some technique that preserves low-frequency variability.

These five temperature reconstructions (Figure 3-10) provide an illustration of the possible local to regional temperature evolution and variability during the last several centuries. Although they represent somewhat different seasonal definitions (see legend to Figure 3-10), they are nevertheless comparable, considering that they all represent "summer temperatures" in a broad sense. Similarities among at least some of the reconstructions are seen as cold periods around AD 800, 1,100, 1,450 and 1,600, but there are also some clear discrepancies between the series. The different locations and environmental conditions of the sites where the trees grew, the different seasonal definition they represent, and various non-climatic factors contribute to the differences between the reconstructions.

3.4.2 Spatio-temporal representation of five published tree ring chronologies

To evaluate the spatial representation of temperature information in the five chronologies, correlations were calculated with observed temperatures in Scandinavia represented on a 0.5°×0.5° grid /Mitchell et al. 2004/ for the 1901–1980 period. Correlations were calculated, for each chronology, with instrumental temperatures averaged over the season for which the chronology is known to contain the strongest climatic signal. The resulting five maps are shown in Figure 3-11 together with a map showing the spatial pattern of the leading mode of summer (June–August) temperature variability in Scandinavia (see /Gouirand et al. submitted manuscript/ for an explanation). It can be seen that none of the five reconstructions exhibit a regional pattern that is very similar to the leading mode of Scandinavian temperature variability. They are, rather, representative of different sub-regions corresponding roughly to where the trees used in the respective reconstructions grew.

Two of the reconstructions /Grudd et al. 2002, Helama et al. 2002/ have their strongest correlations with summer temperatures over the northern part of Scandinavia but weak correlations over the rest of the area (25–40% temperature variance in the northern part, less in the rest of Scandinavia, is 'explained' by these tree-ring data). The reconstruction by /Linderholm and Gunnarson 2005/ does not explain more than 25% of the observed temperature variance anywhere, apart from southeastern Norway and parts of southern Sweden (where the explained

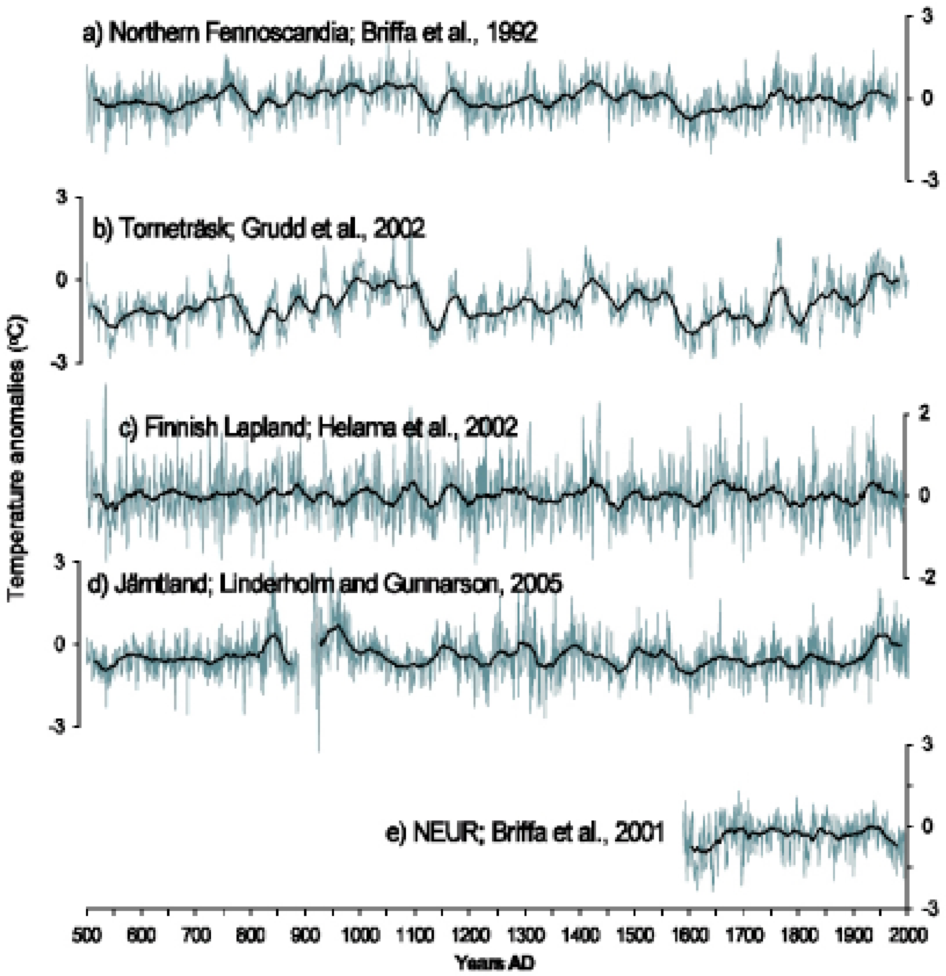

Figure 3-10. *Five tree-ring based long reconstructions of local-to-regional summer temperature anomalies in Fennoscandia. The series are supposed to represent temperatures for the following seasons; (a) April–August /Briffa et al. 1992/, (b) June–August /Grudd et al. 2002/, (c) July /Helama et al. 2002/, (d) June–August /Linderholm and Gunnarson, 2005/, (e) April–September /Briffa et al. 2001/. From /Gouirand et al. submitted manuscript Figure 2/.*

variance is just above 25%). The Northern Europe reconstruction /Briffa et al. 2001/ does also not explain more than 25% of temperature variance over most of Scandinavia. Its strongest correlations are found in eastern Finland. The best reconstruction in terms of regional correlation with temperature variability is the one by /Briffa et al. 1992/. This reconstruction shows at least 25% explained temperature variance over the southern part of Scandinavia and more than 50% over the central part. In the northern part, the explained variance reaches up to 65%. Hence, this reconstruction is most representative of temperature variability at a regional Scandinavian scale, while the other reconstructions are more representative for various sub-regions.

It should be noted that a correlation as weak as $r = 0.24$, which corresponds to an 'explained' variance of only 6%, is said to be different from zero at the 95% confidence level in a statistical sense (assuming serially uncorrelated data). However, for the purpose of making useful climate reconstructions a much stronger correlation is desired. An explained variance above 65% (i.e. a correlation $r > 0.8$) can be considered as very good in this context. In this sense, the reconstruction by /Briffa et al. 1992/ is a valuable proxy record for summer temperatures in northern Fennoscandia.

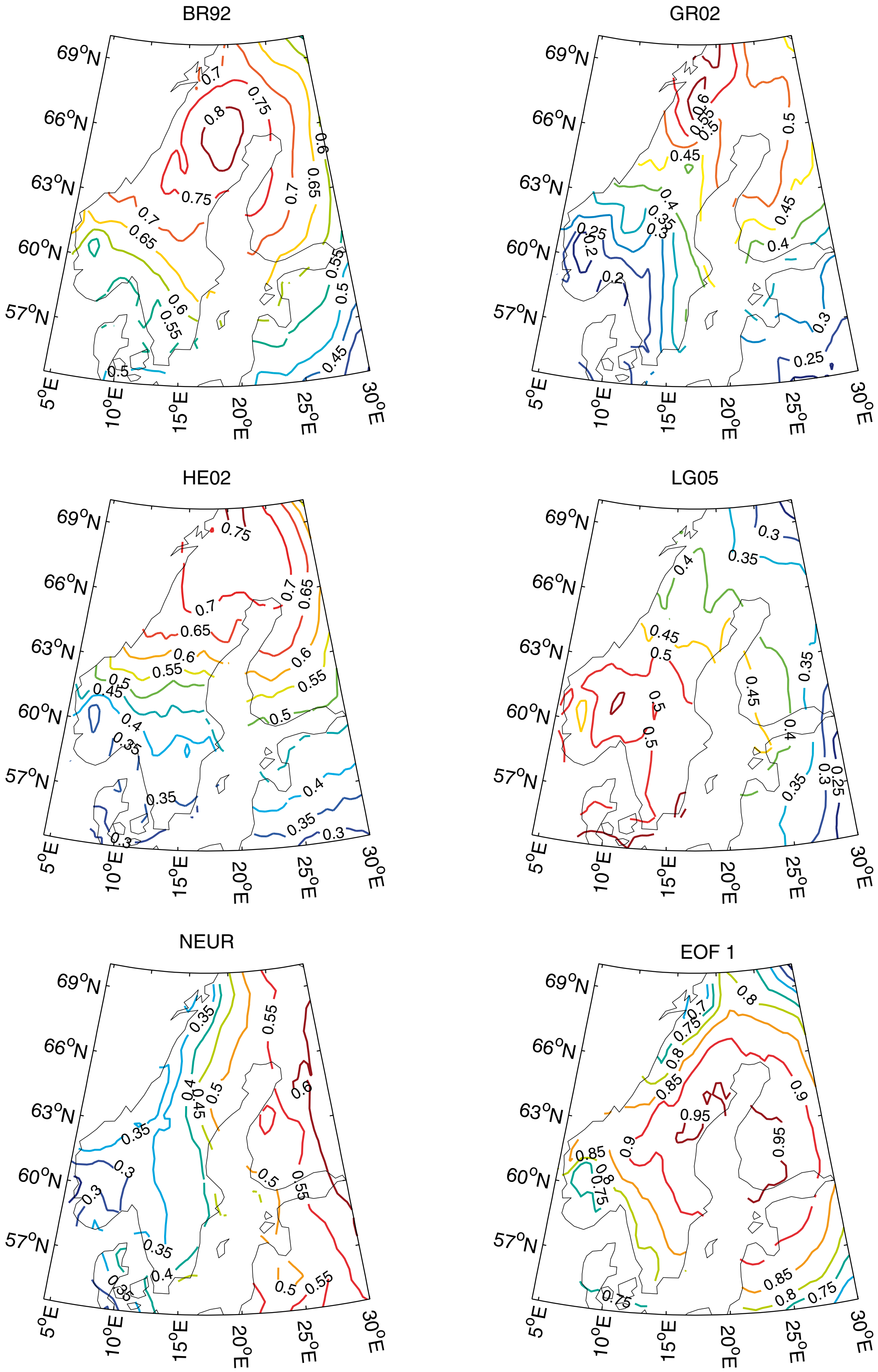

__Figure 3-11.__ Five maps showing the spatial representation of the five temperature reconstructions in Figure 3-13. The isolines show the correlations (×100) between the reconstructions and the observed temperatures during 1901–1980 for the following seasons: April–August (BR92) /Briffa et al. 1992/, June–August (GR02) /Grudd et al. 2002/, July (HE02) /Helama et al. 2002/, June–August (LG05) /Linderholm and Gunnarson 2005/, April–September (NEUR) /Briffa et al. 2001/. The sixth map (EOF1) shows the leading mode of June–August temperature variability in Scandinavia, also expressed as correlations (×100). From /Gouirand et al. submitted manuscript Figure 3/.

3.4.3 Potential for improving temperature reconstructions from tree ring data

To evaluate whether existing temperature reconstructions can be improved, 30 tree ring chronologies were selected among 86 available (see /Gouirand et al. submitted manuscript/ for details). The selection was based on an analysis of correlations between each of the 86 chronologies and observed summer (June-July-August) temperatures for the 1901–1970 period. Two criteria were applied to select the best chronologies: (i) the correlation must exceed 0.5 over a large part of Scandinavia; (ii) the correlation pattern must be similar to the leading mode of variability of the observed Scandinavian temperatures. The 30 selected chronologies are quite well distributed in space over Scandinavia north of 60°N (Figure 3-12) but no one is located south of this latitude.

One of the problems with developing a climate reconstruction from the 30 local chronologies is that they are of different lengths. Rather few start before 1700 and most of them end in the 1970's. To handle this problem, /Gouirand et al. submitted manuscript/ grouped the individual chronologies into seven different pools. The largest pool contains all 30 chronologies that cover the period 1893–1970. The smallest pool contains only the three chronologies that cover the period 442–1970 (see Table 3-2). For each of these seven pools, a temperature reconstruction was developed by calibration against instrumental June–August temperatures during 1901–1970. The method used was a combination of principal component analysis and multiple regression, which is commonly used in palaeoclimatology.

The seven reconstructions were then combined to create a summer temperature reconstruction for the entire period from 442 to 1970. In each sub-period of the resulting reconstruction, the data from the largest pool is used. Hence, data from pool 1 is used for 1893–1970, data from pool 2 is used for 1846–1892, etc, and data from pool 7 is used for the period 442–1397. Figure 3-13 shows smoothed data for the resulting combined reconstruction of Scandinavian summer temperatures, extended from 1971 to 2000 with instrumental data. Three different smoothing filters are used to highlight variability on timescales longer than 10, 30 and 100 years respectively. The 10-year smoothing is also shown with its associated 95% confidence interval. This interval accounts for uncertainties in the statistical calibration to the instrumental data, but does not account for any uncertainties in the older tree-ring data from before the calibration period.

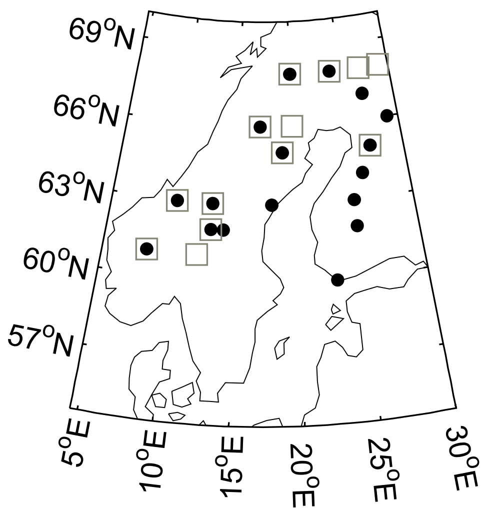

Figure 3-12. Locations of 30 tree-ring chronologies in Fennoscandia which have strong correlations with June–August temperatures. Squares represent tree-ring width chronologies and filled circles represent maximum latewood-density chronologies. From /Gouirand et al. submitted manuscript Figure 7a/.

Table 3-2. Summary statistics for the seven tree-ring pools analysed and used to develop a June–August summer temperature reconstruction for Scandinavia. The first row indicates the first year for which all chronologies in a pool has data. The second row gives the number of chronologies in each pool. The third row gives the number of principal components used in the multiple regression leading to the temperature reconstruction. The last row indicates the percentage of the temperature variance explained. (No principal component decomposition was made for network 7. Instead, the three chronologies were used directly as predictands in a multiple regression model).

Tree-ring pool	1	2	3	4	5	6	7
First year with data	1893	1846	1782	1696	1570	1398	442
Number of chronologies	30	28	22	12	6	4	3
Number of PCs	4	4	2	4	4	3	0
Temperature variance explained (%)	80	80	80	80	65	55	55

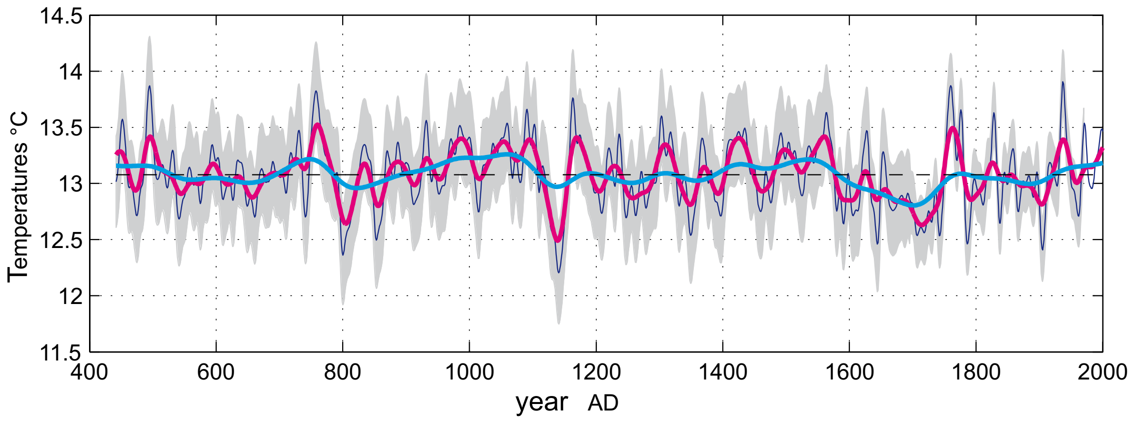

***Figure 3-13**. Fennoscandian summer (June–August) temperature reconstruction for AD 442–1,970 developed by combining tree-ring data from the seven pools of chronologies indicated in Table 3-2. Data are shown for 10-year smoothed temperatures (thin blue), 30-year smoothed temperatures (pink) and 100-year smoothed temperature (thick light blue). The calibration uncertainty for the 10-year smoothed data is illustrated by ± 2 standard errors with grey shading. The smoothed series were extended by instrumental data between 1971 and 2000. From /Gouirand et al. submitted manuscript Figure 10/.*

The confidence interval is broader before 1696 and narrower after this year. This is because data from the four largest pools have a better fit with the instrumental data than the three smallest pools. This behaviour is also illustrated in maps in Figure 3-14. These maps show the patterns of correlations with gridded summer temperatures. The four largest pools show nearly the same patterns, with correlations above 0.85 over large parts of central Scandinavia (i.e. they explain more than 72% of the temperature variance in this region). The three smallest pools show their strongest correlations (about 0.8) over northern Sweden, which corresponds to where most trees in these pools grew.

An interesting observation is that pool 4, which contains 12 chronologies from 8 sites, nearly gives the same result as pool 1 which contains 30 chronologies. Another important finding is that the reconstruction based on pool 4 provides a better result than the best one among the previously available reconstructions (compare with Figure 3-11). Hence, a conclusion from this study is that one could likely improve the quality of regional summer temperature reconstructions for Scandinavia by sampling more trees with data going longer back at the eight key sites, and then build a new reconstruction based on these trees. The location of the sites included in pool 4 is shown in Figure 3-15.

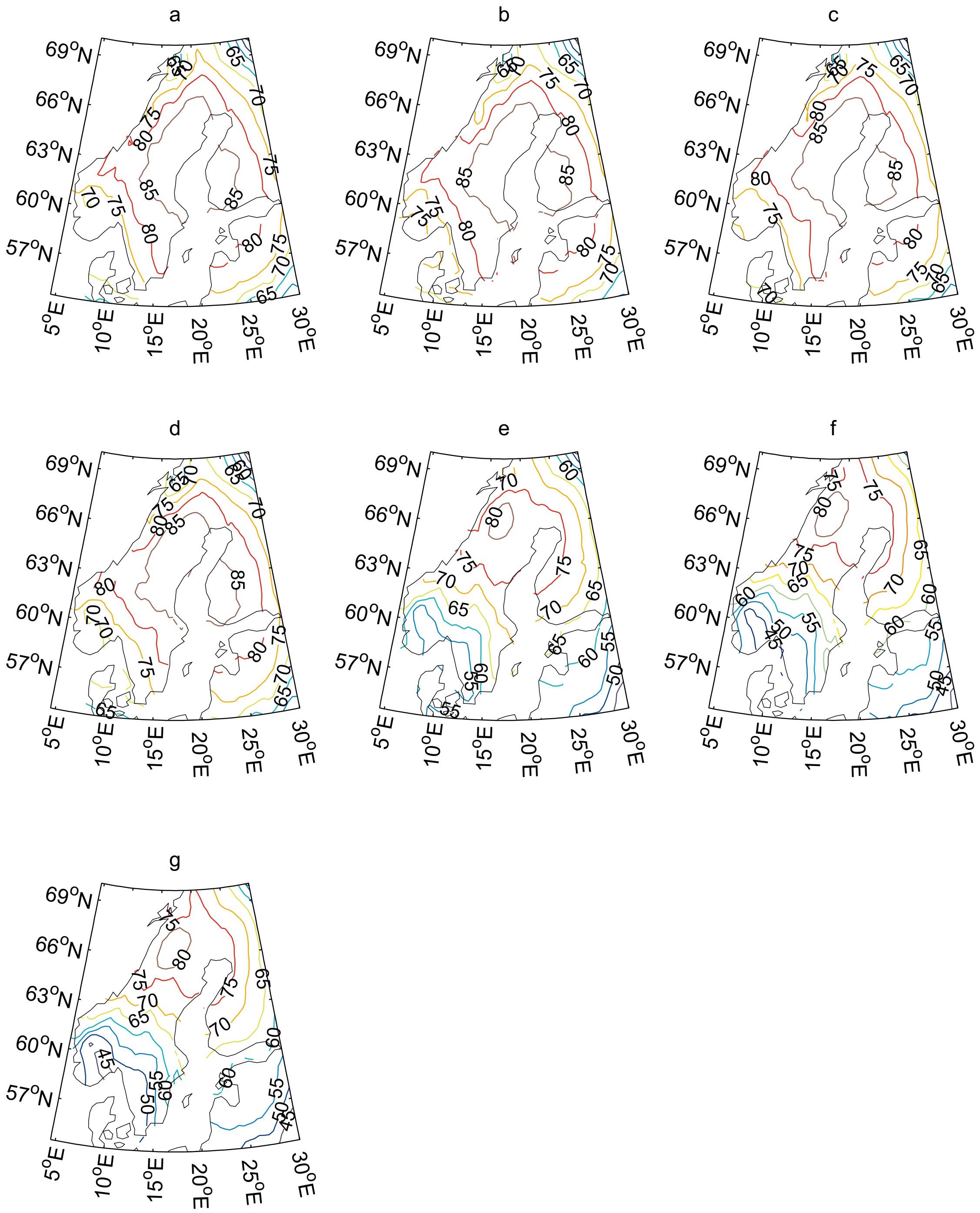

Figure 3-14*. Maps showing correlations (×100) between observed June–August 1901–1970 temperatures and temperatures reconstructed from tree-ring chronologies in each of the seven pools from Table 3-2. The letters a–g denote the pools 1–7. From /Gouirand et al. submitted manuscript Figure 8/.*

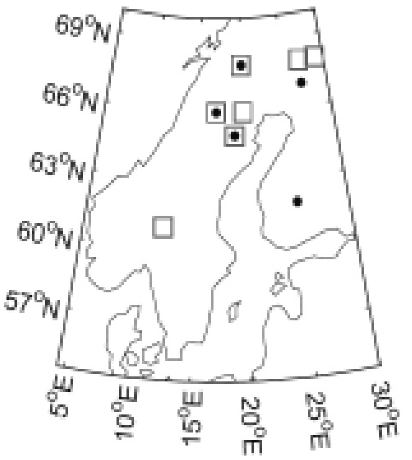

Figure 3-15*. Distribution of the eight "key sites" with 12 tree-ring chronologies which appear to be particularly suitable for a regional summer temperature reconstruction for Fennoscandia. Squares represent tree-ring width chronologies and filled circles represent maximum latewood-density chronologies. From /Gouirand et al. submitted manuscript Figure 7d/.*

The temporal evolution of the combined reconstruction (Figure 3-13) suggests that summer temperatures in some periods in the past nearly 1,600 years may have been slightly colder than the coldest periods in the 20th century. Particularly cold periods in the past are centred around AD 800, 1,150 and 1,700. Similarly, some periods seem to have been slightly warmer than the warmest parts of the 20th century, in particular around AD 750, 1,000–1,150, 1,180, 1,400–1,550 and 1,760. The range of reconstructed summer temperature variability is, however, quite small. The decadal smoothed temperatures fluctuate within ± 0.8°C around the long-term average and the 30-year smoothed temperatures fluctuate within ± 0.5°C.

3.5 Precipitation proxies

Estimations of past precipitation changes can be made from several natural archives, where either physical, chemical or biological indicators can be used as precipitation indicators. Data on past precipitation changes is much scarcer than for temperature, and it is often problematic to differentiate precipitation from the temperature component in the recorded climate signal. Most of the estimations are therefore quantitative, distinguishing only between warm/dry periods and cold/wet periods. In some situations, however, the precipitation component is more easily identified. In section 3.1 an example of quantitative estimations of past precipitation changes using pollen is shown. In this section we give examples of how lake level changes, peat bogs and glacier mass balance have been used as precipitation indicators. It becomes evident that little is yet known as regards details in the Swedish precipitation climate for the last millennium. The available precipitation proxy data generally provide rather low-resolution information over longer periods.

Studies of peat, preferably ombrotrophic mires which only receive water from precipitation, and their past wetness status can give information on past precipitation changes. Physical properties of the peat and the rate of degradation of the peat (humification) can be used as an indicator of dry and wet periods and is thus a measurement of past wetness status. The more degraded the peat is in the peat profile the drier the peat surface has been. A composite diagram of humification changes in peat bogs from Värmland indicate wet conditions at 4,500–4,000, 3,500, 2,800 and 1,700–1,000 cal years BP /Borgmark 2005/. The wetness status of ombrotrophic mires can also be analysed by using biological indicators. *Sphagnum* moss is the main constituent of ombrotrophic mires and different species have different wetness preferences. A change in the sphagnum moss assemblages thus reflects changes in the wetness status of the mires.

Testate amoebae (Protozoa; Rhizopoda) assemblages can also be used as indicators of past wetness changes. Testate amoebae are single celled organisms especially common and diverse in *Sphagnum* dominated peatlands. They have well defined ecological preferences and their sensitivity and relation to surface wetness of *Sphagnum*-dominated peatlands is well established. Testate amoebae are small, they occur in high numbers and produce a shell that is well preserved in peat. This makes them suitable for ecological and palaeoecological studies concerning hydrological conditions in ombrotrophic mires. The relationship between mire surface wetness and climate is, however, not simple and straightforward. There are also differences in the climate control of mire surface wetness between different regions and different climatological settings /Charman et al. 2004, Schoning et al. 2005/.

From studies of sedimentological and biostratigraphical changes in lake sediments, information can be obtained on lake level changes. These can then be transferred into changes in precipitation. Detailed studies of Lake Bysjön in southern Sweden show major changes in the lake level during the Holocene which are assumed to largely be related to changes in precipitation /Digerfeldt 1988/. The record shows substantial changes in the lake level with high stands today and centred at 2,500 and 7,000 ^{14}C-years BP. A long period with low stand is recorded between 6,000 and 3,000 ^{14}C-years BP.

The mass balance of maritime glaciers in Norway has been used for reconstructing past winter precipitation /Nesje et al. 2000/. The mass balance of these glaciers is correlated with the NAO (North Atlantic Oscillation) and in this area the winter precipitation is correlated with the NAO. These relationships have been used as an argument for correlating glacier fluctuations to precipitation changes /Nesje et al. 2001/. The records suggest that winter precipitation exceeded the 1961–1990 mean precipitation most of the time during the Holocene. Major periods with less winter precipitation are recorded between 3,000 and 2,100 cal years BP and 6,500 and 5,700 cal years BP.

3.6 Documentary data

A documentary evidence of climate is a man-made source of climate information /Brázdil et al. 2005/. The source is some kind of document, i.e. a unit of information such as a manuscript, a piece of printed matter (book, newspaper, chronicle, economic report etc), a picture, or an artefact (e.g. a flood mark or an inscription on a house), which refers to weather patterns or impacts on climate. Documentary evidence may include several types of data (e.g. descriptions of weather spells, snowfall, snow cover, ice freeze and ice break-up, floods, stages of vegetation). /Brázdil et al. 2005/ provide an extensive review of documentary data and the related branch of science termed Historical Climatology. This research field is situated at the interface of climatology and (environmental) history, and deals mainly with documentary evidence using methodologies of both climatology and history. Historical Climatology is well developed in some European countries (e.g. Germany, Switzerland, the Czech Republic and the Netherlands) where a wealth of documentary evidence exists for several centuries back, well into the Medieval times. However, very little climate-related research has so far been based on documentary data from Sweden.

An advantage of documentary data compared to natural proxy data is that documentary data can yield an exact dating and information about different seasons with annual or even sub-annual (down to daily) resolution. When calibrated against instrumental data in periods of overlap, documentary evidence can sometimes yield strong correlations. One drawback, however, is that documentary evidence is not available for times before the creation of useful man-made documents. There are also a number of difficulties in handling the data, e.g. the change from one observer/reporter to another, which may lead to artificial changes in the statistical properties of a climate reconstruction. /Brázdil et al. 2005/ discuss in more detail both advantages and drawbacks.

3.6.1 Ice break-up records

Here, we show results from three sites in or nearby Sweden. They are all related to documentary evidence of the ice break-up in lakes, rivers or the Baltic Sea, which have been calibrated against cold-season temperatures. The three series stem from data concerning:

- Torne River, 1693–1999 /Kajander 1993/.
- Lake Mälaren, Bay of Västerås, 1712–1999 /Eklund 1999/.
- Tallinn Harbour, 1500–1997 /Tarand and Nordli 2001/.

Ice break-up dates have been observed in the Torne River at the twin towns of Tornio and Haparanda since 1693. /Kajander 1993/ analysed and published the record of ice break-up dates. /Moberg et al. 2005b/ observed that this series is strongly correlated with mean temperatures for April–May in Haparanda ($r = 0.82$). In Lake Mälaren, the date of ice break-up was reported for the Bay of Västerås from 1712 to 1871. With the aid of similar observations from ten other lakes in south and central Sweden, /Eklund 1999/ developed an extension of the series up to 1999. This extended series is strongly correlated ($r = 0.77$) to February–April mean temperatures in Uppsala /Moberg et al. 2005b/. The series for Tallinn harbour was developed by /Tarand and Nordli 2001/ by combining documentary data before 1757 with instrumental temperature observations after this year. The instrumental data are mainly from Tallinn, but a major data gap has been filled in with data from both Stockholm and St Petersburg, after adjustments to make these data valid for Tallinn. /Tarand and Nordli 2001/ calibrated the ice break-up dates against December–March mean temperatures, but they did not report the correlation between proxy and instrumental data. To obtain an indication of the strength of the proxy-temperature relationship, we have therefore calculated the correlation with December–March temperatures for Uppsala in the period 1723–1756, and found this to be $r = 0.62$. One further issue about the Tallinn series is worth pointing out; in unusually warm winter there is no ice in the harbour. This mainly occurs when the December–March mean temperature is above –2.8°C. Therefore, for winters with no reported ice, /Tarand and Nordli 2001/ applied random estimates of temperatures above –2.8°C using a Monte Carlo simulation technique. All values above this level before 1757 are therefore only random numbers with a realistic distribution.

Figure 3-16 shows all three series calibrated to the seasonal temperatures they best represent. The 20th century data for the Torne River clearly indicate warmer April–May temperatures on average than in the 18th to 19th centuries. The period before the 1740's appears to have been particularly cold, with only a few years around 1700 just above the 1901–1929 mean level, and many years being 2–3°C colder. It appears that a shift from generally colder to warmer conditions occurred in the late 19th century. There is, however, no clear warming trend throughout the 20th century. The Mälaren series (calibrated to Uppsala February–April temperatures) also depict the 20th century as being warmer than the 19th century, but the difference is less marked compared to the Torne River case. The most severe ice conditions (coldest temperatures) seem to have occurred early in the 19th century. In contradiction to the Torne River, the 1720's–1730's around lake Mälaren appears to have been about as mild as much of the 20th century. The 1990's, however, stands out has having several years with notably early ice break-up dates (corresponding to warm February–April temperatures). The Tallinn series provides the longest time perspective, almost five full centuries. It should be remembered, though, that after 1757 this record is based on real instrumental temperatures, and also that before this year temperatures in ice-free years have been randomly generated. Nevertheless, the Tallinn series also indicates the 20th century as having been relatively warm in a historical perspective. In particular the 1990's stand out as an unusually warm period. The coldest individual winters in the 20th century, however, seem to have been about as severe as the coldest winters in the past. The 15th and 16th centuries appear to have been slightly colder on average than the 18th to 19th centuries, with very few winters being above the 1901–1929 average. The coldest period appears to have been a few decades around 1600.

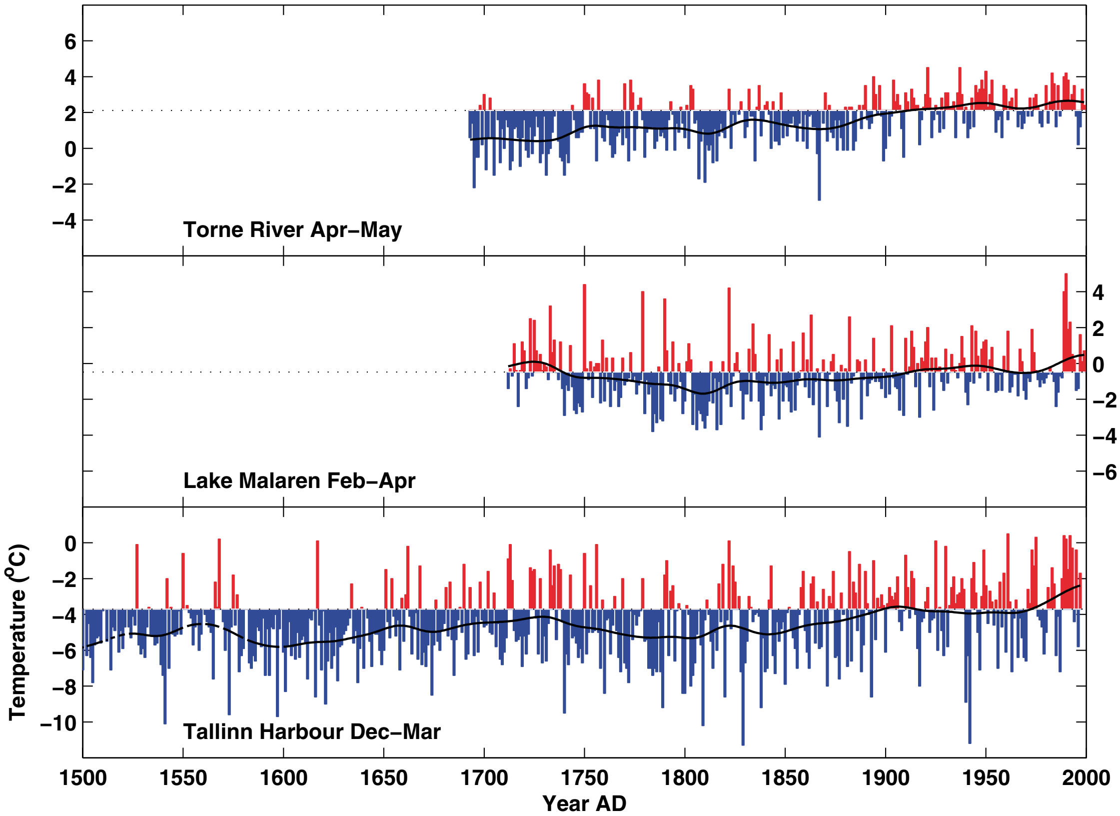

***Figure 3-16**. Cold-season temperatures reconstructed from historical documents with information about the date when ice break-up occurred at Torne River (since 1693) /Kajander 1993/, Bay of Västerås in Lake Mälaren (since 1712) /Eklund 1999/ and Tallinn Harbour (since 1500) /Tarand and Nordli 2001/. The baseline for the red and blue bars is the average for the period 1901–1929. 30-year smoothed data are also shown. The Torne River and Lake Mälaren series were calibrated by /Moberg et al. 2005b/.*

In summary, the three ice-break up series indicate that the 20th century has been a period with rather mild winters or early springs when viewed in a historical context of a few hundred years. However, some years or some decades in the past seem to have been about as warm as the warmest years or decades in the 20th century.

3.7 Long instrumental temperature records

The era of instrumental weather observations in Sweden began with the first observations made in Uppsala in 1722 /Bergström 1990, Moberg and Bergström 1997, Bergström and Moberg 2002/. Already from the beginning several kinds of observations were made, including air temperature, air pressure, precipitation, wind strength, wind direction, cloud amount and cloud characteristics. Sweden also has two other sites with long instrumental records; Stockholm starting in 1756 /Moberg and Bergström 1997, Moberg et al. 2002/ and Lund starting in 1740 /Jönsson and Fortuniak 1995, Bärring et al. 1999/. The most extensively analysed data from Uppsala and Stockholm are the temperature records. For Lund, mainly the air pressure and wind series have been investigated.

Here we analyse temperature and precipitation data from Uppsala. As the data are available at a daily resolution, these records provide detailed information of variations in climate. There are thus good opportunities to characterize the range of how warm/cold or dry/wet the climate has been in the last few centuries. It is, for example, possible to calculate indices for weather extremes and important climate parameters like the length of the growth season or the number of days with frost /Moberg et al. in press/. Unfortunately, reliable analyses cannot be undertaken for all variables all the way back to 1722. The first reliable year for daily and monthly mean temperatures is judged to be 1739. Before this year, observations were taken indoors in an unheated room, and there are also gaps in the Uppsala data (which have been filled in using data from other places in southern Sweden). For precipitation and daily maximum and minimum temperatures, the first reliable year is 1840. Hence, data shown here start either in 1739 or 1840. Figures 3-17 to Figure 3-21 illustrate a selection of analyses of temperature and precipitation data. The temperature data have been adjusted for various biases, such as recent urban warming trends /Bergström and Moberg 2002/ and a supposed poor protection of the thermometer against radiation before the 1860's /Moberg et al. 2003, Moberg et al. 2005b/. As in section 3.6, we use the mean levels during 1901–1929 as a reference climate in all graphs here.

3.7.1 Temperature

Figure 3-17 shows annual and seasonal mean temperatures for Uppsala 1739–2004. The annual temperatures exhibit a warming trend from the 1860's to the early 2000's, where the period since 1989 stands out as remarkably warm. Other warm periods for the annual means occurred in the 1790's, 1820's and 1930's–40's, although they do not match the last 16 years as regards the number of uninterrupted warm years. Some periods before 1900 were colder than the coldest periods in the 20th century, in particular the 1780's and around the 1870's. The smoothed annual mean series reveal pronounced decadal variability before 1830 and after 1930. The 100-year period in between was more characterized by interannual variability, but without marked decadal variations. A comparison of the annual and seasonal series reveals that winter temperatures dominate the variations in annual mean temperatures (because the size of variations is larger in winter than the other seasons). The winter series includes a sequence of warm years near the end of the series, but many individual years in earlier periods were about as warm. The coldest winters in the 20th century were about as cold as the coldest winters in earlier periods. The spring temperatures show rather marked decadal fluctuations around the 1901–1929 average before 1840, and a rather steady warming trend from the 1880's to the early 2000's. For summer and autumn the period 1901–1929 was rather cold compared to much of the rest of the series. In particular, the 1740's–1770's, 1850's, 1930's–1940's and the period after 1990 had warm summers. The recent period of warm summer temperatures, since around 1990, does not appear to be warmer than the previous ones.

Information about variability in temperature extremes can be provided by studying the time series of low and high percentiles in the distribution of daily mean temperatures. Figure 3-18 compares the seasonal mean temperatures with the 2nd and 98th percentiles for summer and winter data respectively. As each season contains about 90 days, the 2nd and the 98th percentiles are nearly the same as the temperature in the second coldest and the second warmest day, respectively, in a season. In summer, there are no clear long term trends in these percentiles. Hence, the variations of the warm and cold extremes seen in the 20th century are rather similar to those in the previous centuries. The winter data, however, show a striking behaviour of the 2nd percentile, which reflects changes in the cold extremes. The period from the 1750's to the 1820's show notably colder winter extreme temperatures compared to the rest of the series. Values of the 2nd percentile down to between –25°C and –30°C occurred quite frequently during 1750–1830, whereas only two 20th century winters (1941/42 and 1986/87) reached just below –25°C. The coldest 2nd percentile value on record was –31°C (in 1874/75). There is almost no long-term variability seen in the 98th percentile series. Therefore, the range of variability of daily winter temperatures was notably larger during the 1750's to 1820's compared to the 20th century.

Two other aspects of temperature climate in Uppsala are shown in Figure 3-19; the length of the growth season and the number of frost days in each year. The frost day series is based on observations of daily minimum temperatures, which stared in 1840. (It should be mentioned that, unlike all other temperature data in this section, the minimum temperatures have not been tested or corrected for systematic errors like urban warming trends). The number of frost days has varied between 100 and 203 days.The data show a clear decreasing trend from, on average,

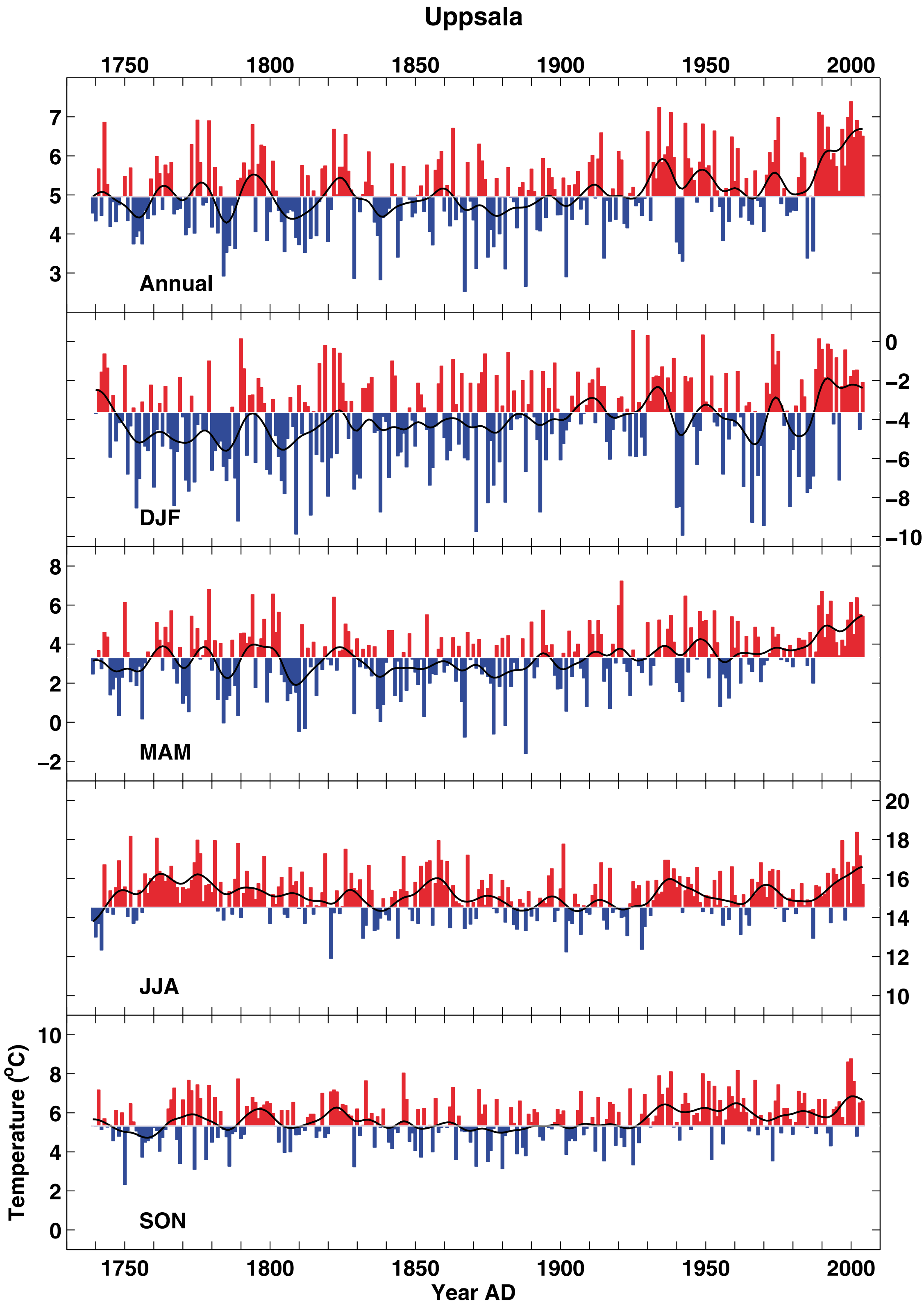

Figure 3-17*. Annual and seasonal mean temperatures for Uppsala 1739–2004. The baseline for the red and blue bars is the average for the period 1901–1929. 10-year smoothed data are also shown. Data from /Bergström and Moberg 2002/, adjusted by /Moberg et al. 2005b/.*

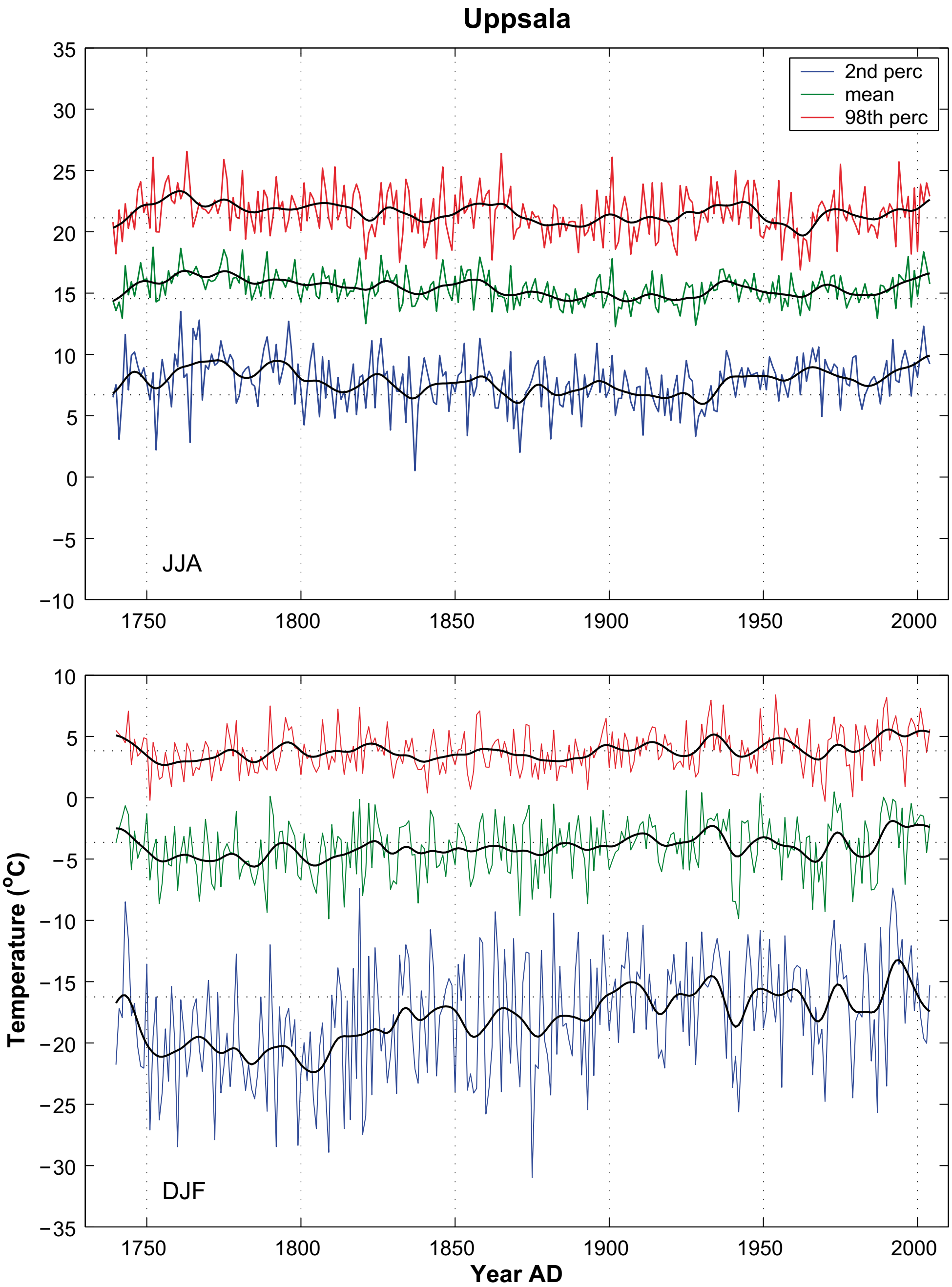

***Figure 3-18**. Summer (June–August) and winter (December–February) mean temperatures for Uppsala 1739–2004 compared with the 2nd and 98th percentiles of daily mean temperatures in the same seasons. The dotted lines show the averages for the period 1901–1929. 10-year smoothed data are also shown. Data from /Bergström and Moberg 2002/, adjusted by /Moberg et al. 2005b/, and with percentiles calculated in /Moberg et al. in press/.*

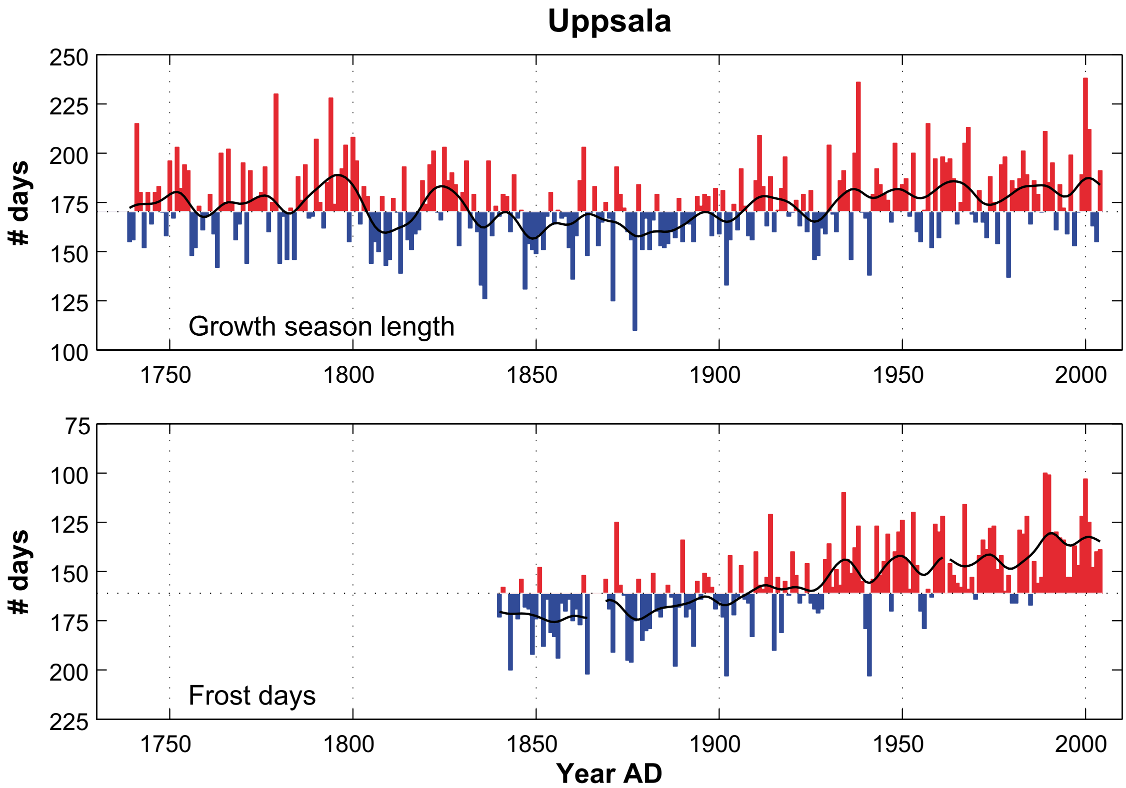

Figure 3-19. An index for the length of the growth season each year in Uppsala (1739–2004) and the number of frost days each year (1840–2004). The baseline for the red and blue bars is the average for the period 1901–1929. 10-year smoothed data are also shown. The growth season length is defined as the number of days between the first and the last occurrence of at least 6 consecutive days with daily mean temperature ≥ +5°C. The number of frost days is defined as the number of days with daily minimum temperatures < 0°C. Data from /Bergström and Moberg 2002/, adjusted by /Moberg et al. 2005b/, and with percentiles calculated in /Moberg et al. in press/.

about 175 days per year around 1850 to about 130 days per year in the 1990's. The three years with the smallest number of frost days all occurred near the end of the series; in 1989, 1990 and 2000. The two years with the largest number of frost days were 1902 and 1941. The length of the growth season shows a corresponding trend with increasing values since the 1840's; from around 160 days per year in the 1850's to around 180 days in the 1990's. Before the 1840's, however, there were long periods when the growth season length was similar to that in the 1990's. The 1790's, in particular, appears to have had at least as long growth seasons as the 1990's. The total range of variability in the growth season length is between 110 days (in 1877) and 238 days (in 2000).

3.7.2 Precipitation

The precipitation data from Uppsala (Figure 3-20), which start in 1840, show no clear signs of any long-term trends in the annual totals, but rather large interannual variability and in some periods also marked interdecadal variability. Annual precipitation has varied between 311 mm (in 1875) and 813 mm (in 1866). The 1901–1929 average of annual precipitation was 540 mm, which is nearly the same as the average over the whole record. Summer has larger precipitation totals than the other seasons, and also larger variability in absolute terms. In winter, the period after 1998 stands out as rather wet, while most of the period 1840–1900 was rather dry.

Figure 3-21 compares the seasonal precipitation totals for summer and winter with two aspects of precipitation extremes; the 98th percentile of daily precipitation and the maximum number of

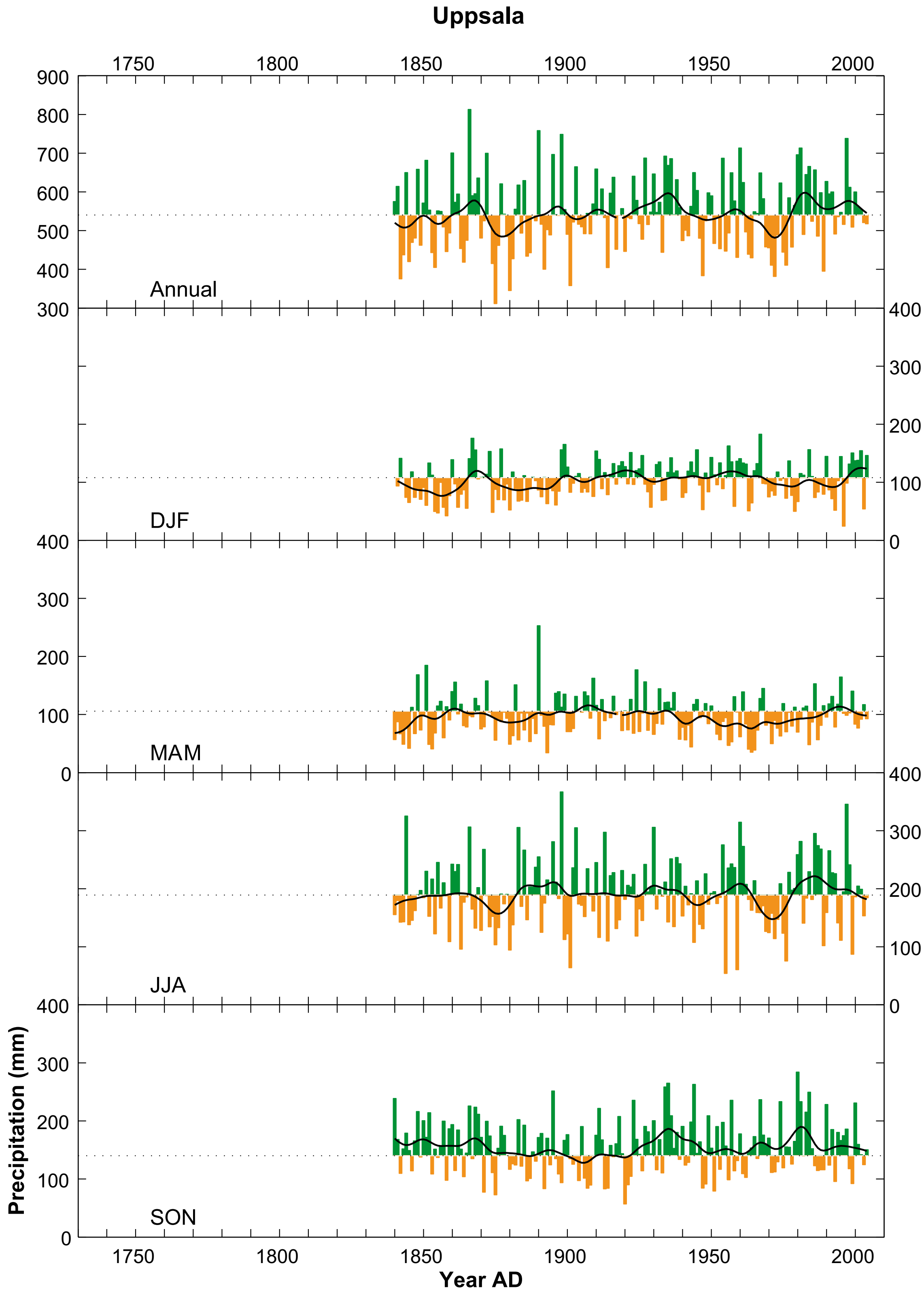

Figure 3-20. *Annual and seasonal precipitation totals for Uppsala 1840–2004. The baseline for the green and orange bars is the average for the period 1901–1929. 10-year smoothed data are also shown. Data from /Moberg et al. in press/.*

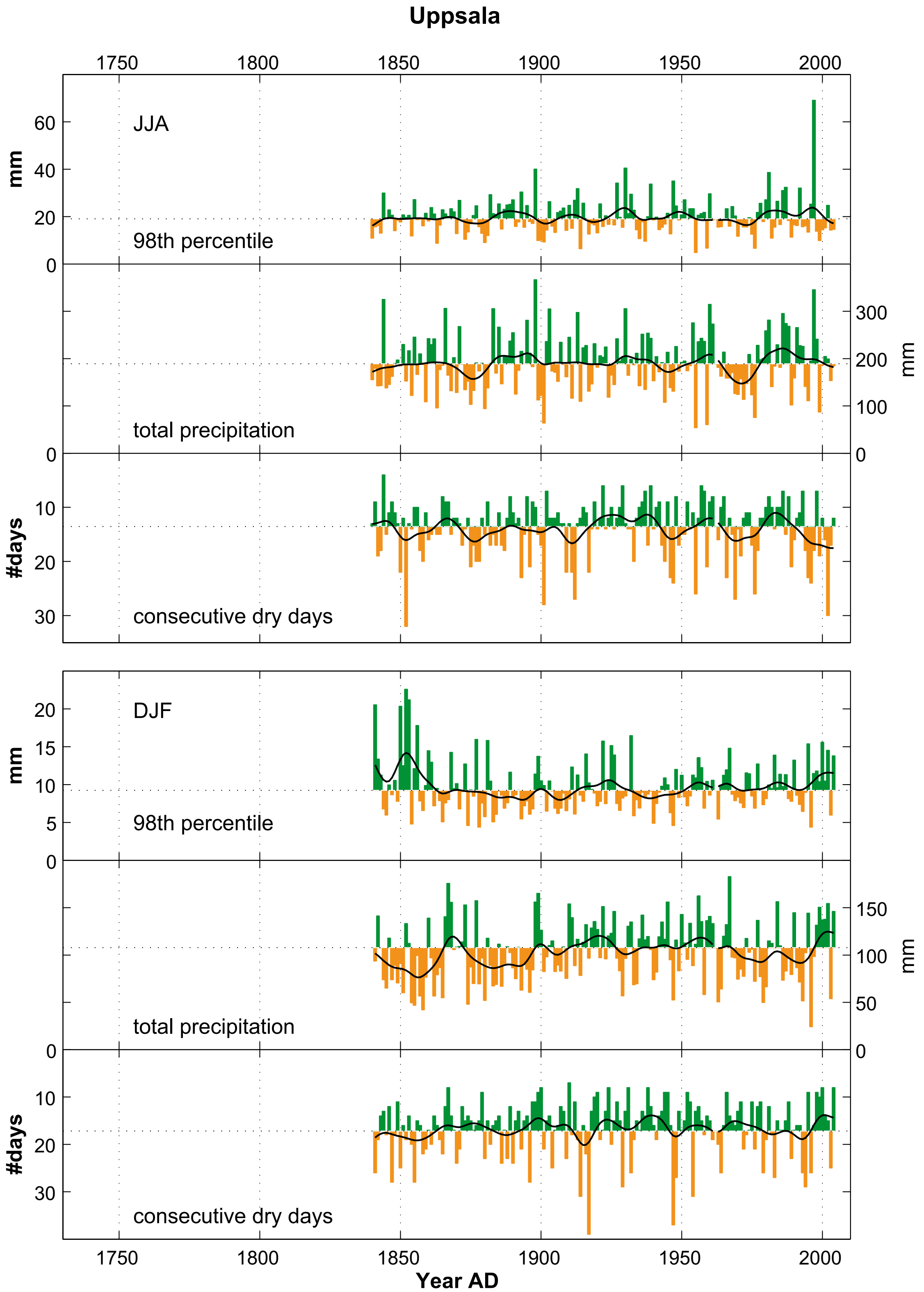

Figure 3-21. *Summer (June–August) and winter (December–February) precipitation totals for Uppsala 1840–2004 compared with the 98th percentile of daily precipitation totals and the maximum number of consecutive dry days in the same seasons. The baseline for the green and orange bars is the average for the period 1901–1929. 10-year smoothed data are also shown. Data from /Moberg et al. in press/.*

consecutive dry days (defined as days with precipitation < 1 mm) in summer and winter respectively. The 98th percentile is approximately equal to the precipitation during the day with the second largest precipitation in a season. The graphs confirm the impression from Figure 3-20 that there have been no clear long-term trends, but a strong interannual, and sometimes also interdecadal, variability. The most extreme single 98th percentile value, by far, is the 69 mm recorded in the summer of 1997. This is 260% more than the 1901–1929 summer average of 19 mm. Another notable observation is the unusually high values of winter precipitation 98th percentiles around 1850, which were clearly above the level in the rather wet period during the most recent few years.

3.8 Discussion of the climate records

Several types of proxy data and instrumental data have been described above. The character and quality of this information depends on the data used.

Lake sediments, wind-blown sand, peat and glacier mass-balance records mostly give **low-resolution climate information.** Often these types of data only provide **qualitative climate information** of, for example, warm vs cold, dry vs wet, warm/dry vs cold/wet, or stormier vs less stormy conditions. In some cases, however, in particular for various lake sediment proxies, **quantitative climate information** can also be obtained. Data of all these types have hitherto commonly been sampled at a time resolution of about a century, which gives too coarse information for detailed studies of climate during the last millennium. A reason for this is that, for example, lake sediment or peat-bog proxy records have traditionally been used in studies of climate changes on much longer time periods than one or two millennia. Another limiting circumstance is the fact that proxy data are not only dependent on climatic changes, but also on several other parameters, including both physical (e.g. solar radiation) and chemical (e.g. pH) parameters. Therefore, there is not only one limiting factor that determines the variations of the indicator analysed in a climate reconstruction. Taken together, the many complexities imply that there are strong limitations on the degree to which we can reconstruct details in time evolution of single climate variables during the last millennium.

Tree-ring data give **quantitative climate information of temperature** variations, mainly for summer. This works particularly well for the northern Scandinavian region. Tree-ring data seems to be the most useful natural proxy data for analysing temperature variability in the last millennium (or even longer) as they provide **annual resolution** and show rather **strong statistical relationships with temperatures**. Near the tree-line in Scandinavia, summer temperature is often the major limiting factor for tree ring growth. Hence, chronologies derived from trees living in a limited area can together reveal, with some precision, the temperature evolution in the area. A disadvantage of tree-ring data, however, is that winter temperatures cannot be reliably reconstructed. Thus, any inferences on climate changes drawn from tree-ring data are biased towards the summer season. Another disadvantage is that the annual growth of tree-rings is dependent on the age of the tree. Although this factor can be taken into account in the data processing, it can nevertheless lead to suppression of slow (century-scale) temperature variations. It is difficult to evaluate how serious this suppression is. One potential possibility to evaluate this problem would be to compare with summer temperatures reconstructed from various indicators in lake sediments, but this potential is currently limited by the low resolution of lake sediment proxy series and by the large discrepancies among available summer temperature reconstructions based on these proxies.

Laminated river sediments may provide **annually resolved climate** information. They can be used for **quantitative** reconstructions of variations in **maximum annual river discharge** over periods longer than a millennium. Hence they can provide important proxies for past hydrological conditions, but at present only one reconstruction is available.

Long instrumental records, going back to the 18th century, provide the **most accurate quantitative representation of past climate**. They give direct information about several climate variables during all parts of the year, including temperature, precipitation, air circulation patterns, clouds, snow cover, etc. They can also provide information down to daily, or even sub-daily, resolution, which means that **weather extremes can be studied** back in time. Their main disadvantage is their relative shortness in comparison with the entire period of interest for long-term climate changes. Another problem is that instrumental records are nearly always affected by various non-climatic distortions due to changes of instruments and routines or relocations of monitoring stations. Sometimes also local environmental changes such as urban warming trends can influence the records. Such factors have to be corrected for before climatic inferences are drawn. Statistical homogenization techniques have been developed for reducing such non-climatic influences, but they can never be entirely eliminated.

In summary, given the available proxy series, it is not possible to reconstruct climate in Sweden during the last millennium in any detail before the start of the instrumental era in the early-to-mid 18th century. Tree-ring data can yield a rather good representation of summer temperatures for the last millennium and even longer back, particularly for the northern half of Sweden, but it is somewhat uncertain if they reliably reproduce low-frequency variations. Proxies from lake sediments are also supposed to provide summer temperature information, but the records have too low resolution and the climate reconstructions show a too large spread to give any reliable indication of the past climate evolution during the last millennium. Proxies for other climate variables (e.g. precipitation, storminess) give mainly qualitative information at low temporal resolution for certain and rather few locations. Annually resolved reconstructions of hydrological conditions (maximum annual river discharge) have been developed, but information is so far severely restricted geographically. Instrumental records are too short for determining the limits within which climate has varied in the last millennium. Thus, although several attempts have been made to reconstruct various past climate variables for the last millennium, the conclusion is that little is actually known in detail.

To increase knowledge of past climate variations in Sweden during the last millennium, it seems necessary to develop many more climate proxy records with annual or at least decadal resolution, for several climate variables and for different seasons. A large number of such proxy records would be necessary, before analyses of the records can be undertaken with statistical techniques such as those that are frequently applied to meteorological data and output from climate model simulations. It is questionable, though, to which extent such an improved knowledge is really possible to derive from proxy data in the future.

4 Climate model simulation

4.1 Global and regional climate models

A climate model incorporates relevant physical and biogeochemical processes in the climate system. Climate models can have varying degrees of complexity. The simplest ones describe the global average radiation balance in one equation, where incoming solar radiation is balanced by outgoing terrestrial radiation. Such a simple model can not be used to infer any information about for instance regional details of the climate and changes due to different causes with time. For these purposes more complex models are needed that take into account processes in the atmosphere, ocean and at the land surface and their interactions. Often fully three-dimensional general circulation models (GCMs) describing the movements in the atmosphere and the oceans are used. These GCMs can be used either for the atmosphere or ocean alone (AGCMs and OGCMs) or in a coupled mode (AOGCMs) in which the atmosphere and ocean interact with each other throughout the integrations. The AGCMs and AOGCMs also include land surface models while OGCMs and AOGCMs include sea ice models. The most complex climate models include atmospheric chemistry, aerosols, dynamic vegetation, biogeochemical processes on land and in the oceans.

A GCM is formulated in a mathematical sense with a number of partial differential equations that describe the 3-dimensional state and temporal evolution of the atmospheric mass, energy and moisture. The time evolution is described by the time tendencies stemming from this system of equations. These tendencies are then added to the current state of the climate system to yield a new state a short time – a time step – ahead. In global models, one time step is typically of the order of 30 minutes. These calculations can be repeated over and over again for tens, hundreds or thousands of model years. Since an initial state is not known exactly, and due to the fact that the climate system is non-linear, climate models can not be used to forecast the state of the climate system at any given time. Rather, they are used to infer information about the climate (i.e. long-term mean and variability of the system), either how it is affected by some external forcing or about the nature of unforced internal variability. The system of equations mentioned above is solved numerically with a typical horizontal resolution of 2–4 degrees (a few hundred kilometres at mid latitudes). This gives a total grid size for the atmosphere of the order of 10,000 grid boxes. In addition there are 20–40 layers in the vertical resulting in a total number of grid boxes of a few hundred thousands for which a large set of equations should be solved roughly every half hour of the simulation. Added to this is the oceanic part of the model with a similar number of integrations. Such computations require good computing facilities.

A climate model does not resolve all the relevant spatial and temporal scales. Examples of processes operating on smaller scales than those explicitly resolved are radiation, evaporation/condensation, turbulence, cloud microphysics, convective clouds etc. These mechanisms are nevertheless very important and need to be taken into consideration. This is achieved by using parameterizations which relate what occurs on the smaller scales to the large resolved scales where explicit information is available. Such parameterizations are essential, but since they are simplifications they contribute to the uncertainty of climate models. Increasing resolution implies fewer parameterisations, but as the climate system processes span over many orders of magnitude, from the planetary scale down to molecular scale (such as dissipation) and, indeed, quantum scale (radiation), there are always some parameterisations in use.

Since the computational demand of a climate model increases rapidly with increasing resolution, present global climate models are seldom run at higher horizontal resolution than a few hundred kilometres. This implies that current GCMs do not resolve regional details of the land-sea distribution and orography. Figure 4-1a shows the land-sea distribution in the European sector from a GCM. It is clearly seen that Europe in the model is not very similar to Europe on a map. To get better regional detail a regional climate model (RCM) can be used. Such a model is set up for a limited part of the globe, for instance Europe, with a much higher resolution than the global model. Current RCMs are often run at 20–50 km resolution (Figure 4-1c). Since the climate system is global the RCM needs information from the rest of the globe. This information is taken at the lateral boundaries from a global model at regular sub-daily intervals. In summary, the global model is needed to provide the large-scale picture and boundary conditions to the regional model, which can add regional detail to the climate calculations.

Due to the complexity of the climate system and all inherent uncertainties in a climate model it is required that it is thoroughly tested. When a global climate model is being set up it is made sure that it can maintain a climate without any long-term drifts in the absence of external forcing. This is done in so called control run experiments. In a fully coupled AOGCM it takes centuries until a steady state is reached due to the slow time scales of the deep ocean. Even after a steady state is reached there is internal variability at different time scales in the control run climate. This internal variability represents the unforced natural variability of the climate system. It is not directly comparable to the natural variability in the real climate system, because the latter more or less constantly experiences some amount of natural forcing, such as changes in Earths orbit around the sun, small variations in the intensity of solar radiation, and volcanic eruptions. Another test of a climate model is to prescribe these external forcing conditions for some past period which is then simulated by the model. In this way the modelled evolution of the climate can be compared to the observed climate. By constraining an AGCM with observed sea surface temperatures also the simulated evolution and temporal variability should be close to the observed climate. Likewise, an RCM can be evaluated against observed climate given that it is forced by realistic boundary conditions. In so called "perfect boundary experiments" RCMs take boundary conditions from analyses of the state of the atmosphere. As an example of results from such an experiment Figure 4-2 shows that the RCM used in this report performs well for monthly precipitation over the Baltic Sea catchment area.

4.2 The global model ECHO-G

The global climate model used in this study is ECHO-G /Legutke and Voss 1999/, which consists of an atmospheric general circulation model known as ECHAM4 /Roeckner et al. 1999/ coupled to the ocean model HOPE-G /Wolff et al. 1997/. A detailed analysis of how this model simulates climatic variations in Scandinavia for the last millennium has been undertaken and reported by /Gouirand et al. 2006/. This article was written as a part of the current project. Some main features from /Gouirand et al. 2006/ are presented and discussed here.

The ECHO-G model has a horizontal resolution of about 3.75° for its atmospheric component and about 2.8° for its ocean component with increasing resolution in the tropical regions reaching 0.5° at the equator. The number of vertical layers is 19 for the atmosphere and 20 for the

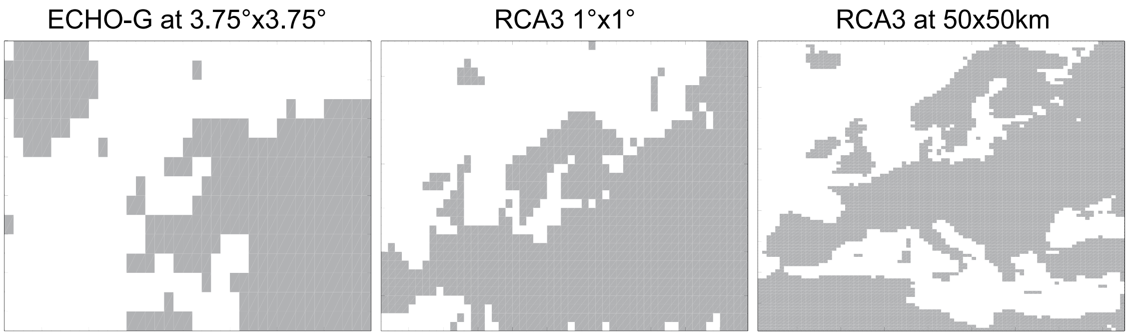

Figure 4-1. *Land-sea mask in (left) the global climate model ECHO-G at 3.75° horizontal resolution, (middle) in the regional climate model RCA3 at 1° horizontal resolution and (right) in RCA3 at 50 km horizontal resolution.*

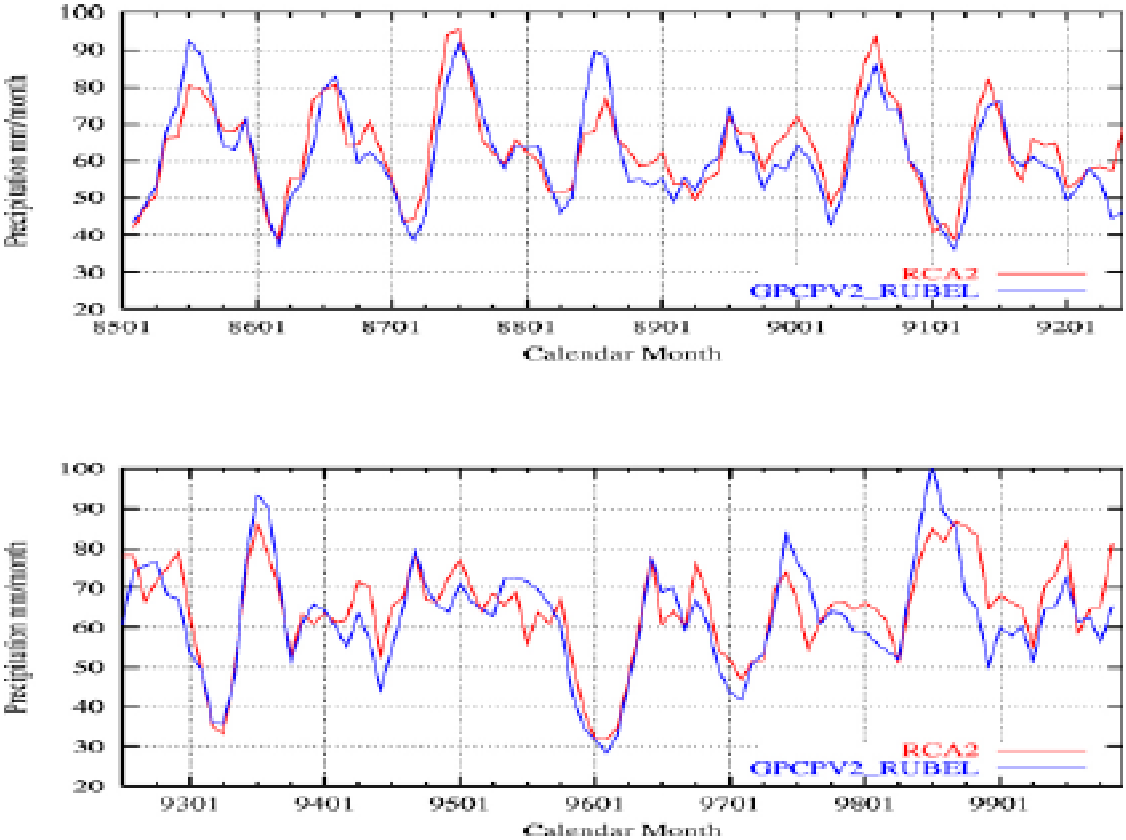

Figure 4-2. *Simulated (red) and observed (blue) monthly mean precipitation over the Baltic Sea catchment area.*

ocean. More details about ECHO-G are given by /Min et al. 2005/. The spatial resolution in the model is rather coarse, and Scandinavia is represented only with a few grid points (Figure 4-1a). To obtain a simulated climate for Sweden with a reasonably high spatial resolution, output data from this global model are used to drive a regional model. Chapter 5 describes the regional model and also shows results comparing output from the regional and global model simulations.

4.3 Forced 1,000-year simulation with ECHO-G

The simulation with ECHO-G used by /Gouirand et al. 2006/ is described by /González-Rouco et al. 2003/ and /von Storch et al. 2004/. It is a 1,000-year long simulation run with reconstructed forcings from three major external variables since AD 1,000; (i) annual global concentrations of CO_2 and CH_4 (Figure 4-3a) derived from air bubbles trapped in polar ice cores /Etheridge et al. 1996, 1998/; (ii) volcanic radiative forcing (Figure 4-3b) estimated from acidity measurements in ice cores /Crowley 2000/; (iii) solar radiative forcing history (Figure 4-3c) estimated from concentrations of ^{10}Be in ice-cores /Bard et al. 2000/, which have been combined with estimates based on historical sunspot observations (the latter are only available after around AD 1,700). The solar and volcanic forcing histories are the same as those described by /Crowley 2000/, but with a rescaling of the solar forcing to obtain the solar irradiance to drive the model. This rescaling yields a change in solar forcing of 0.3% between the mean during the recent period 1960–1990 and the earlier period 1680–1710, when solar forcing is often assumed to have been rather weak (see discussion by /Gouirand et al. 2006/ concerning this choice).

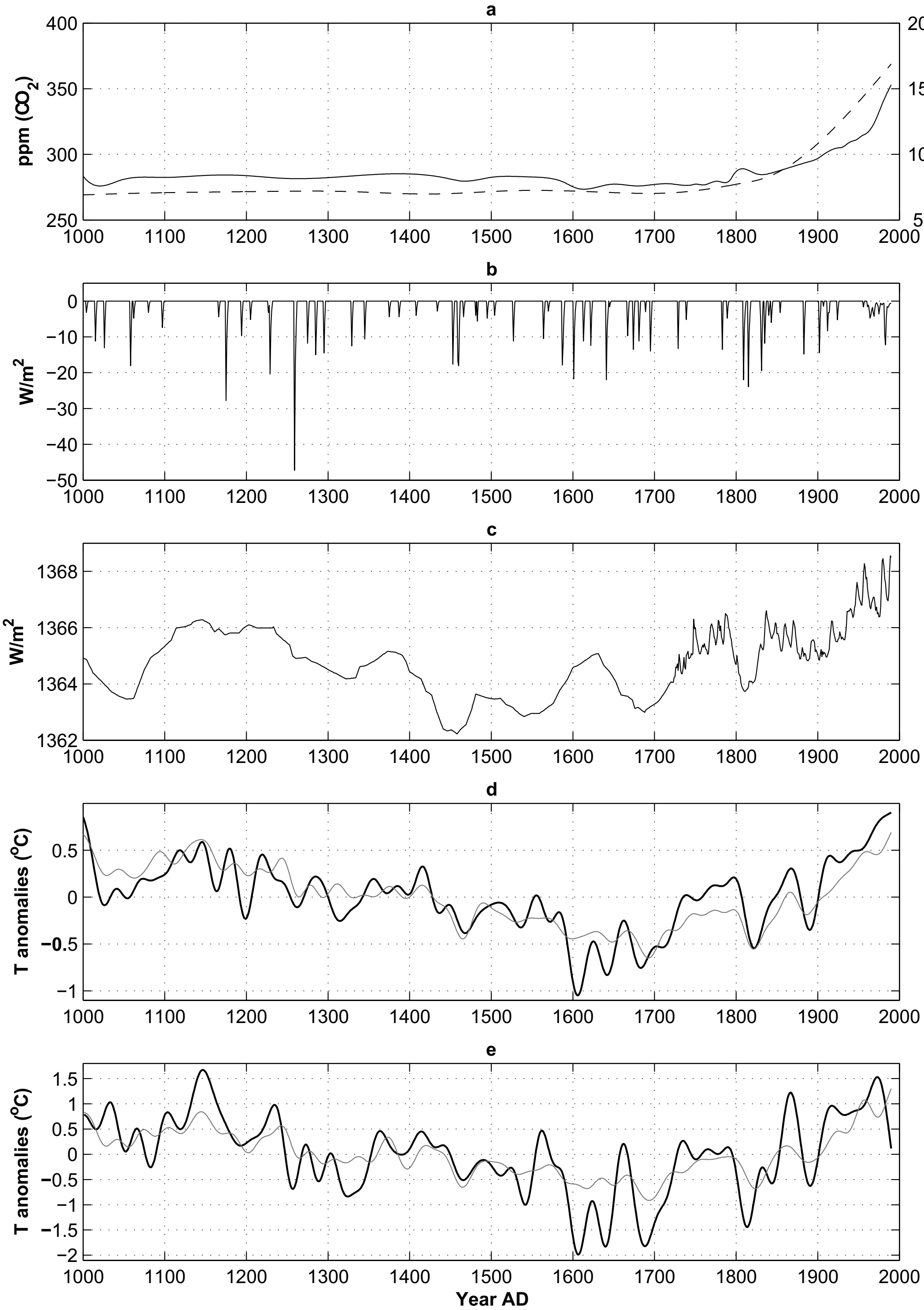

Figure 4-3. *Forcing time series used to drive the global climate model ECHO-G and simulated temperatures obtained from this model. (a) Greenhouse gas concentrations (CO_2 – solid line, CH_4 – dotted line), (b) volcanic forcing, (c) solar forcing, (d) June–August temperatures for Scandinavia (thick black line) and the Northern Hemisphere (thin grey line), (e) December–March temperatures for Scandinavia (thick black line) and the Northern Hemisphere (thin grey line). The temperature series in (d–e) are shown as 30-year smoothed anomalies from the long-term mean. The Scandinavian temperature is averaged over the model region [2.5°E–27.5°E; 57.5°N–67.5°N]. Redrawn from /Gouirand et al. 2006 Figure 1/.*

The solar and volcanic radiative forcings are further aggregated to an effective solar constant used to force the model /González–Rouco et al. 2003, von Storch et al. 2004/. It should be noted that the forcing history used to drive the global model is obtained from various proxy data for the historical forcings. /Gouirand et al. 2006/ discuss various uncertainties in the radiative forcings. They conclude that the greenhouse gas forcing history is rather well known, but solar and volcanic forcing histories have rather large uncertainties. The quality of the output from the global model simulation is dependent on the reliability of the proxy derived forcings. This is important to bear in mind in all comparisons with proxy data or instrumental records. The same holds also for comparison of proxy- or instrumental data with output from the regional model, as the regional model simulation uses the same forcing history as the global model.

Two important comments should be made about the simulated climate. First, the specific simulation used here was started from relatively warm initial conditions and was allowed only 100 years of spin-up before the model-year corresponding to AD 1,000. It has been found later that this spin-up time was too short for the model to be in equilibrium with the forcing in AD 1,000. Another simulation, starting from somewhat colder initial conditions, has Northern Hemisphere annual mean temperatures that are about 0.5°C colder during the period 1000–1200 /González-Rouco et al. 2006/. After around 1550, however, the two simulations have very similar hemispheric temperature levels. This suggests that the simulation used here could be too warm also for the Scandinavian region in the early part of the simulation. It is not possible, however, to say how large this bias is, or when it vanishes in the simulation. But it should be kept in mind that this uncertainty in the initial period of the simulation with the global model is inherited in the subsequent simulation with the regional model.

The second important note, is the fact that no anthropogenic aerosols have been used to force the model. In reality, increased atmospheric concentrations of anthropogenic aerosols during the 20th century have likely led to a negative radiative forcing component, and hence to some cooling effect on climate. However, there still exists large uncertainty in the magnitude of the tropospheric aerosol forcing /IPCC 2001/, although subsequent estimations confirm that the forcing is negative. The omission of anthropogenic aerosol forcing thus suggests that the simulated warming trend in the 20th century is too strong. There is evidence that the negative forcing has been particularly strong over regions with strong emissions of sulfur. Europe is one such region. Taken together the two effects mentioned suggest that the simulation may be too warm both in the early part (due to too short spin-up time) and in the late part (due to omission of anthropogenic aerosols). This can be valid both for the Northern Hemisphere average and for the Scandinavian temperature.

The summer and winter mean temperatures for the period 1000–1990 as simulated with ECHO-G are shown in Figure 4-3d and 4-3e, averaged over both the entire Northern Hemisphere and over the Scandinavian region. The data are shown as smoothed series to highlight slow variations on timescales longer than 30 years. The overall evolution of the Scandinavian temperatures follows that of the Northern Hemisphere, but with larger variations. This is a consequence of the fact that variability is larger in a smaller region due to regional effects. Such effects are partly cancelled in the hemispheric average by opposite variations that occur in other regions. A main feature of the simulated Scandinavian temperature evolution is the multi-centennial variation from relatively warm conditions in the period 1000–1200 to cold conditions, with a minimum around 1600, and then a warming again at the end of the series.

/Gouirand et al. 2006/ compare the Scandinavian temperature simulated by ECHO-G with temperature series reconstructed from proxy data and long instrumental records. For this comparison three datasets are used:

- A tree-ring based northern Fennoscandian summer (April–August) temperature reconstruction of /Briffa et al. 1992/. This series is selected because it has the strongest correlation with observed temperatures among the tree-ring chronologies evaluated in section 3.4.2 (Figure 3-11).

- A winter temperature reconstruction (December–March) based on ice break-up in the harbour of Tallinn extending back to 1500 /Tarand and Nordli 2001/. This is the longest available winter temperature reconstruction for the Scandinavian region (see section 3.6 and Figure 3-16).
- Instrumental temperature data for Uppsala in summer (April–August) and winter (December–March). Summer data are used back to the first year of the record, 1722, but winter data are used back only to 1750. The earlier winter temperature data are excluded to avoid the problem with data being measured in well-ventilated un-heated rooms (see section 3.7). This circumstance is supposed to affect winter temperatures more than summer temperatures, wherefore summer temperatures are accepted back to 1722.

Time series for the simulated, the proxy-data-based and the instrumental temperatures are shown, for 30-year smoothed data, in Figure 4-4. Some similarities can be seen in the evolution of the two temperature series. Both series fluctuate around their long-term means from AD 1,000 to around 1,500. Both series show a decrease in temperatures from 1500 to a relatively cold period around 1600–1650, which is followed by an increase of temperatures until the 20th century. Some details in the multi-decadal variations are similar in both series after around 1500, but hardly any similarities are seen before this year. The range of variability is

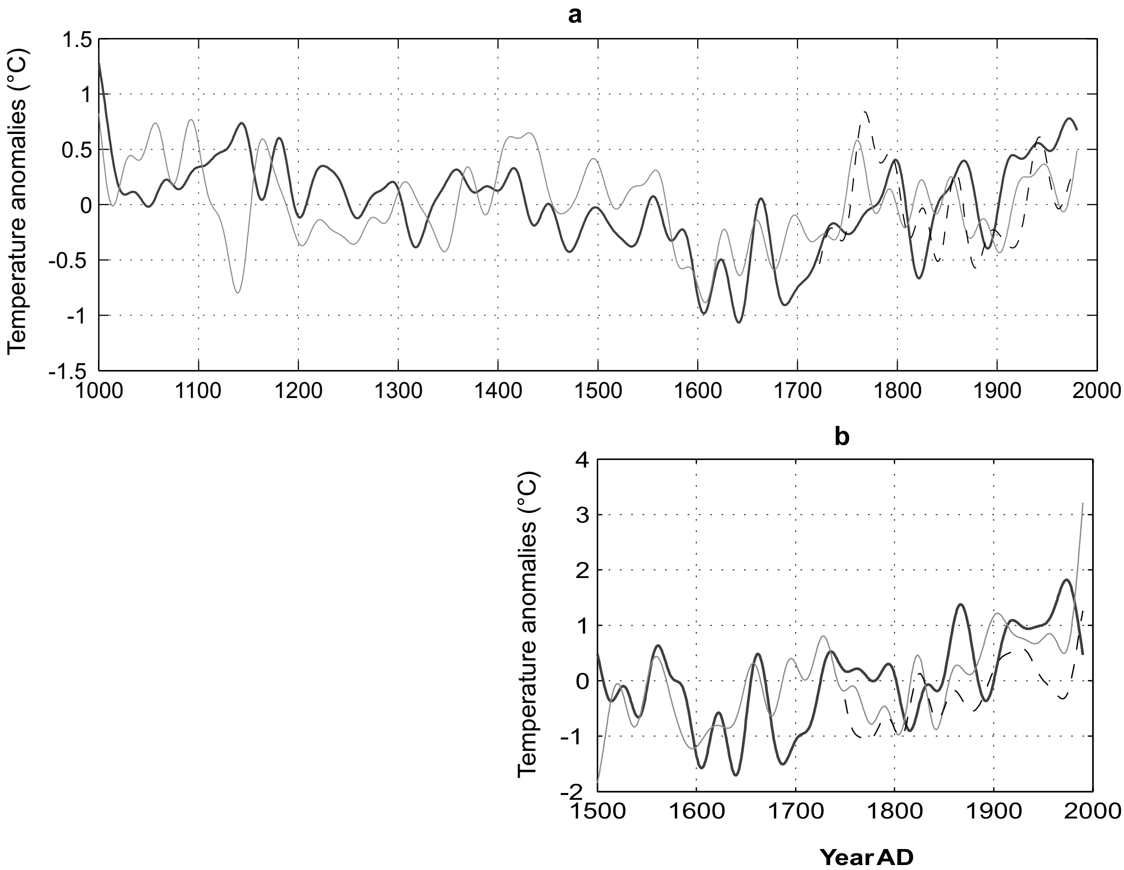

Figure 4-4*. Comparison of Scandinavian temperatures simulated with ECHO-G (thick black lines) and temperatures reconstructed from proxy data (grey lines). Instrumental temperatures from Uppsala are also shown (dotted black). (a) April–August temperatures, (b) December–March temperatures. The proxy data in (a) are based on tree-ring data from northern Fennoscandia /Briffa et al. 1992/, and those in (b) are based on documentary evidence of ice-break up dates in Tallinn Harbour /Tarand and Nordli 2001/. All data are shown as 30-year smoothed anomalies from their respective long-term means. From /Gouirand et al. 2006 Figure 3/.*

about the same in the simulated and the reconstructed temperatures and also in the instrumental temperatures. The model can thus be said to provide ‘realistic’ summer temperature variations, in terms of the range of variability, and to some extent also concerning the long-term temporal temperature evolution.

Also for winter temperatures are there some similarities between simulated and reconstructed temperatures. Both data types show a cold period during the 16th and 17th centuries and a warming trend from the 18th to the 20th century. The warming trend from around 1600 to the early 20th century is of a similar size (~ 2°C) in both series. However, the simulation and the instrumental Tallinn temperature series have stronger warming trends in the 20th century than the Uppsala instrumental series. Nevertheless, the overall long-term evolution of the simulated winter temperatures after 1500 appears rather realistic.

/Gouirand et al. 2006/ also evaluate how well the ECHO-G model reproduces relationships between Scandinavian temperatures and atmospheric circulation pattern, sea surface temperatures and Northern Hemisphere mean temperatures. An analysis of the response of simulated Scandinavian temperatures to volcanic forcing is also made. In summary, realistic relationships with the atmospheric circulation, with some deficiencies in summer, are found. Co-variations with sea surface temperatures in the Norwegian Sea and Northern Hemisphere temperatures are too weak on timescales less than10 years, but slower co-variations (timescales > 10 years) with Northern Hemisphere temperatures in winter are apparently too strong. The model’s summer cooling response to volcanic forcing is found to be realistic, but an expected winter warming could not be detected.

Further analyses by /Gouirand et al. 2006/, of the climate simulated by ECHO-G, provide some insight in possible mechanisms behind temperature variations in Scandinavia. The secular cooling–warming long-term trend behaviour of the simulation can largely be explained by slow changes in radiative forcings, but the amplitude of these overall temperature variations is likely somewhat too large due to the problem with too high temperatures in the early part of the simulation (caused by a too short spinup period in combination with rather warm initial conditions) and the omission of anthropogenic aerosol forcing in the simulation. Decadal and multidecadal deviations from the centennial cooling–warming trends seem to be the result of a mixture of causes. Temporary decreases in solar radiation can explain some cold intervals in both winter and summer, but not all. Sequences with strong volcanic forcing events can also contribute in summer. The coldest period in the simulation occurs between 1590 and 1650 in both winter and summer. In winter this cold period is associated with an average negative North Atlantic Oscillation (NAO) phase in the simulation (see Figure 4-5). This can explain the systematically low winter temperatures in Scandinavia, through a weakened westerly flow of mild air onto this region. It is more difficult to explain why simulated summer temperatures are also at their minimum in the same period. Several strong volcanic forcing events between 1590 and 1650 seem to have contributed to the cold summers. /Gouirand et al. 2006/ point out that cold conditions in this period are also recorded in Scandinavian proxy data for both winter and summer and, moreover, that proxy data suggest an average negative NAO phase in winters in the same period.

Based on the results from these analyses of ECHO-G, we consider the 1,000-year simulation with ECHO-G to provide a sufficiently reliable representation of climate in Scandinavia and surrounding regions, to motivate that it is used to drive a regional model, which is the focus in the remaining part of this report.

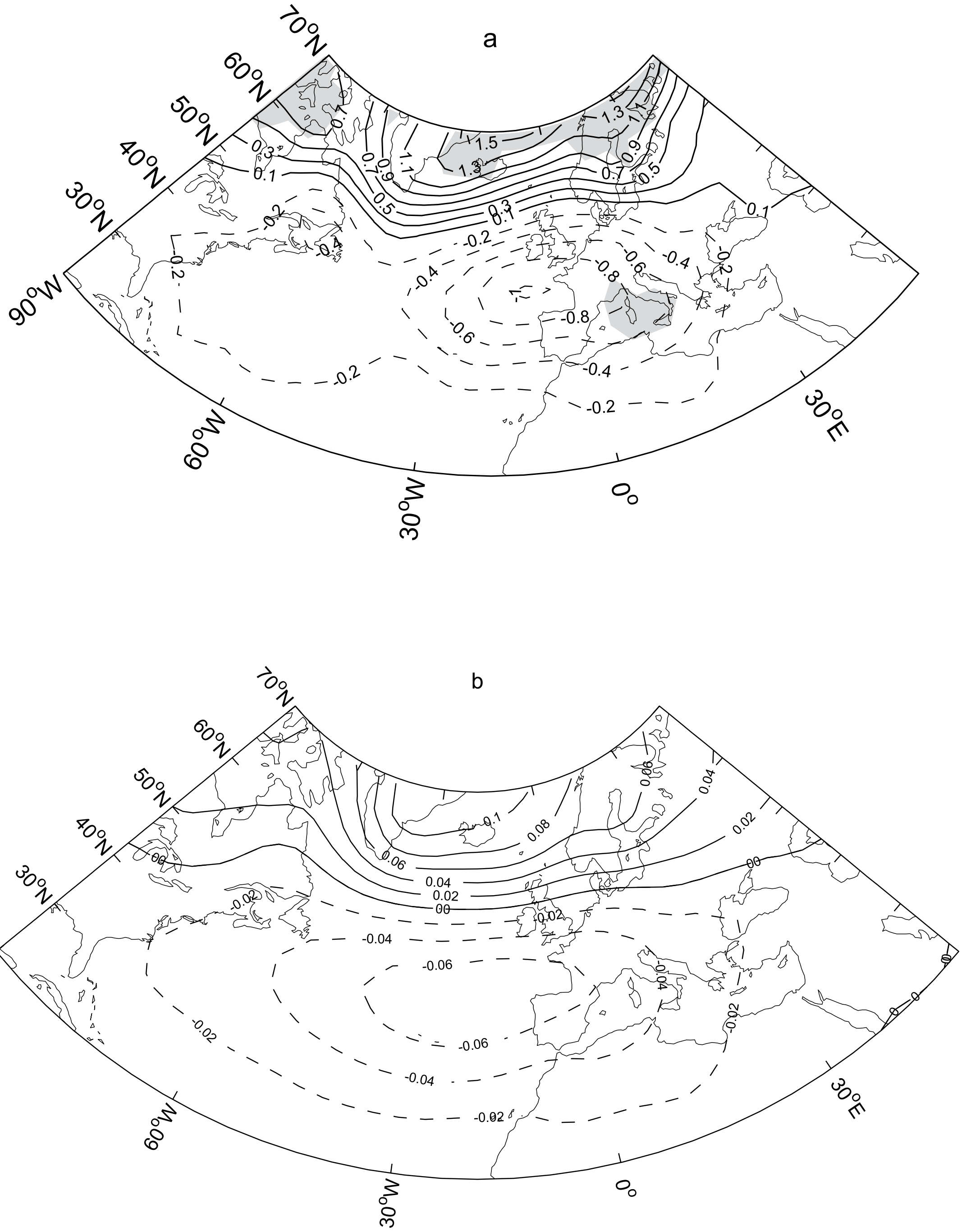

Figure 4-5. *Analysis of sea level pressures simulated with ECHO-G for December-March over the North Atlantic and European sector. The map in (a) shows average anomalies for AD 1,590–1,650. Negative (positive) anomalies from the entire period AD 1,000–1,990 are represented by dashed (solid) lines. Contour interval is 0.2 hPa. Grey shading indicates significant anomalies at the 0.1 level. The map in (b) shows the leading mode of variation in (the first Empirical Orthogonal Function, EOF), which explains 37% of the variance, calculated for the period AD 1,000–1,990. The similarity between the two maps reveal that the cold winters during AD 1,590–1,650 ares associated with the North Atlantic Oscillation (NAO) being on average in a negative phase. From /Gouirand et al. 2006 Figure 9/.*

5 Regional model simulation of past Scandinavian climate

5.1 The regional model RCA

The atmospheric model RCA3 /Kjellström et al. 2005/ builds on RCA2 /Jones et al. 2004/ which in turn originally builds on the numerical weather prediction (NWP) model HIRLAM. HIRLAM is used operationally at several European weather institutes. An advantage of having a NWP model as the basis for a regional climate model is that it is being tested extensively in everyday routine work at these institutes. The major changes in RCA3 compared to RCA2 concerns the treatment of land surface processes. In RCA3 these processes are calculated separately for forests, open land areas and lakes. One advantage of this approach is that information can be stored separately for better evaluation against observations. Among other changes in the model are improvements in the treatment of turbulence, radiation and clouds. The modifications lead to a better representation of both temperature and precipitation /Kjellström et al. 2005/.

For the purpose of this study RCA3 is coupled to the lake model FLAKE (http://nwpi.krc.karelia.ru/flake/) that is applied for the Baltic Sea and the lakes in an area approximately covering the Baltic Sea drainage basin. The motivation for using this lake model for the Baltic Sea is that it makes considerable improvements to the results as compared to taking SSTs and sea ice directly from the coarse global model. FLAKE takes as input radiative and heat fluxes from the atmosphere as well as solid precipitation. Calculations of sea (lake) surface temperature and ice/snow conditions are then calculated locally for each grid box. An even better simulation would be achieved if a full 3D ocean model for the Baltic Sea was used instead. Such a fully coupled model, that takes into consideration also ocean currents, exists for the Baltic Sea (RCAO), /Döscher et al. 2002/ but it would have been too computationally demanding for the long regional model simulations targeted in this study.

5.2 Experiment setup

The regional model RCA3 was used to dynamically downscale the ECHO-G results for three different time periods: 1000–1199, 1551–1749 and 1751–1929. The first two periods were relatively warm and cold, respectively. The third period coincides with the instrumental observations becoming available, and also includes a part of the 20th century when the geographical coverage of the observational data gets better. This is used in the evaluation of the model.

In the experiments lateral boundary conditions and sea surface temperatures and sea ice conditions for the Atlantic were taken from the global model every twelve hours. The ECHO-G data was taken at its original resolution of 3.75° horizontal resolution and 19 vertical levels while RCA3 was set up on a 1°×1° horizontal resolution (Figure 4-1b) with 24 vertical levels. A time step of 30 minutes was used for the integrations.

Apart from the forcing imposed from the boundary conditions from the global model we applied the same radiative forcing as in the global model (section 4.2.1), except for the greenhouse gases for which only CO_2 was used in RCA3 whereas ECHO-G also used CH_4. We did not include land uplift and there were no changes in land use in the simulations. Hence the fractions of land, forests and lakes were the same throughout time. Output data for most variables are stored on a daily basis, except for surface pressure which is stored three-hourly throughout the integrations.

Before conducting the climate reconstruction simulations, RCA3/FLAKE in its present configuration was tested in a perfect boundary experiment forced with ERA40-data /Uppala et al. 2005/ on its lateral boundaries.

5.3 Evaluation of RCA3 – perfect boundary experiments

Given appropriate boundary conditions the RCA model is capable of simulating climate conditions in a realistic way /Jones et al. 2004, Kjellström et al. 2005/ (see also Figure 4-2). Climate models are, however, never perfect. Figure 5-1 shows the bias in the temperature climate in Europe as simulated for the time period 1961–1999 in RCA3 without FLAKE. In general, the temperatures during winter are too high in Scandinavia and slightly too low during summer in much of northern Europe. Part of the warm bias in northern Scandinavia during winter is probably an artefact of comparing gridbox averages from the model to a climatology that is based on point observations made in (cold) valley stations /Räisänen et al. 2003/. Apart from this specific wintertime problem both the winter and summer biases in temperature seem to be related to a too extensive cloud cover that holds too much cloud water in RCA3 /Kjellström et al. 2005/.

Regardless of the above mentioned biases in temperature the combination RCA3/FLAKE manages to capture the seasonal cycle of sea surface temperature and sea-ice conditions in most parts of the Baltic Sea. During the test period 1993–1996 the freezing and melting of the sea ice occurs at the right time of year (Figure 5-2). It should be noted that the absolute numbers are not the same for the two curves since they represent different features of the sea ice. Also the sea surface temperatures are in general well simulated as compared to the few available ship measurements (Figure 5-2), although there is a tendency for a warm bias in fall.

A problem in the present setup of RCA3 is that the computationally expensive long integrations force us to use a rather coarse horizontal resolution (1°×1°). This resolution implies that the Scandinavian mountain range is too low and is not as efficient in terms of forcing precipitation as it should be. Figure 5-3 shows the precipitation as observed /Mitchell et al. 2004/ and as simulated in RCA3 at 50×50 km for the time period 1961–1999 and as simulated by RCA3 at 1°×1° for the time period 1901–1929. Even if the simulated time periods are not the same it is clearly seen that the model at its 1°×1° resolution overestimates the precipitation on the east side of the mountain range. This implies that precipitation in Sweden is overestimated in the simulation.

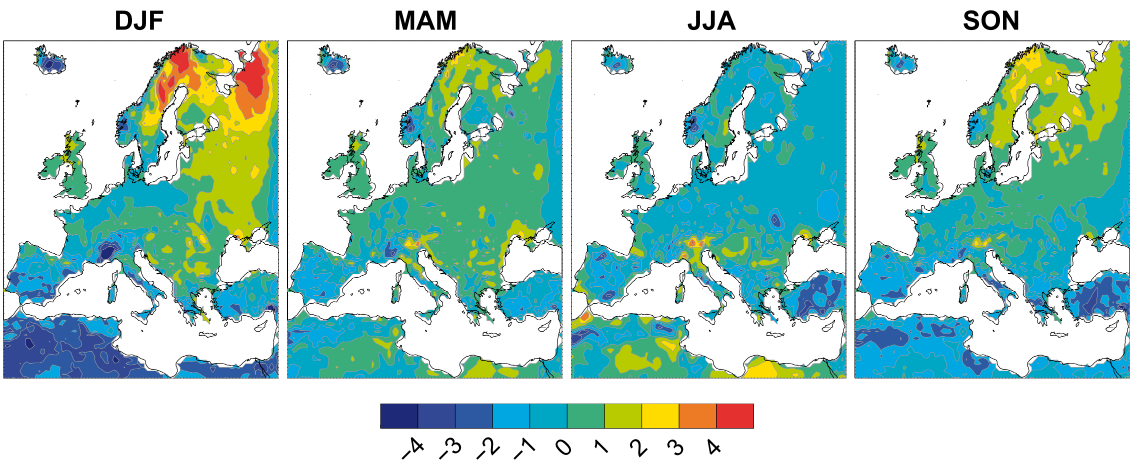

Figure 5-1. Seasonal mean bias in 2m-temperature in RCA3 as compared to the observational climatology from the Climate Research Unit at the University of East Anglia, UK /Mitchell et al. 2004/. From left to right: DJF, MAM, JJA, SON.

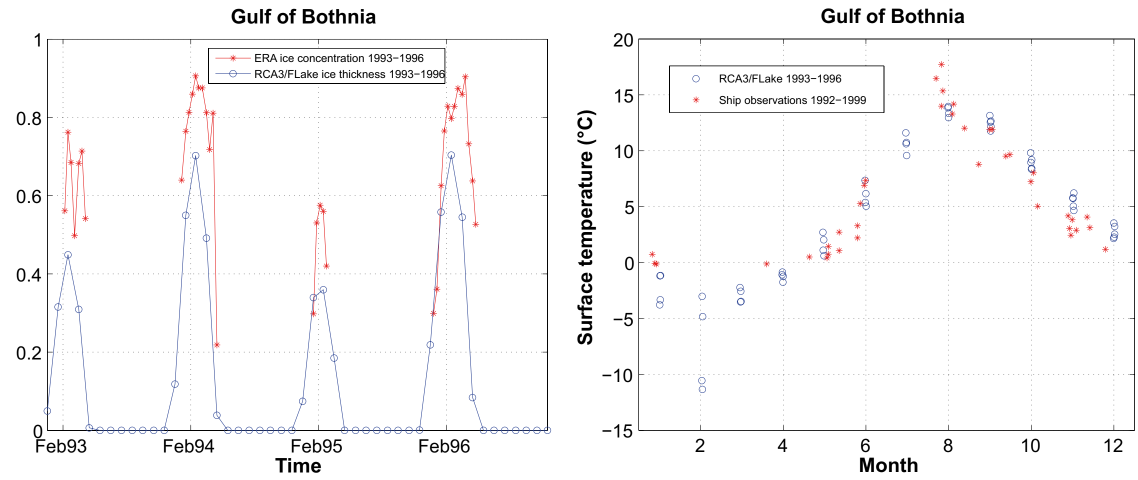

Figure 5-2. *Seasonal cycle of (left) sea ice thickness simulated with RCA3/FLAKE and sea ice concentration from the ERA40 reanalysis (Uppala et al. 2005), and (right) sea surface temperature as simulated by RCA3/FLAKE and as observed by SMHI.*

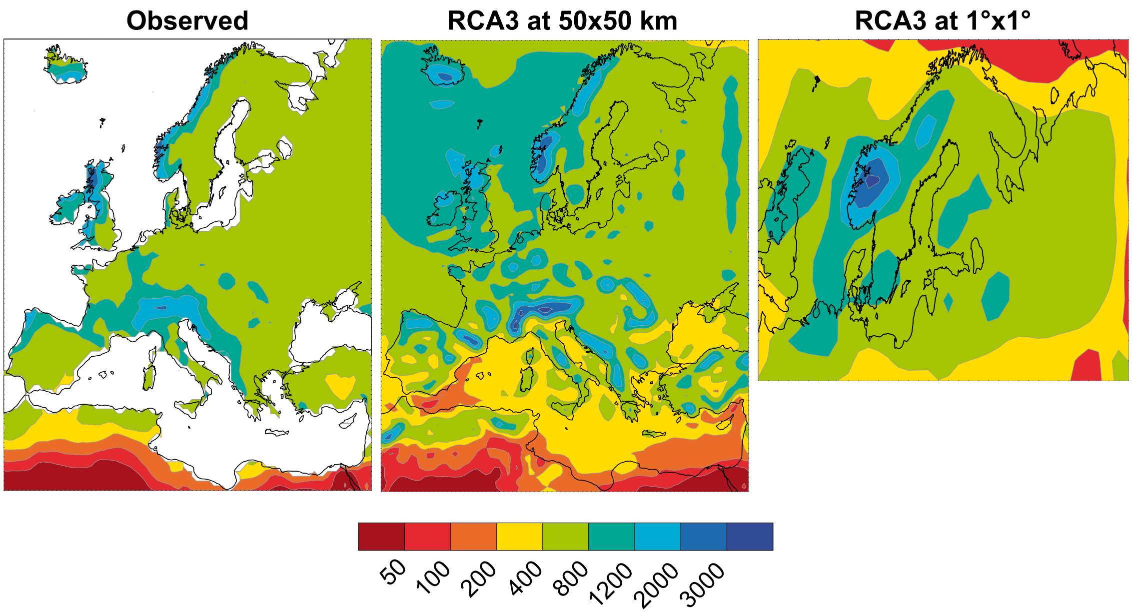

Figure 5-3. *Annual precipitation in (left) the observational climatology from the Climate Research Unit at the University of East Anglia, UK /Mitchell et al. 2004/, and (middle and right) as simulated by RCA3 at two different resolutions (50×50 km and 1°×1°). The observations and high-resolution simulation are for the period 1961–1999 while the coarse resolution RCM results are from the period 1901–1929 in the experiments presented in this report. Unit: mm.*

In summary, there is a general good agreement between RCA3 in its present setup and observations in the perfect boundary experiment in terms of the temperature climate. The overestimated precipitation in Sweden is a systematic feature due to the coarse horizontal resolution. We argue that this overestimation is present in all simulated time periods, so that the anomalies with respect to a certain reference period are useful even if the absolute numbers given from the model are biased to some extent. We conclude that RCA3/FLAKE in its present configuration can be used for the downscaling experiments outlined in this project, and for the kind of analyses undertaken here on the model output data.

5.4 Evaluation of RCA3 – the climate change experiments

In this part we compare model output from the first decades of the 20th century to available observations. As described in section 4.1 it is not to be expected that RCA3/FLAKE should capture the actual evolution of the climate in this period. Instead, we investigate how well it captures the statistical properties of the observed climate.

We begin by looking at the large-scale circulation in the European area for which RCA3/FLAKE was used here. Figure 5-4 shows the bias in 30-year seasonally averaged mean sea level pressure (MSLP) in the RCA3 domain compared to the observations from /Smith and Reynolds 2004/. It is seen that the model consequently underestimates the MSLP in an area including southern Scandinavia, while it is overestimated in the northeast and in the southwest. This pattern indicates too cyclonic time-mean conditions in the middle of the domain. There is an indication that this bias in MSLP is a general feature of ECHO-G since a very similar bias pattern for the seasons are found when comparing the simulated climate in the period 1871–1900 to the corresponding observational data set for that period (not shown). A very similar bias pattern was found for the time period 1961–1990 in the ECHAM4 model /Räisänen et al. 2003/ which shares much of its formulation with ECHO-G.

An implication of the biases in MSLP is that the westerly flow from the Atlantic Ocean to southern Scandinavia is too strong in the model. This, in turn, may lead to too high temperatures in this area during winter and too low temperatures during summer. These features are confirmed in Figure 5-5, which shows the bias in 2m-temperature with respect to the observed climatology. It can be noted that the errors in large parts of the model domain are larger than in the perfect-boundary experiment described above.

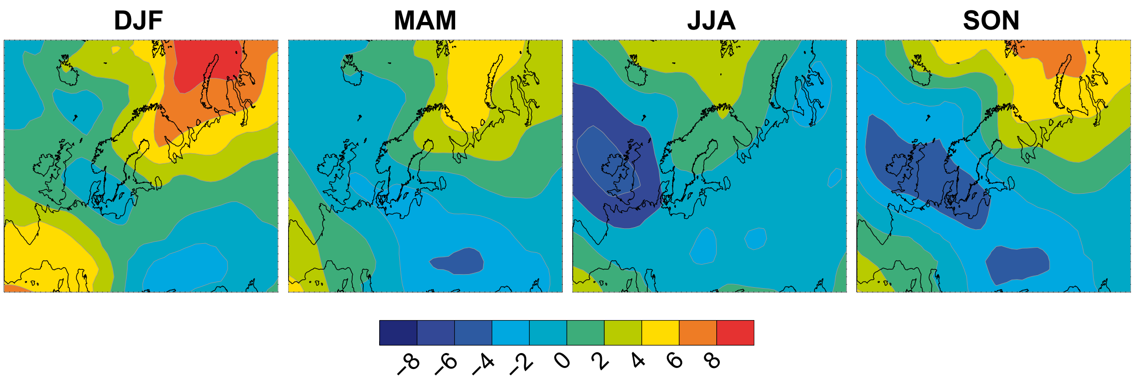

Figure 5-4. *Seasonal mean bias in mean sea level pressure in RCA3 as compared to the observational climatology from /Smith and Reynolds 2004/. From left to right: DJF, MAM, JJA, SON.*

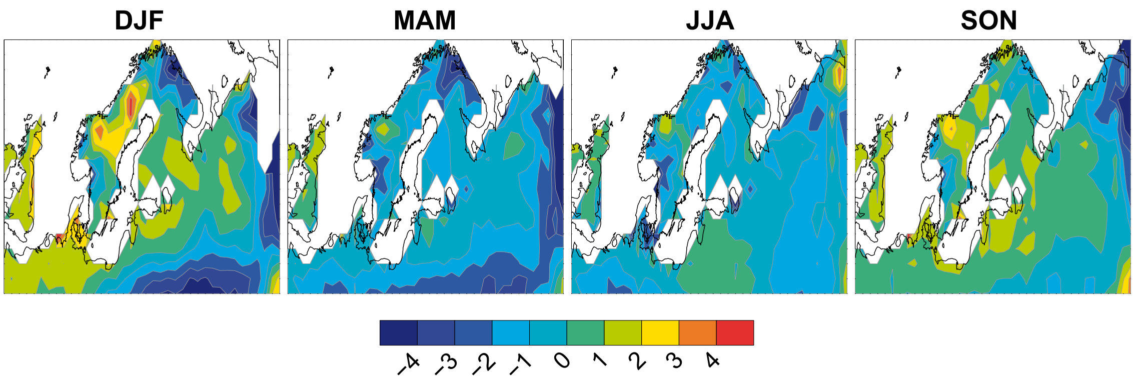

Figure 5-5. *Seasonal mean bias in 2m-temperature in RCA3 as compared to the observational climatology from the Climate Research Unit at the University of East Anglia, UK /Mitchell et al. 2004/. From left to right: DJF, MAM, JJA, SON.*

5.5 Comparison with proxy data and long instrumental records

In this section we compare data from the RCA3/FLAKE simulation with climate proxy data. We require that the proxy data have annual resolution and represent a climate variable which enables an easy direct comparison with model data. This restricts the proxy data to only consist of tree-ring based summer temperature reconstructions for the full millennium and documentary-data based winter temperature reconstructions for the last 500 years. Meaningful comparison between model and proxy data for other variables can unfortunately not be made, essentially because of the low temporal resolution of other proxy data. Comparison with the annually resolved river discharge proxy data could in principle be undertaken. However, in order to do this, it would first be necessary to run a hydrological model for the actual drainage basin, using RCA3/FLAKE data as input. Such a model study has not been undertaken. For temperatures, however, more detailed data comparisons can be made by using instrumental data, which are available at a daily resolution about 250 years back. We compare the simulated and observed frequency distributions of daily mean temperatures for Stockholm in the period of overlapping data, 1756–1929. For brevity, we will simply write RCA when we mean RCA3/FLAKE in the rest of this report.

5.5.1 RCA simulation vs temperatures reconstructed from proxy data

Two direct comparisons between RCA and proxy data are made:

- Reconstructed summer (June–August, JJA) temperatures for the grid point nearest to Haparanda in the tree-ring based reconstruction developed in /Gouirand et al. submitted manuscript/ (shown in Figure 3-13) are compared with JJA temperatures for the corresponding grid point in the RCA simulation.
- Reconstructed winter (December–March, DJFM) temperatures for Tallinn /Tarand and Nordli 2001/ are compared with DJFM temperatures for the corresponding grid point in the RCA simulation.

Figures 5-6 shows annual values and smoothed temperatures depicting variability at timescales longer than 30 years. As mentioned in section 3.4, the tree-ring series covers the period 442–1970, but here the series is extended with instrumental data to include also 1971–2000. The Tallinn series covers the period 1500–1997. It is based on proxy-data before 1757 and instrumental temperatures after this year (see section 3.6).

For summer, the simulated Haparanda temperatures are on average about 2°C to 3°C colder than the corresponding temperatures reconstructed from tree-ring data. The mean absolute temperature level for the tree-ring record is close to the corresponding level in instrumental data (see /Gouirand et al. submitted manuscript/). This indicates that the RCA simulation has too cold summer temperatures for this grid point, which is in line with the evaluation of the model (see sections 5.3 and 5.4). There is hardly any agreement seen between details in the temporal evolution of the reconstructed and simulated temperatures. Nevertheless, both the reconstructed and simulated temperatures are relatively cold from 1600 to 1700, although coldness in this period is much more marked in the simulation. A warming trend of about 1°C occurs from 1650 to 1930 in the simulation. There is a warming over this period also in the tree-ring reconstruction, but it is much smaller. In the simulation, the temperature difference between the period 1000–1200 and the cold spell around 1600 is slightly larger than 1°C. According to the tree-ring data, the corresponding temperature difference is substantially smaller.

The variances of simulated and reconstructed temperatures are nearly equal after around 1700 (which is the period when the tree-ring data are most reliable; see /Gouirand et al. submitted manuscript/). In this period the standard deviation of reconstructed and simulated temperatures are nearly the same, 0.82°C and 0.85°C respectively. Hence, because the variance in the tree-ring data is likely too small (65% temperature variance is explained in the calibration period), the simulated temperature variance is likely also somewhat too small. For comparison,

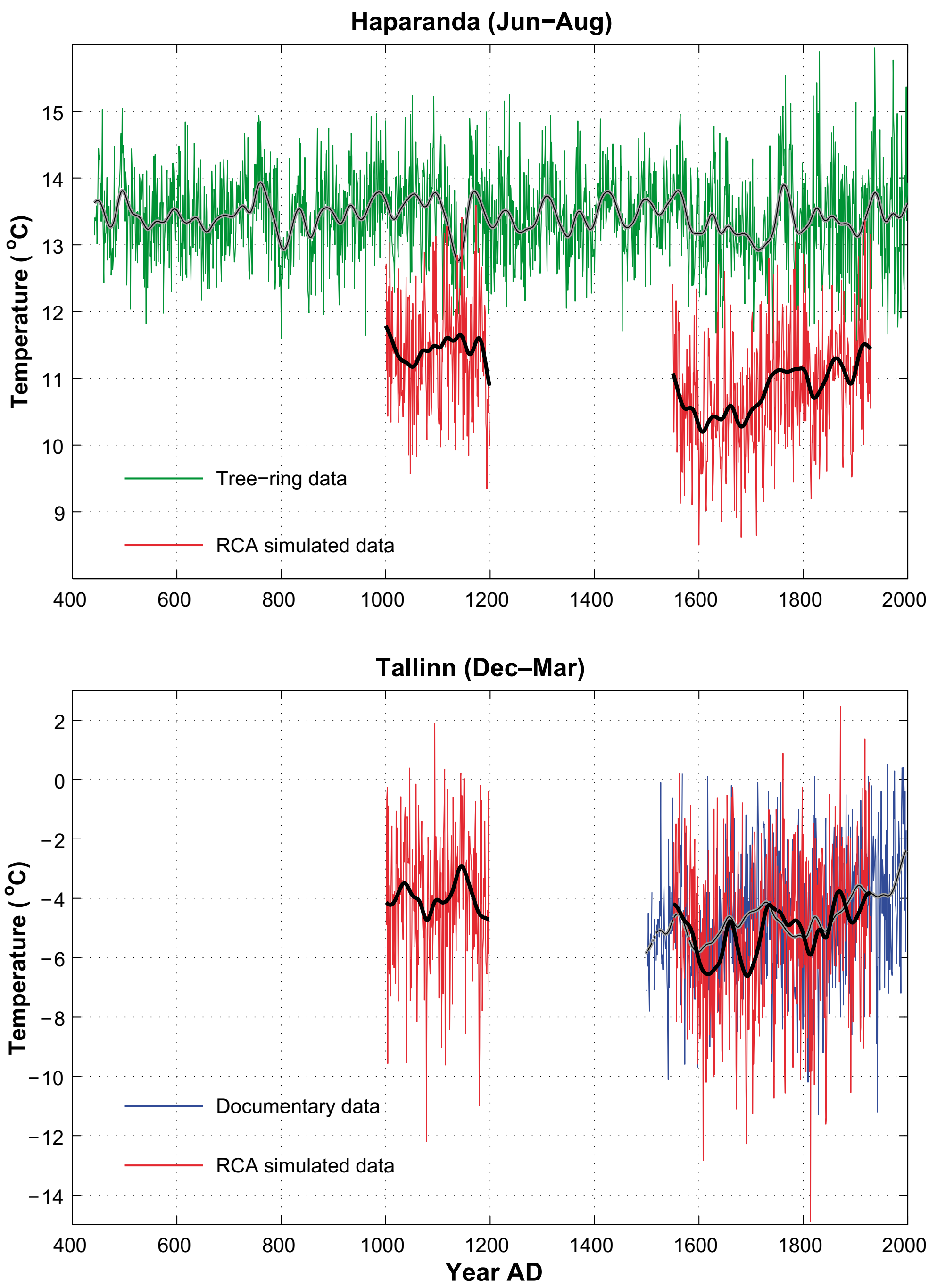

Figure 5-6. *Comparison of local temperatures simulated with RCA and temperatures reconstructed from proxy data. Upper plot: simulated (red) and reconstructed (green) June–August temperatures for Haparanda. Lower plot: simulated (red) and reconstructed (blue) December–March temperatures for Tallinn. The proxy data for summer temperatures are obtained from the Haparanda grid point in the same dataset as for the tree-ring reconstruction used in Figure 3-13. The tree-ring record is available for the period AD 442–1,970. The series is extended for 1971–2000 using instrumental data /Mitchell et al. 2004/ for the same grid point. The proxy data for winter temperatures are documentary evidence of ice break-up dates, as in Figure 3-16. Data are also shown as 30-year smoothed values.*

the standard deviation for instrumental data in the 20th century is 1.1°C. On the contrary, the long-term variations in the simulation are larger than in the reconstruction. Considering that the simulated year-to-year variations are likely somewhat too small, but the long-term variations likely somewhat too large, we argue that the RCA simulation can be used for approximately estimating the possible range of summer temperatures in Sweden for the last millennium, with relatively little risk of missing the exceptional extremes (provided that account is taken for the systematic biases in mean levels). However, statements can only be made in statistical terms without saying exactly when cold or warm extremes occurred.

For winter the reconstructed and simulated temperatures for Tallinn have nearly the same mean values in the period of overlapping data, 1550–1929 (–4.8°C in reconstruction, and –5.1°C in simulation). The standard deviation in this period is somewhat larger in the simulation (2.7°C) than in the reconstruction (2.0°C). Moreover, the total range of winter temperatures in the simulation lies between –14.9°C and +2.5°C, while reconstructed temperatures vary between –11.3°C and +0.5°C. Hence, it appears that the simulated winter temperature variance is somewhat too large for this grid point. Moreover, during the periods 1600–1650 and 1680–1720, the simulated temperatures are on average about 1°C colder than the reconstructed ones. A warming trend appears from 1850 to 1930 in both the simulation and the reconstruction. Despite the slightly too large variance, and some differences in details in the temperature evolution, the behaviour of the simulation is rather similar to reality in winter. Hence, it appears that the RCA simulation can be rather reliably used for estimating the total range of winter temperatures in Sweden for the last millennium. It seems, at least, that the RCA simulation does not show a too small range for winter temperature variations, for the Tallinn grid point and for the last half millennium.

5.5.2 Observed and simulated Stockholm daily temperatures

Here, we compare the frequency distributions of observed and simulated daily mean temperatures for Stockholm during the 1756–1929 period for each of the four seasons (Figure 5-7). The instrumental temperature data (from /Moberg et al. 2002/) have here been adjusted for a supposed warm bias in summers before 1859, as discussed by /Moberg et al. 2003/ and as used in /Moberg et al. 2005b/. Overall, the main characteristics of the distribution of the observed data are recognized also in the simulation, but there are some differences.

In winter the two distributions are quite similar. The simulation, however, has slightly more winter days with temperatures around –4°C but fewer days with temperatures around +4°C. In spring, the distribution of simulated temperatures is slightly narrower than the distribution of observational data. In particular, there are slightly more spring days with temperatures around 0°C in the simulation compared to the observations (39% vs 31%). In summer, the distribution of simulated data is clearly too narrow. Nearly all simulated summer temperatures lie in the classes centred between +9 to +18°C, whereas the majority of observed data are distributed among the classes centred between +6°C and +24°C. In particular, the simulation has too many summer days in the class at +12°C (46% compared to only 21% in the observations). Moreover, the simulation has substantially too few summer days in the warm class at +18°C (7% compared to 26% in observations). This comparison of distributions provides some more detail to the previously observed cold bias of simulated summer temperatures. In autumn, there are also some differences between the distributions. In particular, there are too many simulated days in the relatively cold class at –2°C (15% vs 9%) and too many days in the relatively warm class at +14°C (14% vs 4%).

In summary, the model simulates too many cold days and too few warm days in summer and autumn. In summer, the distribution of simulated data is also too narrow. The distributions of simulated temperatures in winter and spring are better behaved.

5.6 Data stored from the RCA simulation

Output data from the RCA simulation has been stored for several climate variables. Data are available on request from the Rossby Centre, SMHI. Please contact Rossby.Data@smhi.se for information. A list of the data stored is given in Table 5-1.

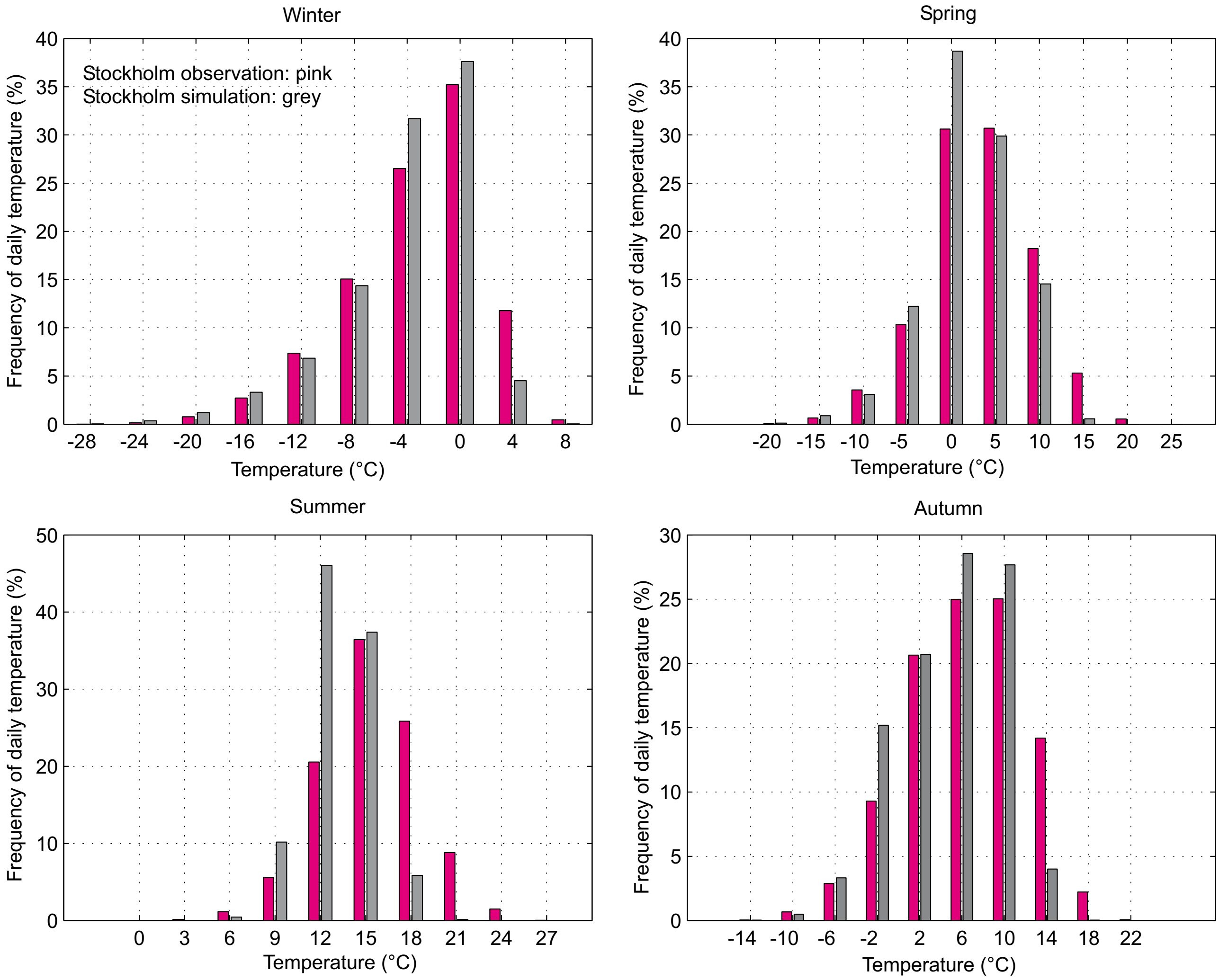

***Figure 5-7.** Frequency distributions of daily mean temperatures in Stockholm as observed (pink) during AD 1,756–1,929 and as simulated (grey) with RCA for the same period.*

Table 5-1. List of variables stored from the simulation with the regional climate model RCA3/FLAKE. Gridded data, at 1°×1° spatial resolution for the region depicted in Figure 4-1c, are available for the time periods 1000.05.01–1199.12.30, 1550.05.01–1749.12.30 and 1750.05.01–1929.12.30.

#	Name	Unit	Storage interval
1	Sea level pressure	Pa	3H
2	Geopotential height at 500 hpa	geopotential metre	24H
3	Sea surface temperature	K	24H
4	2M maximum temperature	K	24H
5	2M minimum temperature	K	24H
6	10M maximum wind speed	m/s	24H
7	U10 wind component at max wind speed	m/s	24H
8	V10 wind component at max wind speed	m/s	24H
9	Total precipitation	mm/day	24H
10	Total cloud cover (fraction, 0–1)	–	24H
11	Water run-off	mm/day	24H
12	Sea or lake ice concentration	–	24H
13	2M temperature (T2m)	K	24H
14	2M specific humidity (q2m)	kg/kg	24H
15	Grid averaged sensible heat flux (H)	W/m^2	24H
16	Grid averaged latent heat flux (LE)	W/m^2	24H
17	Fraction snow on open land (0–1)	–	24H
18	Fraction snow in forest (0–1)	–	24H
19	Fraction snow on sea ice (0–1)	–	24H
20	Latent heat flux (with unit given corresponding to evaporation)	mm/day	24H
21	Grid averaged snow water equivalents	m	24H
22	Lake surface temperature, incl. Ice and snow	K	24H
23	Lake ice depth	m	24H
24	Open land snow (snow water eq.), land-value	m	24H
25	Density of open land snow	kg/m^3	24H
26	Top soil water	m	24H
27	Deep soil water	m	24H

6 Past Swedish climate – synthesis

In this chapter, the overall aim is to illustrate the range within which climate in Sweden has likely varied during the last millennium. As the proxy data do not really have a strong enough potential for showing details (see discussion in section 3.8), the analysis here is mainly based on data from the RCA simulation. Instrumental observational evidence for the 20th century is also used. An effort is made to define the natural limits for how warm/cold or how wet/dry the climate could have been in the last millennium. The instrumental data depict the limits of variations in the 20th century, whereas the model output is used to place the observational evidence in a tentative historical perspective.

Two different types of analyses are made:

- Construction of a tentative evolution of the annual mean climate in Sweden during a large part of the last millennium by combining simulated and observational data, focusing on large-scale annual averages for temperature, precipitation and runoff for the northern and southern parts of Sweden.
- Comparison of the frequency distribution of simulated daily maximum and minimum temperatures, precipitation, runoff and evaporation in two 30-year periods that are assumed to represent unusually warm and cold conditions respectively in the last millennium. This analysis is entirely based on simulated data and is made for locations in the model domain corresponding to Forsmark and Oskarshamn.

6.1 Annual climate series for northern and southern Sweden

In this analysis Sweden is divided into a northern and a southern region, following the regionalisation used by /Lindström and Alexandersson 2004/. They used the drainage basin of the river Dalälven to divide between north (approximately 2/3 of the total area) and south. /Lindström and Alexandersson 2004/ calculated areal averages from observations of temperature, precipitation and river runoff for both parts of Sweden over the period 1901–2002. Their observational data are reproduced here and shown in the rightmost panel in Figure 6-1. These data are taken to represent the observational evidence of climate in Sweden since 1901. The simulated data from RCA are also shown in Figure 6-1, for the period 1001–1199 in the leftmost panel and AD 1,551–1,929 in the middle panel. All data are shown as anomalies from the period 1901–1929. Smoothed data depicting variations slower than about 30 years are also shown. The use of anomalies from a common time period means that the problem with systematic biases (errors in the mean level) in the simulated data are largely eliminated in the comparison between the simulation and the observations. Table 6-1 provides a comparison of the total range of variability in the simulation and the observations for all three variables and for both regions.

6.1.1 Temperature

In the observations, most years after 1929 have been warmer than the 1901–1929 average. The warmest years cluster in the 1930's–1940's and after around 1990. The overall level of warmth has been rather similar in both these 20th century periods, but in both regions the very warmest years occurred in the 1930's. In the simulation, the period from 1551 to 1900 is notably cold, with the smoothed 30-year variations being constantly below the 1901–1929 average in both regions. Hence, the 20th century stands out as a warm period. The minimum of the smoothed temperatures occurs in the first decade of the 17th century, and reaches down to an anomaly of –1.8°C in the northern region and –1.4°C in the southern part. Given that the warmest levels of the smoothed curves for the observational data are about +1°C for both regions, the

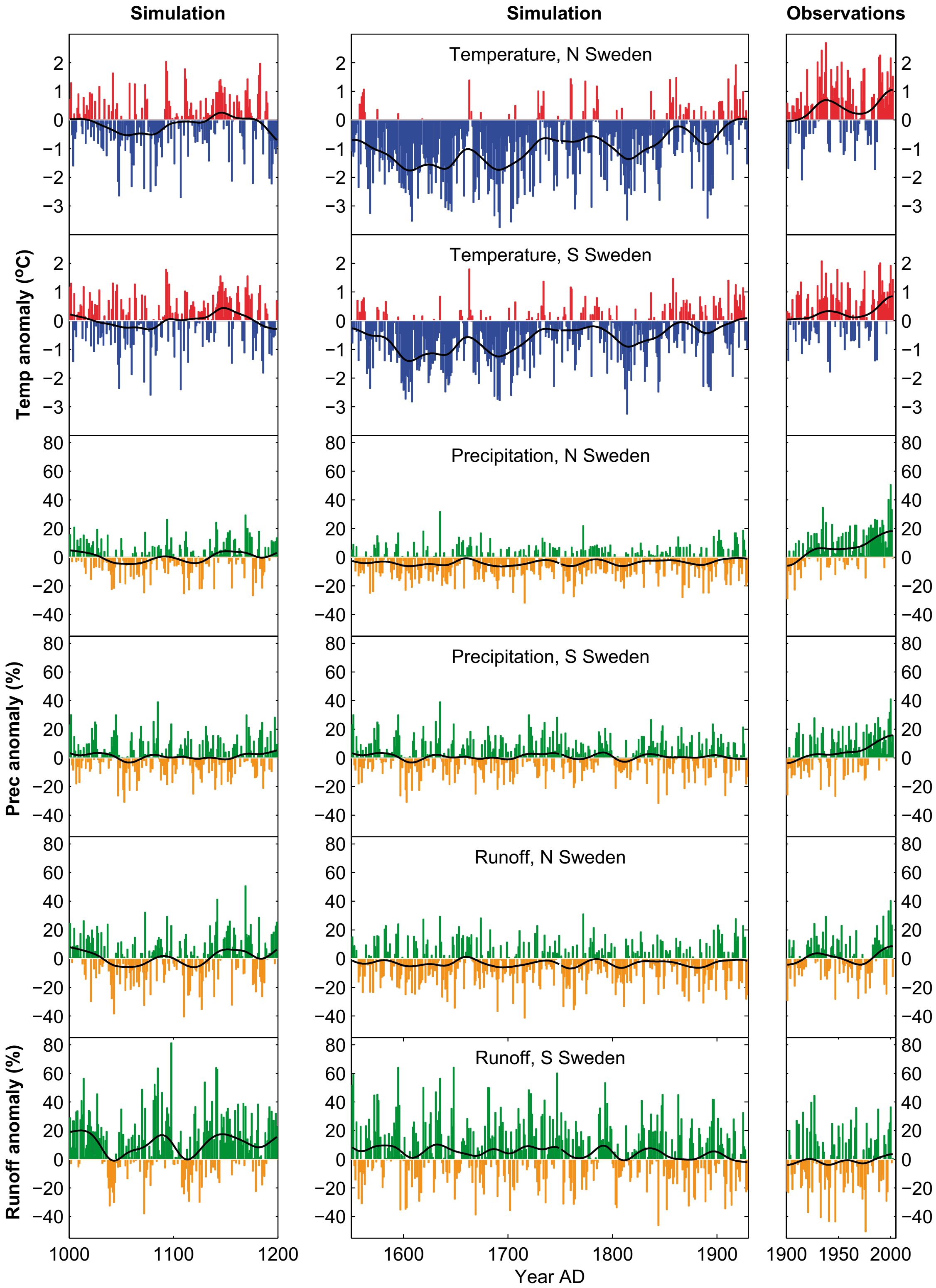

***Figure 6-1**. Tentative evolution of climate in northern and southern Sweden during the last millennium. Simulated data (AD 1,001–1,199 and AD 1,551–1,929) are obtained with RCA. Observational data (1901–2002) are from /Lindström and Alexandersson 2004/. All data are shown as anomalies from the respective mean values during the period 1901–1929. 30-year smoothed data are also shown. Annual mean temperatures and annual totals of precipitation and runoff are used.*

Table 6-1. Observed averages of annual mean temperatures (T), annual precipitation totals (P), and annual runoff totals (Q) during 1901–1929 for northern and southern Sweden are given in the left column. The other four columns show the minimum and maximum deviations (anomalies) from the 1901–1929 averages, as found in the observations (1901–2002) and in the RCA simulations (1001–1199 and 1551–1929).

	Observed 1901–1929 average	Observed min anomaly	Simulated min anomaly	Observed max anomaly	Simulated max anomaly
T north	–0.1°C	–2.1°C	–3.8°C	+2.8°C	+2.0°C
T south	+5.4°C	–1.8°C	–3.3°C	+2.1°C	+1.8°C
P north	566 mm	–29%	–32%	+51%	32%
P south	621 mm	–27%	–32%	+41%	39%
Q north	424 mm	–29%	–42%	+40%	51%
Q south	295 mm	–51%	–46%	+44%	81%

combined model and observational data suggest that the total warming from the coldest 30-year period during the last five centuries in Sweden has been on the order of 2.5°C for annual mean temperatures. Several individual years in the period 1551–1900 in the simulation were notably colder than the coldest observed years in the 20th century. The first 200 years of the RCA simulation have temperatures that fluctuate around the 1901–1929 mean level in both regions. Given that the global model used to drive the regional model was not in equilibrium in the early period, but instead about 0.5°C too warm on a global level, it is likely that also the simulated temperatures for Sweden are slightly too warm in the period 1001–1199. It is not possible to state exactly how much too warm the early simulation is, but the simulated temperatures for Sweden before 1200 should probably be reduced by about the same amount as the global mean bias . This would lead to simulated temperatures during 1001–1199 being on average slightly colder than the 1901–1929 average.

It is tempting to draw the conclusion that the 20th century in Sweden was the warmest century in the last millennium, with the last 70 years standing out as a particularly warm period. However, it is not really possible to verify this from analyses of temperature proxy data. Detailed proxy-data based temperature reconstructions for the entire millennium are only available for warm-season temperatures in northern Sweden. These data (see section 3.4) indicate that some previous periods may have been as warm as much of the 20th century, or even slightly warmer. As no proxy data for winter temperatures are available before 1500, it is not possible to judge what the annual mean temperatures are likely to have been before this time. However, available proxy data for summer and winter temperatures for the last five centuries support the conclusion that annual mean temperatures for Sweden in the 20th century, in particular the last 70 years, have been unusually warm in at least a 500-year context.

6.1.2 Precipitation

The observed precipitation shows an increasing trend during the 20th century. The wettest year was 2000. For both regions, the 20th century stands out as the wettest century when compared with the simulated data. In particular the period since the late 1970's is characterized by an unusual sequence of wet years. However, apart from this most recent wet period, the rest of the 20th century does not stand out as unique as there are indications of similar conditions in the earliest 200-year period. It appears that data observed in the 20th century captures rather well the entire range of variability in annual precipitation totals during the last millennium.

6.1.3 Runoff

For runoff, the comparison between observed and simulated data is somewhat complicated because of different ways of producing the data. The observational series is based on discharge measurements in a number of rivers, whereas runoff in the simulation is calculated as the residual between modelled precipitation and evaporation, taking account also for storage in the soil. The way of presenting the data as anomalies in percent from the 1901–1929 average makes it technically possible to compare the data, but caution should be taken in the interpretation of results.

/Lindström and Alexandersson 2004/ noted that although the observed runoff had increased over the 20th century, the increase was not statistically significant at the 5% level. The increase in runoff is more pronounced in the northern part of Sweden than in the southern part. In the northern region, most years after 1982 have been above the 1901–1929 level, but a similar behaviour is not observed in the south. Compared to the simulation, the 20th century in the southern region appears to have had a somewhat smaller level of runoff (approximately 5% on average) than the period 1551–1750. The earliest 200 years in the simulation appear to have had even higher runoff values than 1551–1750, but doubt must be cast on the early values given the problem with the driving global model not being in equilibrium in this period. But even if the earliest simulated data are rejected, it appears for the southern region that the highest runoff value observed in the 20th century is smaller than the earlier simulated data. The situation is different in the northern part, where the high runoff value in 2000 is higher than all simulated values during 1551–1929. In summary, it appears that there have occurred years in the past centuries with higher annual runoff values than in the 20th century in the southern part of Sweden, but possibly not in the northern part.

6.2 Frequency distribution of simulated daily temperatures, precipitation, runoff and evaporation at Forsmark and Oskarshamn in a warm and a cold 30-year period

This section provides a perception of the tentative difference in daily climate statistics, between two 30-year periods that are considered as unusually warm and cold in a context of the last millennium. The analysis is made for the locations in the model domain that correspond to where Forsmark and Oskarshamn are located. Five climate variables are analysed; daily minimum temperatures (Tmin), daily maximum temperatures (Tmax), daily precipitation, daily runoff and daily evaporation.

The period AD 1,121–1,150 is chosen to represent warm conditions, while the period 1601–1630 represents cold conditions. In southern Sweden (using the data in Figure 6-1), the annual mean temperature anomaly (compared to 1901–1929) is +0.3°C in the warm period and –1.4°C in the cold period. Hence, the mean temperature difference between the two periods is about 1.7°C. This is about twice as much as the observed change of the 20th century. The mean level of the warm period is approximately 0.1°C below the average anomaly after 1930 in the observations. It can thus be said that the chosen warm period is roughly representative for the post-1930 average climate. The chosen cold period has an annual mean temperature anomaly that is about the same as the coldest observed individual years in the 20th century (1902, 1940–1942, 1985 and 1987).

The use of only simulated data facilitates a direct comparison of statistics in the warm and cold period. It would be more difficult to compare, for example, a cold period in the simulation with a warm period in the observations. Such a comparison would require that account is taken not only for the average bias in the simulation, but also for errors in the frequency distribution of simulated data (as evidenced for the case of Stockholm in Figure 5-7).

Frequency distributions for each of the five climate variables, for each of the two periods, and for both sites, are compared for each of the four seasons in Figures 6-2 to 6-10. In each histogram, the bars show the percentage of days sorted into 10 classes. For Tmin, Tmax and evaporation, all days in a 30-year period are used for calculating the histograms. In these cases, the sum of the 10 bars is always 100% for each period. In the case of precipitation and runoff, the histograms are based only on days with values higher than 1 mm (= 'wet' days). The percentage of days with values less than 1 mm (= 'dry' days) is indicated with numbers written in the upper right corner in each graph. For these two variables, the sum of the percentages of wet days (given by the bars) plus the percentage of dry days (given by the written numbers) is 100%. The numbers in the histograms are also presented in Table 6-2.

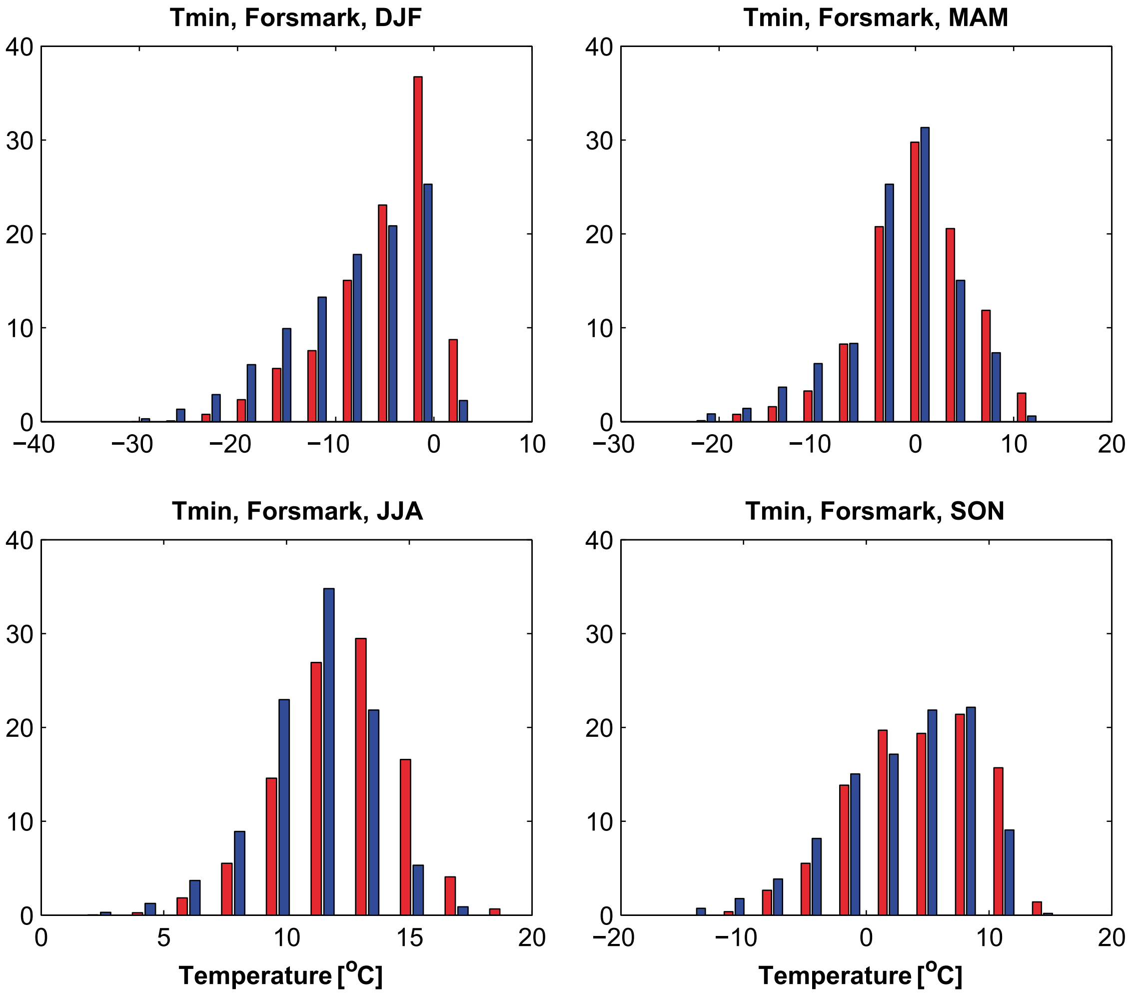

***Figure 6-2**. Frequency distributions of RCA-simulated daily minimum temperatures in a warm (red bars) and a cold (blue bars) 30-year period (AD 1,121–1,150 and 1,601–1,630) for the model grid point corresponding to Forsmark in winter, spring, summer and autumn. The numbers on the vertical axis give the percentage of days in each class.*

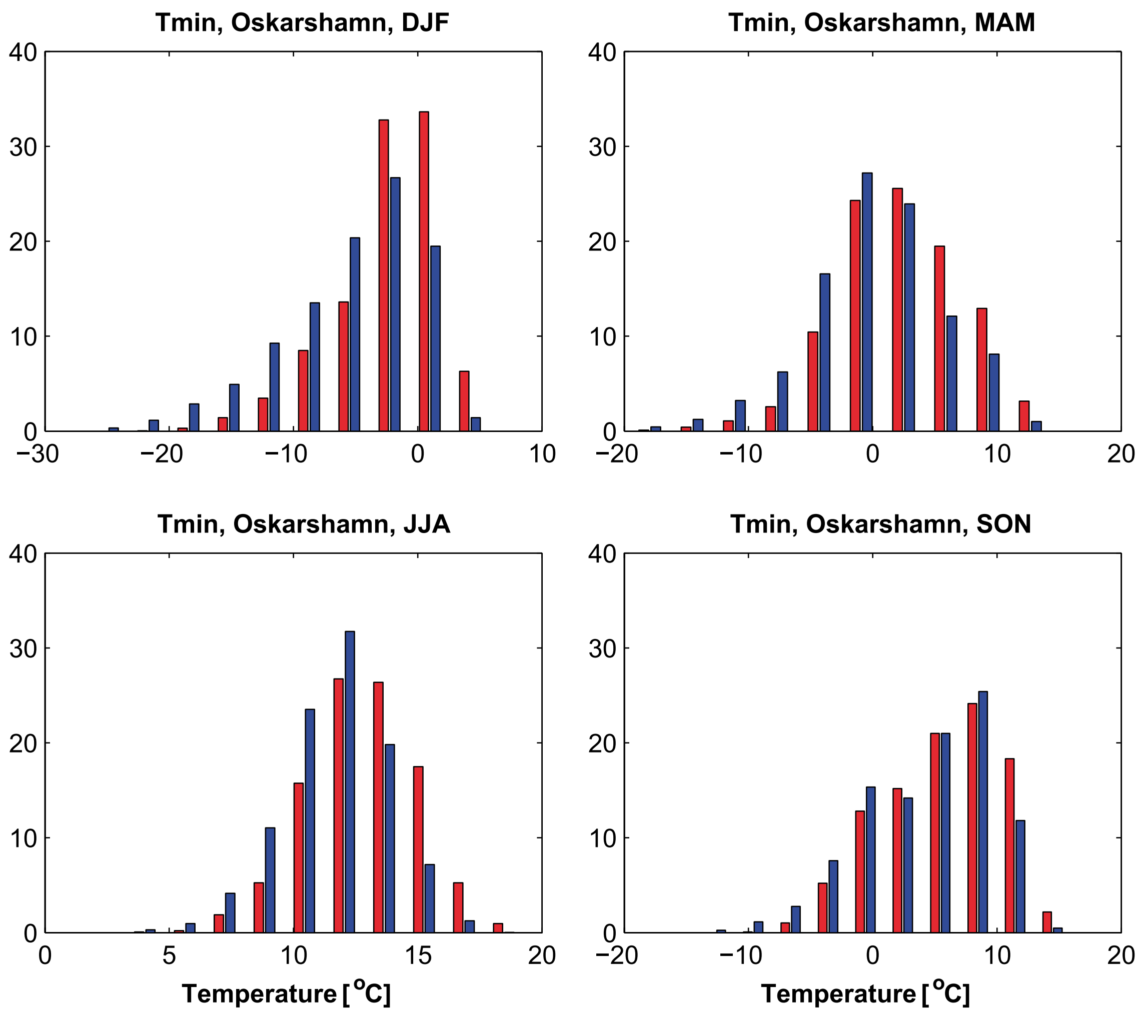

***Figure 6-3**. Same as Figure 6-2, but for Oskarshamn.*

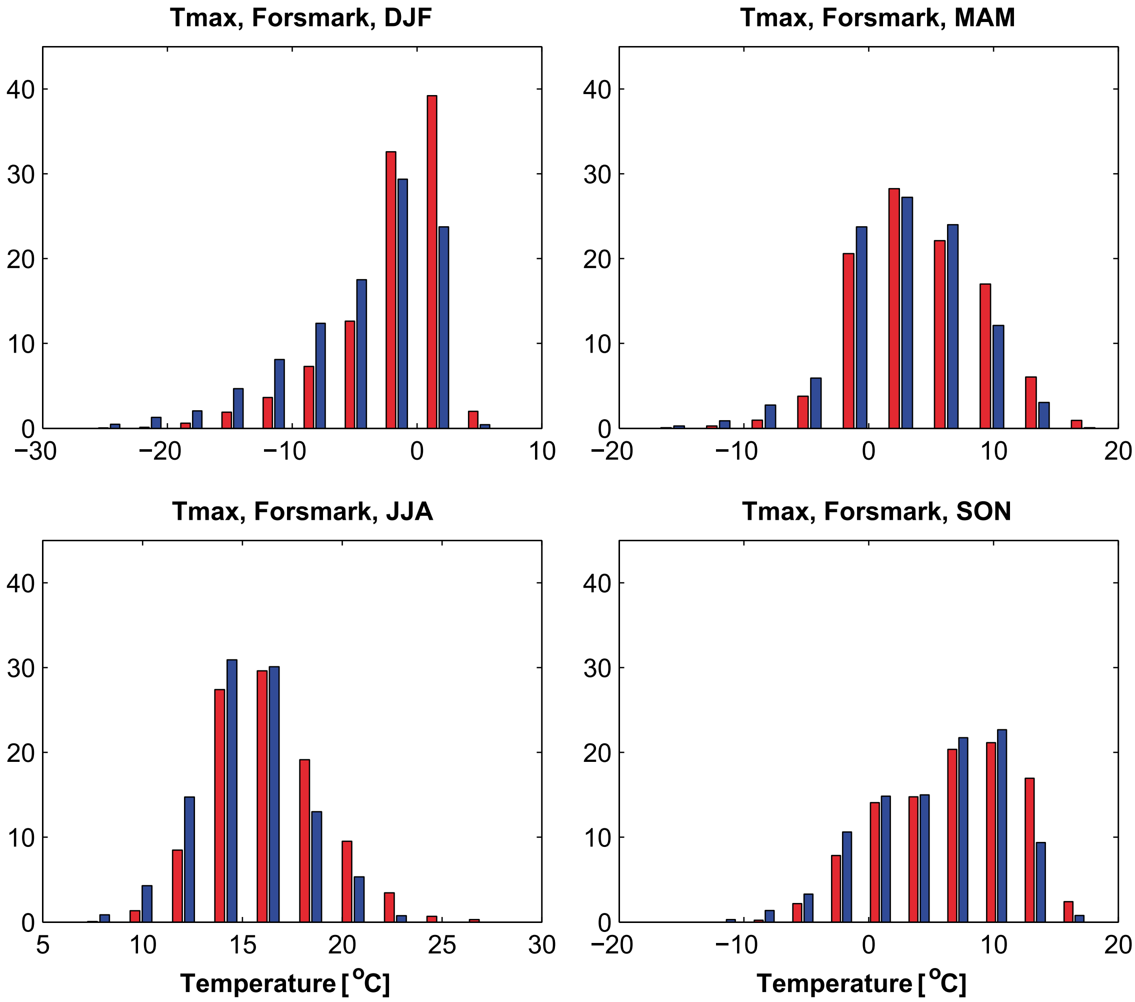

Figure 6-4. *Frequency distributions of RCA-simulated daily maximum temperatures in a warm (red bars) and a cold (blue bars) 30-year period (AD 1,121–1,150 and 1,601–1,630) for the model grid point corresponding to Forsmark in winter, spring, summer and autumn. The numbers on the vertical axis give the percentage of days in each class.*

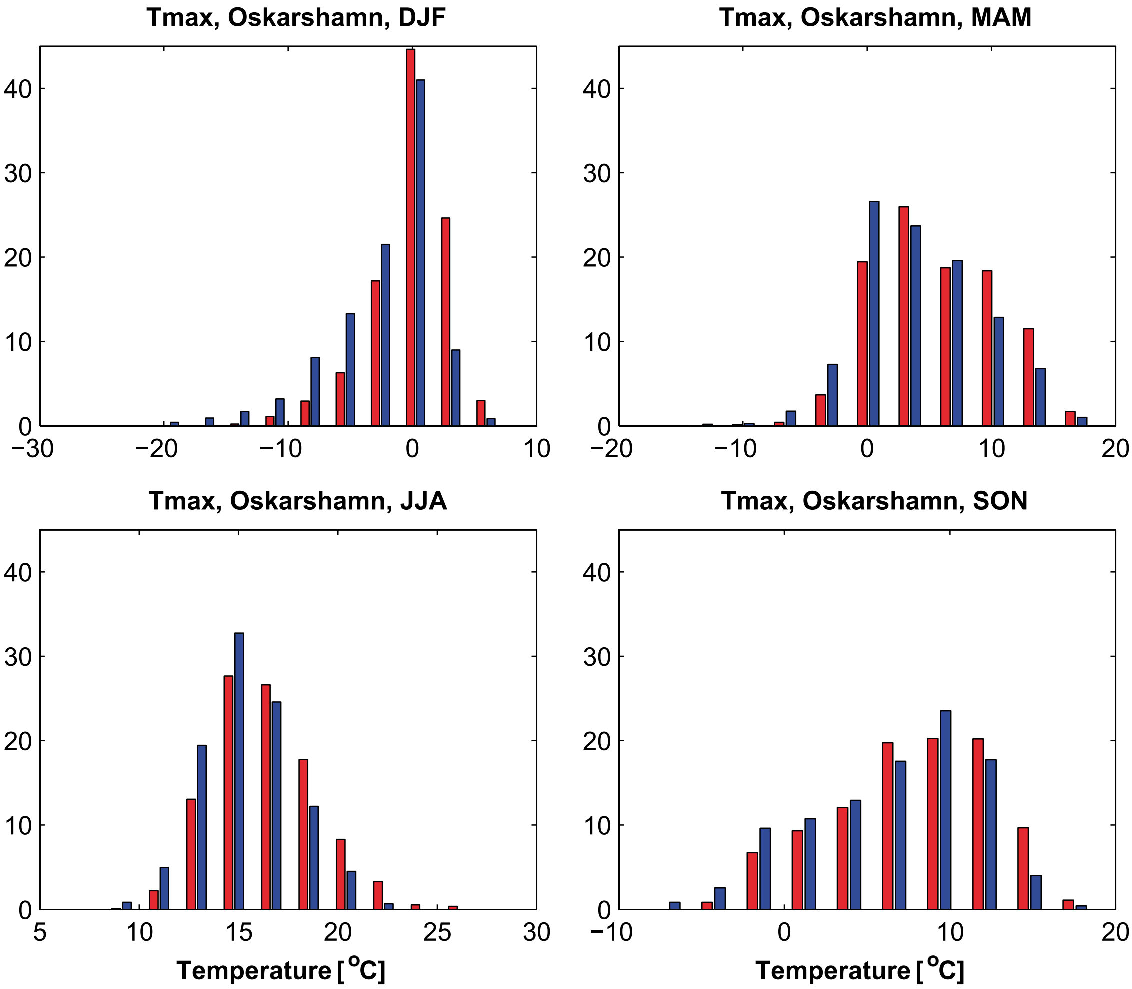

***Figure 6-5**. Same as Figure 6-4, but for Oskarshamn.*

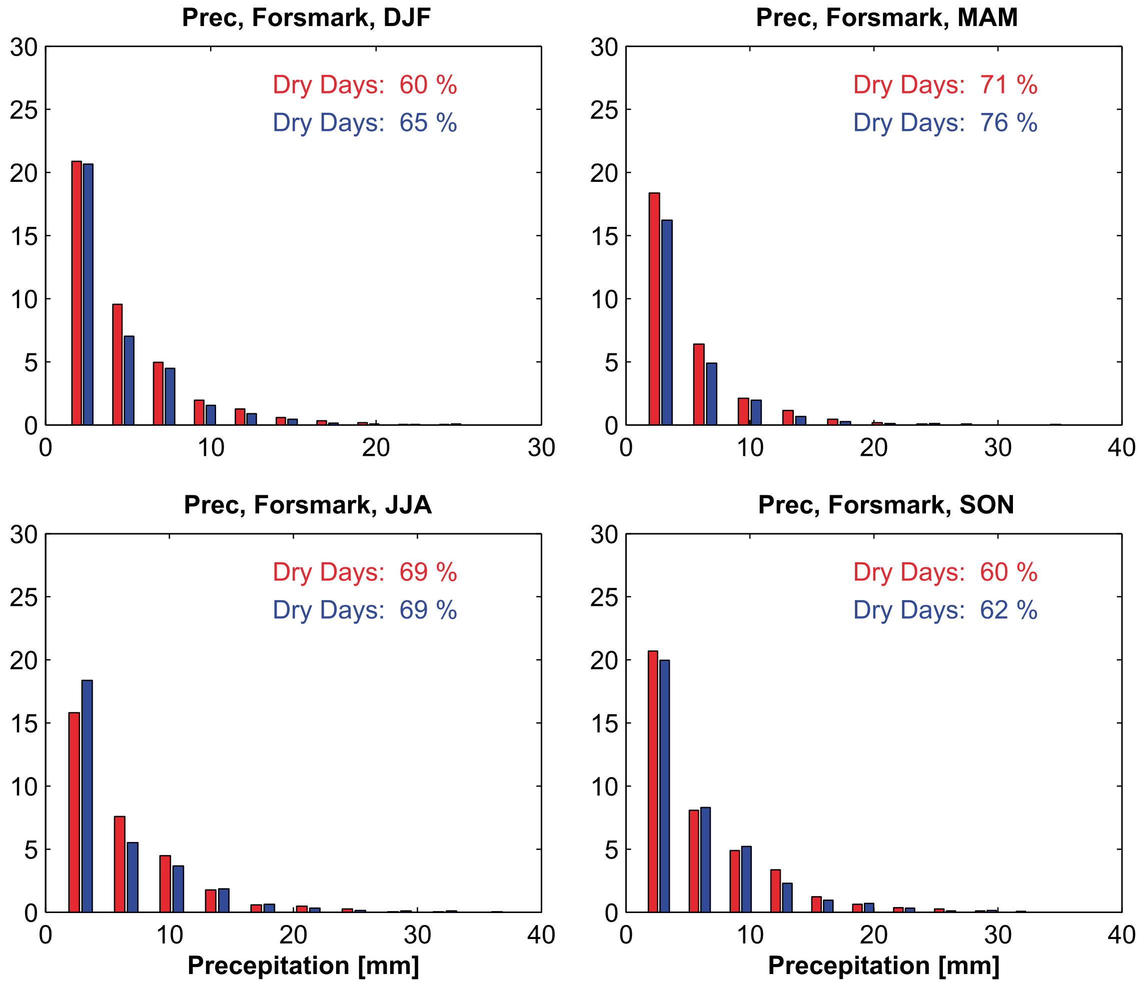

***Figure 6-6**. Frequency distributions of RCA-simulated daily precipitation totals in a warm (red bars) and a cold (blue bars) 30-year period (AD 1,121–1,150 and 1,601–1,630) for the model grid point corresponding to Forsmark in winter, spring, summer and autumn. The distributions are shown for days with precipitation > 1 mm. The numbers on the vertical axis give the percentage of days in each class. The percentage of dry days (< 1 mm) is indicated with numbers in the upper right corners. The upper red (lower blue) value is for the warm (cold) period.*

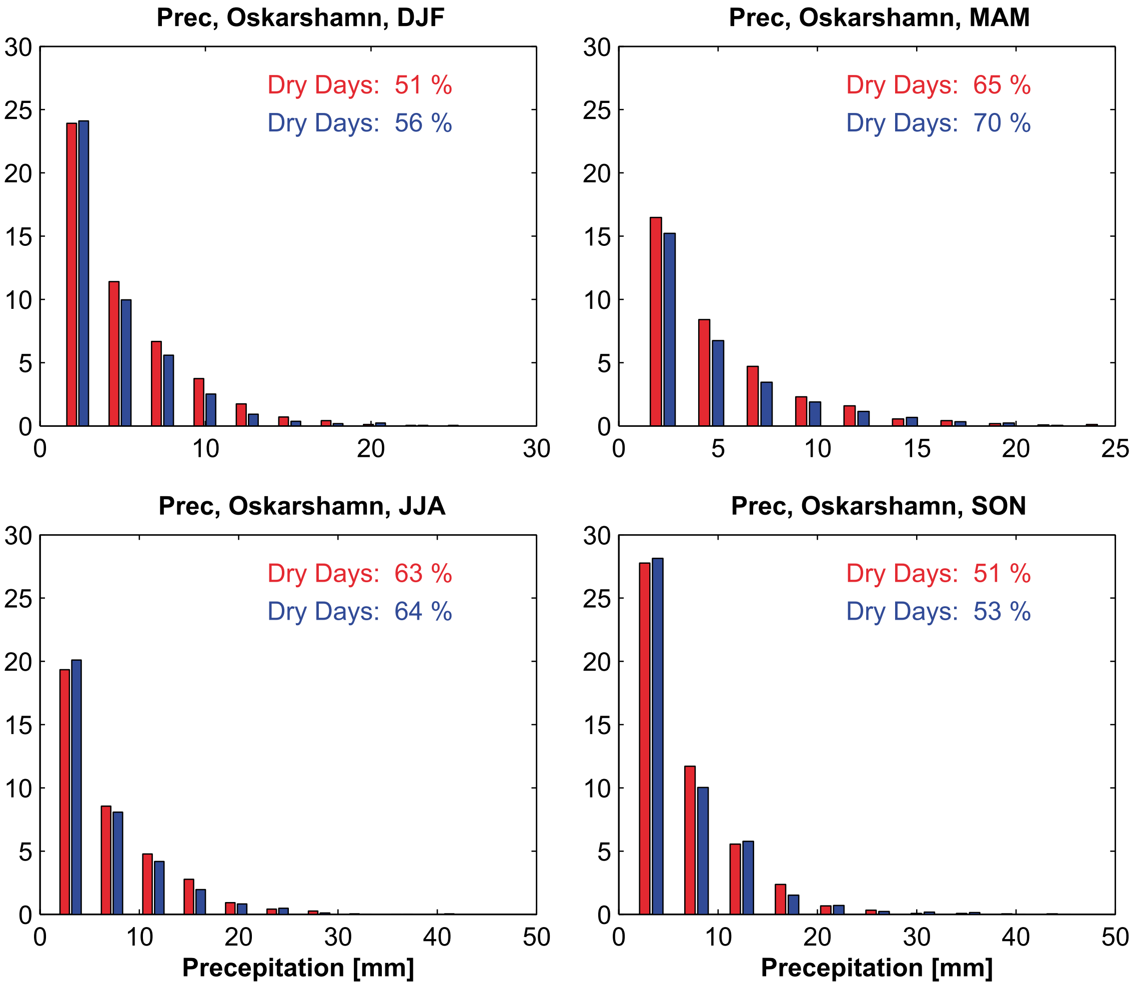

***Figure 6-7**. Same as Figure 6-6, but for Oskarshamn.*

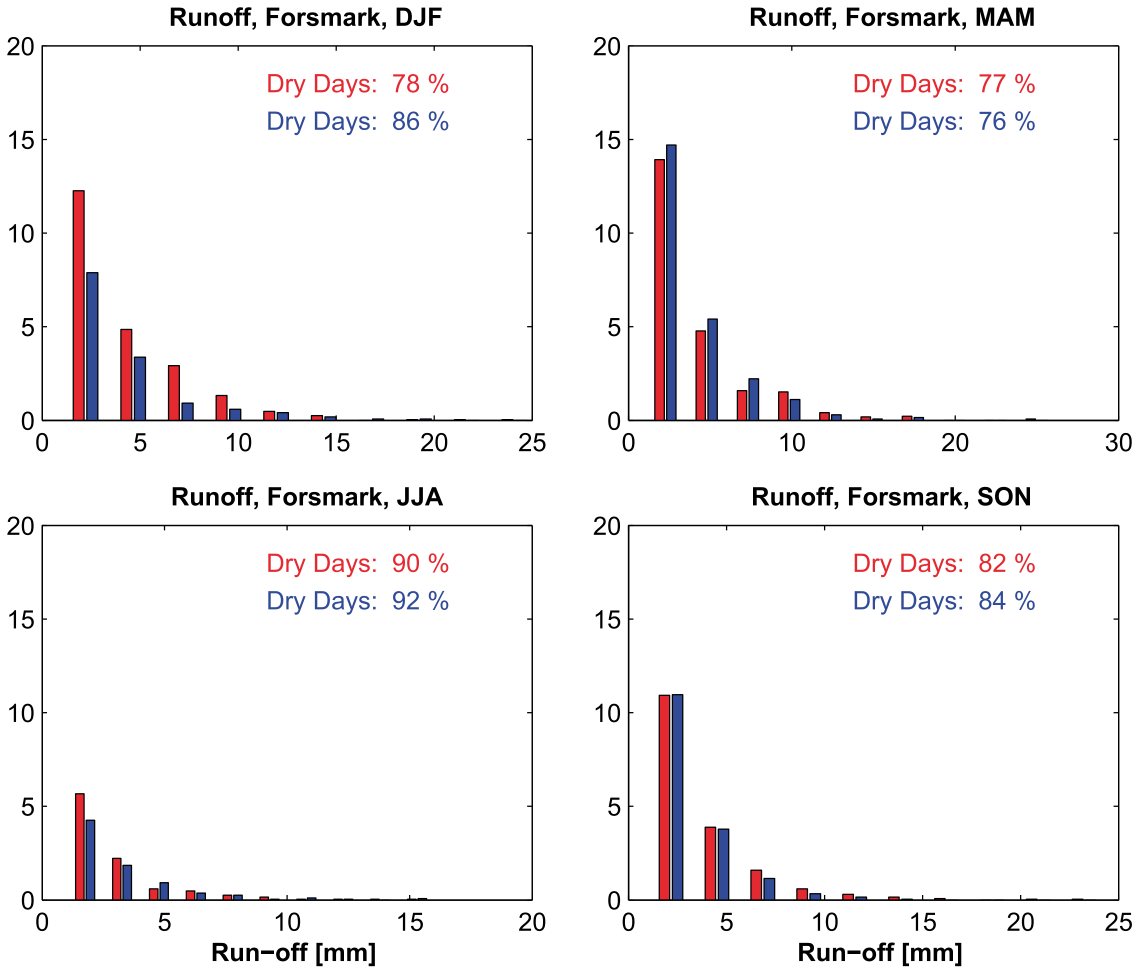

***Figure 6-8**. Frequency distributions of RCA-simulated daily runoff totals in a warm (red bars) and a cold (blue bars) 30-year period (AD 1,121–1,150 and 1,601–1,630) for the model grid point corresponding to Forsmark in winter, spring, summer and autumn. The distributions are shown for days with runoff > 1 mm. The numbers on the vertical axis give the percentage of days in each class. The percentage of dry days (< 1 mm) is indicated with numbers in the upper right corners. The upper red (lower blue) value is for the warm (cold) period.*

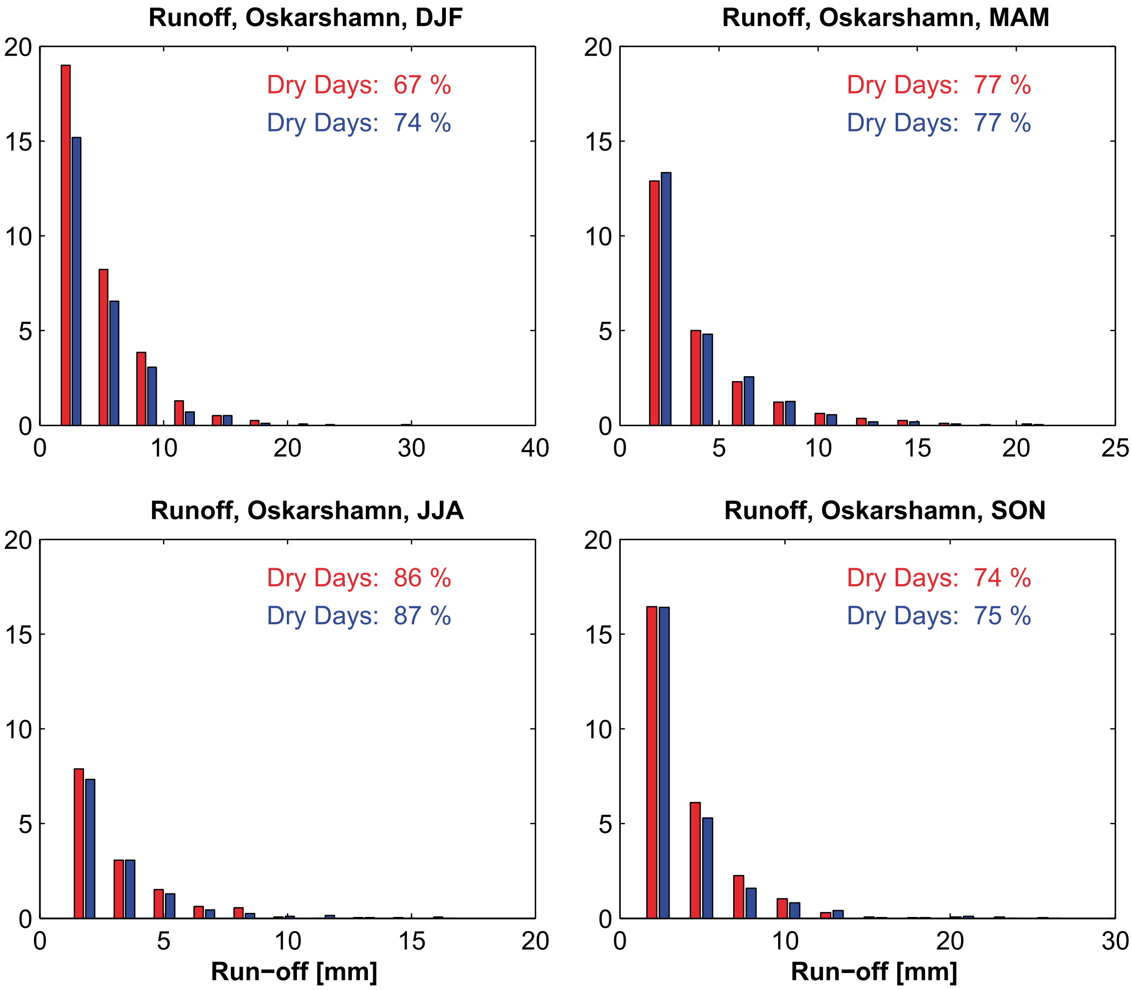

Figure 6-9*. Same as Figure 6-8, but for Oskarshamn.*

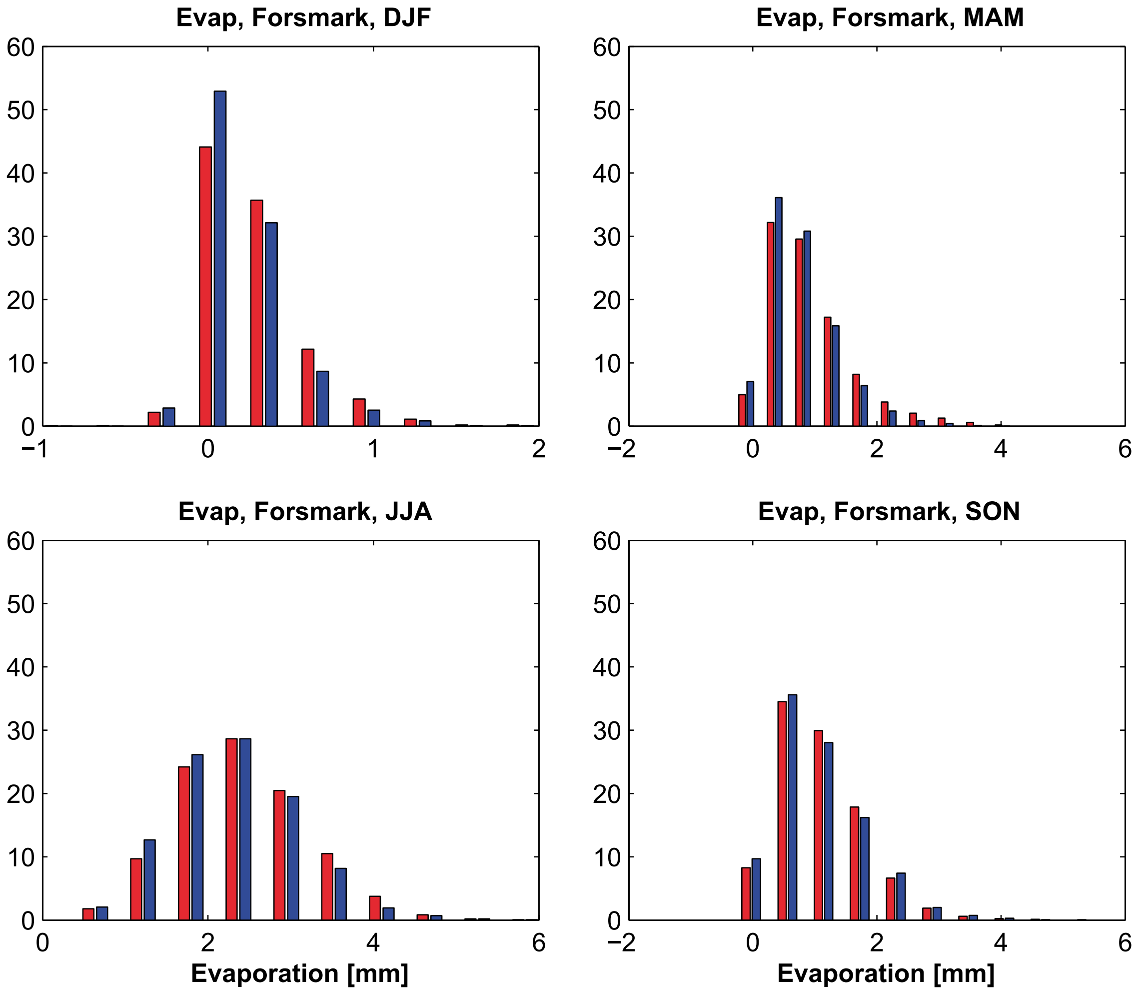

Figure 6-10*. Frequency distributions of RCA-simulated daily evaporation totals in a warm (red bars) and a cold (blue bars) 30-year period (AD 1,121–1,150 and 1,601–1,630) for the model grid point corresponding to Forsmark in winter, spring, summer and autumn. The numbers on the vertical axis give the percentage of days in each class.*

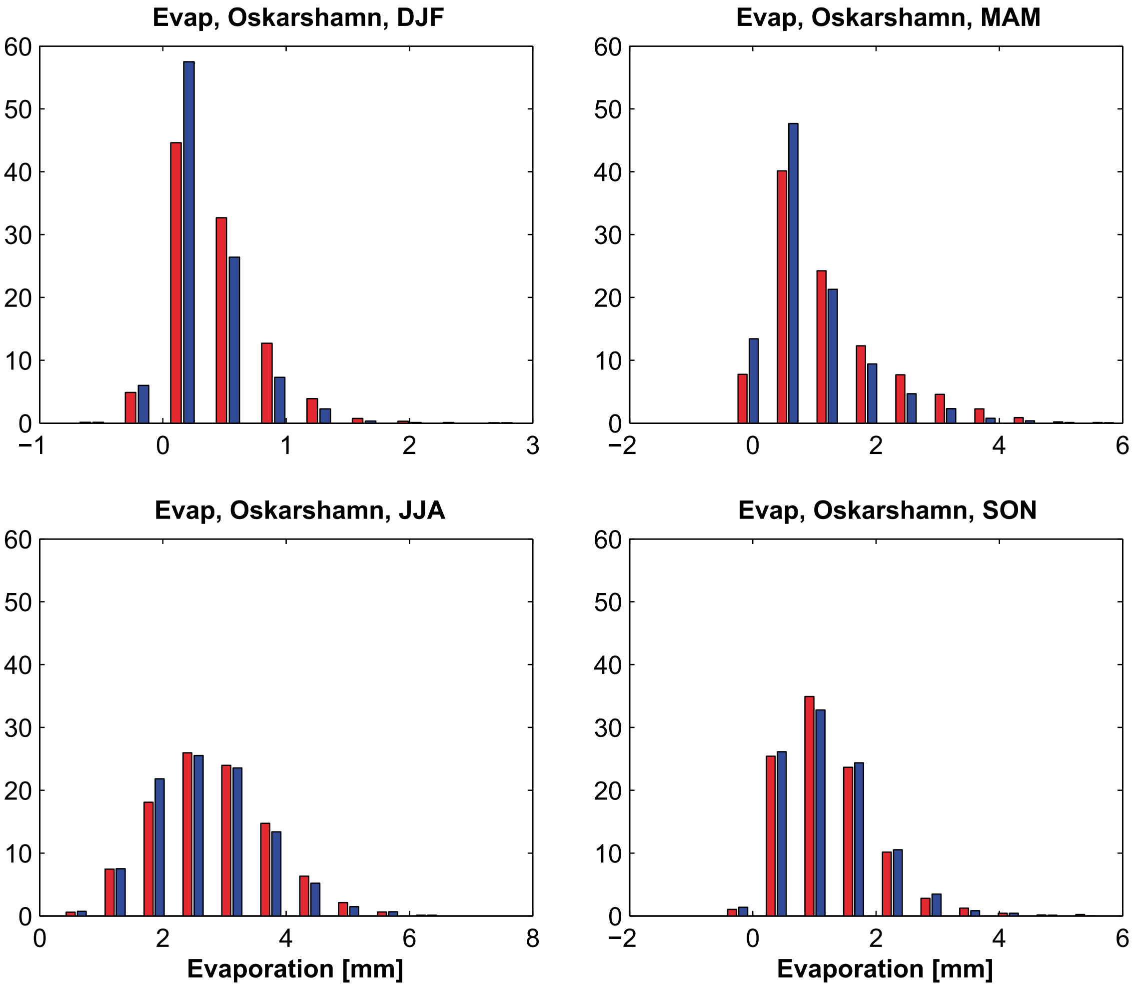

***Figure 6-11**. Same as Figure 6-10, but for Oskarshamn.*

6.2.1 Daily climate histograms – results

The differences in the distributions of daily climate data, between the warm and cold period, is most clearly seen in the winter season. There is a shift of the entire distribution of daily maximum and minimum temperatures, such that days with very cold temperatures well below freezing are much more common in the cold period. The warm period has instead many more winter days with temperatures near or above freezing. There are also clear differences between the warm and cold period reflected in the hydrological variables in winter. The number of days with no precipitation or no runoff (or very small values) is higher in the cold period. Moreover, the amount of winter precipitation is larger in the warm period, which is reflected as higher frequency bars (more days) for most classes of daily precipitation amounts. Similarly, the frequencies of daily runoff values are generally higher in the warm period. In addition, the number of days when evaporation is near zero is markedly larger in the cold period.

These differences in temperature and hydrological variables between the warm and cold period in the RCA simulation can be largely understood in terms of different circulation patterns. As mentioned in section 4.3, /Gouirand et al. 2006/ investigated this aspect in the global model ECHO-G, which provides the boundary conditions for RCA. Recall that they found that the coldest period in winter (1590–1650, which includes the 30-year period 1601–1630 analysed in RCA) is characterized by a systematic anomaly in the North Atlantic Oscillation, such that this atmospheric mode on average is in its negative phase. This implies less advection of mild and moist air from the North Atlantic to Sweden, and instead more influence of high pressure situations. This in turn favours lower winter temperatures and drier conditions, which is in agreement with the climate statistics in the RCA simulation.

There is also a difference seen in spring between the warm and cold period, both in the temperature and precipitation statistics. The distribution of daily temperature minima is shifted towards colder temperatures in the cold period, and towards warmer temperatures in the warm period. One consequence of this is that the warm period has more days with temperatures above freezing. There are also many more days with relatively high temperature maxima (above +10°C) in the warm period. Just like in winter, there are more dry days in spring in the cold period and higher frequencies throughout the distribution of daily precipitation amounts. The number of days with no runoff in spring is about the same in both periods, but, at least at Forsmark, there is a tendency for higher frequencies of daily runoff values that are less than 10 mm/day in the cold period. These higher frequencies of small to moderate runoff amounts in spring may reflect that there is more snow melting in spring in the cold period, whereas snow can melt earlier in the year in the warm period.

The summer season also shows clear differences as regards the distribution of daily temperatures. There are markedly higher frequencies of days with warm summer temperatures in the warm period, and accordingly more days with cold summer temperatures in the cold period. Less clear differences are seen in the hydrological variables in summer, but there is a tendency for higher frequencies of moderate precipitation events (about 5–20 mm/day) in the warm period at both Forsmark and Oskarshamn, but lower frequencies of low precipitation events (< ~ 5 mm/day). The number of dry days in summer is about the same in the two periods. Taken together, this implies that summer rainfall is more intense in the warm period, although it does not rain more often often.

Also autumn shows a shift in the temperature distribution, towards more warm days in the warm period and more cold days in the cold period. There are, however, no clear and systematic changes in the distributions of the three hydrological variables.

Table 6-2. Frequency distributions of RCA-simulated daily minimum and maximum temperatures, precipitation, runoff and evaporation during the warm 30-year period AD 1,121–1,150 and the cold 30-year period AD 1,601–1,630. The numbers tabulated here are the same data as presented graphically in Figures 6-2 to 6-11. The numbers in the first column in each part of the table give the central values in each class.

Tmin, Forsmark

DJF			MAM			JJA			SON		
Tmin	Warm	Cold	Tmin	Warm	Cold	Tmin	Warm	Cold	Tmin	Warm	Cold
–29.9	0.0	0.3	–21.3	0.1	0.8	2.4	0.0	0.3	–13.9	0.0	0.7
–26.3	0.1	1.3	–17.7	0.8	1.4	4.2	0.3	1.3	–10.8	0.4	1.8
–22.7	0.8	2.9	–14.1	1.6	3.7	6.0	1.9	3.7	–7.6	2.7	3.9
–19.1	2.3	6.1	–10.4	3.3	6.2	7.8	5.5	8.9	–4.5	5.5	8.2
–15.5	5.7	9.9	–6.8	8.3	8.3	9.7	14.6	23.0	–1.4	13.9	15.0
–11.9	7.6	13.3	–3.2	20.8	25.3	11.5	26.9	34.8	1.8	19.7	17.2
–8.3	15.0	17.8	0.5	29.8	31.3	13.3	29.5	21.9	4.9	19.4	21.9
–4.7	23.1	20.9	4.1	20.6	15.0	15.1	16.6	5.3	8.1	21.4	22.2
–1.1	36.7	25.3	7.7	11.9	7.3	16.9	4.1	0.9	11.2	15.7	9.1
2.5	8.7	2.3	11.3	3.0	0.6	18.8	0.7	0.0	14.4	1.4	0.2

Tmin, Oskarshamn

DJF			MAM			JJA			SON		
Tmin	Warm	Cold	Tmin	Warm	Cold	Tmin	Warm	Cold	Tmin	Warm	Cold
–24.9	0.0	0.3	–17.9	0.1	0.4	4.0	0.1	0.3	–12.6	0.0	0.3
–21.7	0.0	1.2	–14.5	0.4	1.2	5.6	0.2	1.0	–9.6	0.1	1.2
–18.5	0.3	2.9	–11.1	1.1	3.2	7.2	1.9	4.2	–6.6	1.0	2.8
–15.2	1.4	4.9	–7.7	2.6	6.2	8.8	5.3	11.0	–3.6	5.2	7.6
–12.0	3.5	9.3	–4.3	10.4	16.6	10.4	15.7	23.5	–0.6	12.8	15.3
–8.7	8.5	13.5	–0.9	24.3	27.2	12.0	26.7	31.7	2.4	15.2	14.2
–5.5	13.6	20.4	2.5	25.6	23.9	13.7	26.4	19.8	5.4	21.0	21.0
–2.3	32.8	26.7	5.9	19.5	12.1	15.3	17.5	7.2	8.5	24.2	25.4
1.0	33.6	19.5	9.3	12.9	8.1	16.9	5.3	1.3	11.5	18.3	11.8
4.2	6.3	1.4	12.7	3.2	1.0	18.5	1.0	0.0	14.5	2.2	0.5

Tmax, Forsmark

DJF			MAM			JJA			SON		
Tmax	Warm	Cold	Tmax	Warm	Cold	Tmax	Warm	Cold	Tmax	Warm	Cold
–24.7	0.0	0.5	–15.7	0.1	0.3	7.8	0.1	0.9	–11.5	0.0	0.3
–21.4	0.1	1.3	–12.1	0.3	0.9	9.9	1.3	4.3	–8.4	0.2	1.4
–18.1	0.6	2.0	–8.4	1.0	2.7	12.1	8.5	14.7	–5.3	2.2	3.3
–14.8	1.9	4.7	–4.8	3.8	5.9	14.2	27.4	30.9	–2.2	7.9	10.6
–11.5	3.6	8.1	–1.1	20.6	23.7	16.3	29.6	30.1	0.9	14.1	14.9
–8.2	7.3	12.4	2.6	28.3	27.2	18.4	19.2	13.0	4.0	14.8	15.0
–4.9	12.6	17.5	6.2	22.1	24.0	20.6	9.5	5.3	7.1	20.4	21.7
–1.6	32.6	29.4	9.9	17.0	12.1	22.7	3.4	0.7	10.2	21.2	22.7
1.7	39.2	23.7	13.5	6.0	3.0	24.8	0.7	0.0	13.4	17.0	9.4
5.0	2.0	0.4	17.2	0.9	0.1	26.9	0.3	0.0	16.5	2.4	0.8

Tmax, Oskarshamn											
DJF			**MAM**			**JJA**			**SON**		
Tmax	**Warm**	**Cold**	**Tmax**	**Warm**	**Cold**	**Tmax**	**Warm**	**Cold**	**Tmax**	**Warm**	**Cold**
–19.6	0.0	0.4	–13.3	0.0	0.2	9.1	0.1	0.9	–7.0	0.0	0.9
–16.7	0.0	0.9	–10.0	0.2	0.3	11.0	2.2	5.0	–4.3	0.9	2.6
–13.9	0.2	1.7	–6.6	0.4	1.7	12.9	13.1	19.4	–1.6	6.7	9.6
–11.1	1.1	3.2	–3.3	3.7	7.3	14.8	27.7	32.7	1.2	9.3	10.7
–8.2	2.9	8.1	0.1	19.4	26.6	16.7	26.6	24.6	3.9	12.1	12.9
–5.4	6.3	13.3	3.4	26.0	23.7	18.5	17.8	12.2	6.6	19.7	17.6
–2.6	17.2	21.5	6.8	18.7	19.6	20.4	8.3	4.5	9.4	20.3	23.6
0.3	44.6	41.0	10.1	18.4	12.9	22.3	3.3	0.7	12.1	20.2	17.7
3.1	24.6	9.0	13.5	11.5	6.8	24.2	0.6	0.0	14.8	9.7	4.0
5.9	3.0	0.9	16.8	1.7	1.0	26.1	0.4	0.0	17.5	1.1	0.4

Prec, Forsmark											
DJF			**MAM**			**JJA**			**SON**		
Prec	**Warm**	**Cold**	**Prec**	**Warm**	**Cold**	**Prec**	**Warm**	**Cold**	**Prec**	**Warm**	**Cold**
2.2	20.9	20.7	2.8	18.4	16.2	2.8	15.8	18.4	2.7	20.7	20.0
4.7	9.6	7.0	6.4	6.4	4.9	6.5	7.6	5.5	6.0	8.1	8.3
7.2	5.0	4.5	10.0	2.1	2.0	10.2	4.5	3.7	9.3	4.9	5.2
9.7	2.0	1.6	13.6	1.2	0.7	13.9	1.8	1.9	12.5	3.4	2.3
12.1	1.3	0.9	17.2	0.4	0.3	17.5	0.6	0.6	15.8	1.2	1.0
14.6	0.6	0.4	20.8	0.2	0.1	21.2	0.5	0.3	19.1	0.6	0.7
17.1	0.3	0.2	24.4	0.1	0.1	24.9	0.3	0.2	22.4	0.4	0.3
19.5	0.2	0.1	28.0	0.1	0.0	28.6	0.0	0.1	25.7	0.3	0.1
22.0	0.0	0.0	31.6	0.0	0.0	32.2	0.0	0.1	29.0	0.1	0.2
24.5	0.0	0.1	35.2	0.0	0.0	35.9	0.0	0.0	32.3	0.1	0.0
Amount of dry days											
	60.2	64.6		71.2	75.8		68.9	69.2		60.3	62.0

Prec, Oskarshamn											
DJF			**MAM**			**JJA**			**SON**		
Prec	**Warm**	**Cold**	**Prec**	**Warm**	**Cold**	**Prec**	**Warm**	**Cold**	**Prec**	**Warm**	**Cold**
2.3	23.9	24.1	2.2	16.5	15.2	3.1	19.3	20.1	3.3	27.8	28.2
4.8	11.4	10.0	4.7	8.4	6.7	7.3	8.6	8.1	7.8	11.7	10.0
7.4	6.7	5.6	7.1	4.7	3.4	11.4	4.8	4.2	12.4	5.6	5.8
10.0	3.7	2.5	9.5	2.3	1.9	15.6	2.8	2.0	17.0	2.4	1.5
12.5	1.7	0.9	12.0	1.6	1.2	19.8	0.9	0.8	21.5	0.7	0.7
15.1	0.7	0.4	14.4	0.6	0.7	23.9	0.4	0.5	26.1	0.3	0.2
17.7	0.4	0.2	16.9	0.4	0.3	28.1	0.3	0.1	30.6	0.1	0.2
20.2	0.1	0.2	19.3	0.2	0.2	32.3	0.0	0.0	35.2	0.1	0.2
22.8	0.0	0.0	21.7	0.1	0.0	36.5	0.0	0.0	39.7	0.0	0.0
25.3	0.0	0.0	24.2	0.1	0.0	40.6	0.0	0.0	44.3	0.0	0.0
Amount of dry days											
	51.2	56.1		65.2	70.3		62.9	64.2		51.4	53.3

Runoff, Forsmark

DJF			MAM			JJA			SON		
Runoff	Warm	Cold	Runoff	Warm	Cold	Runoff	Warm	Cold	Runoff	Warm	Cold
2.2	12.3	7.9	2.3	13.9	14.7	1.8	5.7	4.3	2.2	10.9	11.0
4.7	4.9	3.4	4.8	4.8	5.4	3.3	2.2	1.9	4.5	3.9	3.8
7.1	2.9	0.9	7.3	1.6	2.2	4.8	0.6	0.9	6.9	1.6	1.2
9.5	1.3	0.6	9.8	1.5	1.1	6.3	0.5	0.4	9.2	0.6	0.3
11.9	0.5	0.4	12.4	0.4	0.3	7.8	0.3	0.3	11.5	0.3	0.2
14.4	0.3	0.2	14.9	0.2	0.1	9.3	0.2	0.0	13.9	0.2	0.0
16.8	0.0	0.1	17.4	0.2	0.2	10.8	0.0	0.1	16.2	0.1	0.0
19.2	0.0	0.1	19.9	0.0	0.0	12.3	0.0	0.0	18.6	0.0	0.0
21.7	0.0	0.0	22.5	0.0	0.0	13.8	0.0	0.0	20.9	0.0	0.0
24.1	0.0	0.0	25.0	0.1	0.0	15.3	0.0	0.1	23.2	0.0	0.0
					Amount of dry days						
	77.8	86.5		77.3	76.0		90.5	92.1		82.4	83.6

Runoff, Oskarshamn

DJF			MAM			JJA			SON		
Runoff	Warm	Cold	Runoff	Warm	Cold	Runoff	Warm	Cold	Runoff	Warm	Cold
2.5	19.0	15.2	2.0	12.9	13.3	1.8	7.9	7.3	2.3	16.4	16.4
5.6	8.2	6.6	4.1	5.0	4.8	3.4	3.1	3.1	5.0	6.1	5.3
8.6	3.9	3.1	6.2	2.3	2.6	5.0	1.5	1.3	7.6	2.3	1.6
11.7	1.3	0.7	8.3	1.2	1.3	6.6	0.6	0.4	10.2	1.0	0.8
14.7	0.5	0.5	10.4	0.6	0.6	8.3	0.6	0.3	12.8	0.3	0.4
17.8	0.3	0.1	12.5	0.4	0.2	9.9	0.1	0.1	15.5	0.1	0.0
20.8	0.0	0.1	14.6	0.3	0.2	11.5	0.0	0.2	18.1	0.0	0.0
23.9	0.0	0.0	16.7	0.1	0.1	13.1	0.0	0.0	20.7	0.1	0.1
26.9	0.0	0.0	18.7	0.0	0.0	14.7	0.0	0.0	23.4	0.1	0.0
30.0	0.0	0.0	20.8	0.1	0.0	16.3	0.1	0.0	26.0	0.0	0.0
					Amount of dry days						
	66.8	73.8		77.1	77.0		86.1	87.3		73.6	75.3

Evap, Forsmark

DJF			MAM			JJA			SON		
Evap	Warm	Cold	Evap	Warm	Cold	Evap	Warm	Cold	Evap	Warm	Cold
–0.9	0.0	0.0	–0.1	5.0	7.0	0.6	1.8	2.0	0.0	8.3	9.7
–0.6	0.0	0.0	0.4	32.2	36.1	1.2	9.7	12.7	0.6	34.5	35.6
–0.3	2.2	2.9	0.8	29.6	30.8	1.8	24.2	26.2	1.1	29.9	28.0
0.0	44.1	52.9	1.3	17.2	15.9	2.4	28.6	28.6	1.7	17.9	16.2
0.3	35.7	32.2	1.7	8.2	6.4	3.0	20.5	19.5	2.3	6.6	7.4
0.7	12.2	8.7	2.2	3.8	2.4	3.5	10.5	8.2	2.9	1.9	2.0
1.0	4.3	2.5	2.7	2.0	0.9	4.1	3.7	1.9	3.5	0.6	0.7
1.3	1.1	0.8	3.1	1.3	0.4	4.7	0.8	0.7	4.1	0.2	0.3
1.6	0.2	0.0	3.6	0.6	0.1	5.3	0.2	0.2	4.6	0.1	0.0
1.9	0.2	0.0	4.0	0.2	0.0	5.8	0.0	0.0	5.2	0.0	0.0

Evap, Oskarshamn											
DJF			**MAM**			**JJA**			**SON**		
Evap	**Warm**	**Cold**	**Evap**	**Warm**	**Cold**	**Evap**	**Warm**	**Cold**	**Evap**	**Warm**	**Cold**
–0.6	0.1	0.1	–0.1	7.7	13.4	0.6	0.6	0.7	–0.3	1.0	1.4
–0.2	4.9	6.0	0.6	40.2	47.7	1.2	7.4	7.5	0.4	25.4	26.2
0.2	44.6	57.5	1.2	24.2	21.3	1.9	18.1	21.8	1.0	34.9	32.8
0.5	32.7	26.4	1.9	12.3	9.4	2.5	26.0	25.5	1.6	23.7	24.4
0.9	12.7	7.3	2.5	7.7	4.7	3.1	24.0	23.6	2.3	10.2	10.5
1.3	3.9	2.3	3.1	4.6	2.3	3.8	14.7	13.4	2.9	2.8	3.5
1.6	0.7	0.3	3.8	2.3	0.8	4.4	6.3	5.2	3.5	1.2	0.8
2.0	0.3	0.1	4.4	0.9	0.4	5.0	2.1	1.5	4.2	0.4	0.4
2.4	0.1	0.0	5.1	0.2	0.1	5.7	0.6	0.7	4.8	0.2	0.1
2.7	0.0	0.0	5.7	0.1	0.0	6.3	0.1	0.1	5.4	0.2	0.0

7 Conclusions

Climate variability is an important constraint for societies. On short time scales, it is the current mean state of the climate system and its unforced internal variability around the mean that affect society and our environment. However, both of these components vary depending on the evolution of the climate system, due to evolving external climate forcing factors such as changes in incoming solar radiation, greenhouse gases and particles in the atmosphere. Indeed, there were certainly no periods in the past, and there will consequently also be no periods in the future, without changes in external climate forcing. This, in addition to the difficulties in obtaining information on past climates, and the limitations of climate models, places constraints on how well we can understand the climate system. This bears directly on our possibilities to deal with future climate, for which actual predictions in any deterministic sense are still beyond our reach. Nevertheless, future climate changes are of most interest to us, as these changes will have an impact on the future activities of societies. Hence, there is a need for obtaining an understanding of how the future climate is likely to behave, including both human and natural influences.

When it comes to the effect of changing external forcing on the properties of the climate system, such as its mean state around which internal variability occurs and the size of these internal variations including extreme weather events, useful knowledge can be gained by data-based investigations of past climates and also by modelling past climate changes. Model projections of climate, whether they are for the past or the future, are of course dependent on knowledge of external forcing factors.

The most complete picture of climate variability and climate change, which we have, is the period with instrumental observations starting around the middle 19th century. Longer instrumental series exist, but they are few. Therefore, to extend our knowledge further back in time, studies of various proxy data are needed. However, these are often difficult to interpret, are only available from few locations, are of limited precision and address few aspects of climate. Climate models, on the other hand, provide comprehensive and consistent accounts of the climate system in space, time and in terms of many different aspects of climate. Model simulations are, however, compromised by uncertainties in external forcing, by parameterisation approximations and by the rather prohibitive computational cost of detailed and long simulations. The same lack of data that limits experimental studies also affects climate models by reducing the possibilities of model evaluation. Thus, it is clear that investigations based on instrumental observations, proxy data and climate models have their respective strengths and weaknesses. This means that these techniques can complement one other, as has been pursued in the present investigation.

The aim of this study was to reconstruct Swedish climate variability during the past 2,000 years, by means of a range of climate proxies and advanced global and regional climate modelling studies. By itself, this represented a new generation of regional climate studies. Our inventory of available proxy data, although more extensive than attempted before, resulted in still too few sources to allow for any complete reconstruction. Additional perspectives on our recent climate could be gained by comparing the differences between more recent observations on one hand, and model simulated past periods on the other hand, for a common period covering the early decades of the 20th century.

A main conclusion of the present study is that there have been both relatively warm and cold past periods, as well as some relatively wet and dry periods in our region during the past 1,000 to 2,000 years. Against many of these, the late 20th century period stands out as a relatively warm one. In particular, it appears that the last 70-year period was the warmest period in Sweden over at least the last 500 years. Exactly how unusual the past few decades might be can, however, not yet be established due to the inherent limitations of the proxy data. There are also indications that significant past changes in precipitation, river runoff and aspects such as storminess have occurred. The available proxy data, unfortunately, do not allow accurate quantitative estimations of these aspects.

This study did not concern anthropogenic climate change as such. Neither did it deal with future climate. However, it provides a perspective to stakeholders concerned about climate variability and change forward in time. It seems reasonable to conclude that the future major climate shaping factor during the 21st century, and also for quite some time beyond it, will be the evolution of greenhouse gas emissions. Indeed, it seems as if there are no past analogies to the projected anthropogenic climate change. However, it is equally reasonable to expect that relatively significant unforced and naturally forced climate variability as those that occurred in the past, will also take place in the future and will be superimposed on anthropogenic induced climate changes. All of these elements should be considered when taking decisions that deal with future conditions over decades, centuries and even millennia.

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