Stormy records from peat bogs in south-west Sweden : implications for regional climatic variability and vegetation changes during the past 6500 years

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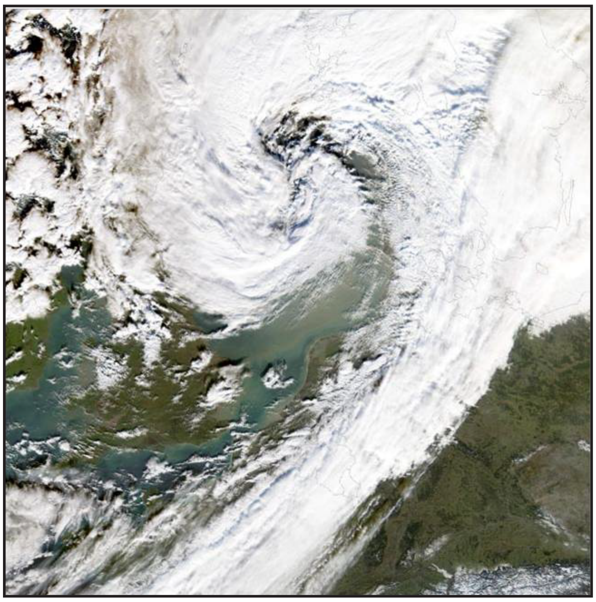

Rixt de Jong

LUNDQUA Thesis 58
Quaternary Sciences
Department of Geology
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Cover; Satellite image taken over north-west Europe on 8 Januari 2005, showing the cyclone (named 'Gudrun') that caused extensive damage in southern Sweden. Image courtesy; http://visibleearth.nasa.gov

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Stormy records from peat bogs in south-west Sweden -implications for regional climatic variability and vegetation changes during the past 6500 years

Rixt de Jong

Avhandling

Att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggande av filosofie doktorsexamen, offentligen försvaras i Geologiska Instituationenens föreläsningssal Pangea, Sölvegatan 12, fredagen den 1 juni 2007 kl. 14.15

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Stormy records from peat bogs in south-west Sweden -implications for regional scale climatic variability and vegetation changes during the past 6500 years

Abstract

This thesis aims to reconstruct and explain variations in storm activity, humidity, vegetation composition and land cover in south-west Sweden during the past 6500 years. Two ombrotrophic bogs, Store Mosse and Undarsmosse, situated on the coastal plain of Halland, were selected for this purpose. The coastal plain of Halland is positioned in the cyclone path and is therefore particularly sensitive to changing cyclone frequencies and associated storms. Cyclones have a strong control on the climate in this region, by moderating summer and winter temperatures and being the main source of precipitation. Aeolian sediment influx (ASI) was used as a proxy for storm activity. Bog surface wetness reconstructions were based on organic bulk density values from both study sites, whereas testate amoebae analysis was applied on cores from Undarsmosse bog only. Pollen analysis was carried out to reconstruct vegetation and land use changes. In addition the hypothetical regional scale vegetation composition around the Store Mosse bog was reconstructed by applying the REVEALS model, which corrects for differences in pollen productivity and dispersal between plant taxa. The land use reconstructions were also used to discriminate between climatic and human induced variations in ASI values, since increased sediment availability resulting from human activity may have affected sand influx into the bogs. The reconstructions of storm activity are similar at both study sites, with peaks of storminess around 4700, 2800-2000, 1500, 1100, 700 and 400-50 cal. yrs BP. These time periods are in good agreement with, for example, dune re-activation phases in Denmark. A comparison to land use in the region shows that ASI values are highest when the indications for cultivated fields are low, which implies that land use cannot explain the occurrence of ASI peaks. These are therefore most likely causally related to regional scale climatic changes. Humidity shifts were recorded around 4800, 2000 and 400 cal. yrs BP at both sites, which concurs with lake chemistry and lake level reconstructions from southern Sweden. These results were used to propose a regional scale reconstruction of climatic change, and may be used to infer variations in past atmospheric circulation patterns. In addition, a detailed comparison between ASI values and testate amoebae based wetness reconstructions has revealed an enigmatic pattern of increased storm activity during shifts in humidity during the past 1700 years.

Key words Holocene climate, south-west Sweden, aeolian activity, humidity changes, vegetation development, REVEALS vegetation modelling, atmospheric circulation changes, peat sediments.

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Stormy records from peat bogs in south-west Sweden

Implications for regional climatic variability and vegetation changes during the past 6500 years

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This thesis is based on three papers listed below as Appendices I - III. All the papers have been submitted to peer-reviewed international journals. Paper I is reprinted with the permission of John Wiley and Sons Ltd. Paper II has been submitted to the journal indicated. Paper III is reprinted with permission of Copernicus GmbH (EGU).

Appendix I: De Jong, R., Björck, S., Björkman, L., Clemmensen, L.B. 2006. Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, SW Sweden. *Journal of Quaternary Science* 21 (8), 905-919.

Appendix II: De Jong, R., Broström, A., Gaillard-Lemdahl, M-J., Hellman, S., Sugita, S. Late Holocene vegetation, land-use and land cover changes in Halland south-west Sweden; a quantitative reconstruction using the REVEALS model. Manuscript submitted to *the Holocene.*

Appendix III: De Jong, R., Schoning, K., Björck, S., 2007. Increased aeolian activity during climatic regime shifts as recorded in a raised bog in south-west Sweden during the past 1700 years. *Climate of the Past Discussions* 3, 383-408 (SRef-ID: 1814-9359/cpd/2007-3-383). Climate of the Past Discussions is the access reviewed discussion forum that precedes publication in *Climate of the Past*.

Contents

1. Introduction

1.1 Background

The climate of the North Atlantic region has experienced considerable variability on a range of time scales (Hurrell, 1995), thereby affecting regional climates, vegetation development and possibly also the development of agriculture (Berglund, 2003). To reconstruct and understand climatic variability in this region during the past several thousand years, knowledge on parameters such as temperature, humidity and wind characteristics are needed. A reconstruction of the wind climate is especially important because it is linked directly to atmospheric circulation patterns, as will be explained in section 1.5. Such information can be used to explore the causes of regional climatic changes, and, when combined with knowledge on vegetation development, the effects climate may have on vegetation development and human activity can be studied.

Many studies have focused on temperature (e.g. Dahl-Jenssen *et al.*, 1998; Mann *et al.*, 1998; Moberg *et al.*, 2005) and humidity changes in the North Atlantic region (e.g. Hughes *et al*, 2000; Barber *et al*, 2003; Charman *et al.*, 2006). Dune development studies (e.g. Clarke *et al.*, 2002; Wilson *et al.*, 2004; Clemmensen *et al.*, 2006) have been used to infer changes in the wind climate, but detailed reconstructions of storm frequency and intensity (storminess) have been difficult because dune building is also affected by e.g. sea level changes and land use. A different method for reconstructing past storminess was shown by Björck and Clemmensen (2004), who used the number of sand grains deposited into raised bogs (aeolian sediment influx, ASI) as a proxy for winter storminess. The ASI method has also been applied in this study to reconstruct past changes in storminess and will be discussed in section 1.2.

The coastal area of south-west Scandinavia is located ideally to register changes in atmospheric circulation and storminess in particular. The coastal zone of the province of Halland (Figure 1) is situated in a region which is strongly affected by extratropical cyclones; precipitation is high year-round and wind speeds are high due to the position at the open sea of the Kattegat. On the other hand, so-called blocking situations also occur in this region, bringing completely different weather to the study area. Blocking may occur when a high pressure area is situated over Scandinavia, and is associated with strong easterly winds, very low air temperatures in winter (Jönsson, 1994; Barry and Chorley, 1998) and dry, warm conditions in summer. However, not much is known about long term changes in the position, strength and frequency of cyclones and associated storms in this region, or about the frequency and intensity of blocking situations and the associated easterly airflow. The major meteorological features in the North Atlantic region are described in section 1.5.

The reconstruction of storminess during the past 6500 years is important for several reasons, especially when combined with information on e.g. humidity and temperature changes;

- These parameters provide important indications for the character of atmospheric circulation in the past, which is necessary for our general understanding of the Holocene climate
- Extreme events, such as strong storms, are likely to have a much more pronounced effect on society than gradual changes. Knowledge on the natural occurrence of such extreme events is especially important in the light of a possible increase in the frequency of extreme events in the future, due to climate change.

When the climatic development can be reconstructed for a certain region, this information can also be used to study the possible causal links with vegetation development and land use changes.

1.2 Proxy based reconstructions of storminess

There is no direct way of reconstructing past storminess beyond the range of measurement data, which, in south Sweden, reach back until ca. 1840 (Alexandersson *et al.*, 1998; Nilsson *et al.*, 2004). Therefore proxy-based reconstructions are an important source of information for time periods up to several thousand years in the past. Dune development studies along the west European coastlines are often interpreted in terms of climatic change. However, the timing of development phases varies between sites, indicating that site specific factors also exert a control on dune formation (Wilson *et al.*, 2004). In addition, aeolian activity phases can be erosive, and therefore it can be difficult to obtain a complete record of all dune-building events. Nevertheless, many dune studies from north-west Europe show a general agreement, with main phases of dune-building between ca. 2800-2400 (e.g. Wilson *et al.*, 2001; 2004; Clemmensen *et al.*, 2006) and 650 -50 years BP (Wilson *et al.*, 2001; 2004, Clarke *et al.*, 2002; Clemmensen *et al.*, 2006). These events have frequently been interpreted as periods with increased storminess and wetter and cooler conditions.

As mentioned before, Björck and Clemmensen (2004) used a new proxy to reconstruct past storminess variation. They calculated the number of sand grains deposited in two raised bogs in Halland, and interpreted these as aeolian sediment influx (ASI) during high-energy wind events. Since peat bogs accumulate organic matter continuously, this method has two great advantages; accumulation of a complete record without erosion, and the availability of organic matter for radiocarbon dating throughout the cores. Interpreting ASI records is, however, not easy. The transport of sand grains > 90 µm, according to Tsoar and Pye (1987), occurs primarily as bedload, thus grains of this size or larger saltate or creep over the surface. Therefore, the presence of large sand grains in the central part of wet and irregular bogs appears enigmatic. Sand transport may, however, be facilitated by a snow cover on the bog. Under such conditions sand grains could saltate more easily and sand and snow could also be transported together over much longer distances. Therefore Björck and Clemmensen (2004) tentatively interpreted their ASI record as a winter storm proxy. Transport in suspension over short distances during exceptionally strong winds can not, however, be excluded as an additional or alternative mechanism.

1.3 Vegetation development and human impact

Sand influx into raised bogs, however, is not only controlled by the transporting mechanism, but also by sediment availability. Sediment availability is mainly controlled by the degree of vegetation cover and soil moisture; a high moisture content can reduce sediment availability (Li *et al.* 2004; Wiggs *et al.*, 2004). Any disturbance in the vegetation cover, by heavy grazing, cutting or burning of vegetation, could potentially lead to increased soil erosion. Since *ca.* 6000 cal. yrs BP the human disturbance of the natural vegetation has increased in a stepwise manner (e.g. Iversen, 1941; Berglund, 1969; 2003). The original forest vegetation has disappeared in large parts of south-west Sweden and is currently replaced by vast open areas of agriculture and pasture. The transition from the pristine broadleaved forest, that is thought to have been present until *ca.* 6000 years ago, to the modern day landscape, has been stepwise, with contracting and expanding cultural land areas (Berglund, 2003). The causes for these waves of expansion and contraction are debated: climatic as well as demographic and political causes have been put forward (Berglund, 2003). Although a general picture of vegetation development is available from several small sites, mainly in the upland region of Halland (e.g. Digerfeldt, 1982; Björkman and Bradshaw, 1996; Lagerås, 2007), little is known about the development of vegetation on the coastal plain (Figure 1) and therefore it is necessary to reconstruct vegetation and land use changes here. Since this area is both sensitive to cyclonic activity and very suitable for land use, it is an ideal area to explore the potential relationships between changing climate and land use.

1.4 Project objectives

The objectives of this thesis can be divided in two main themes; climatic reconstructions, with a focus on storminess, and vegetation and land use reconstructions. A major difficulty is that these two themes cannot be studied separately, since climate may have affected vegetation and land use changes, and land use changes may have affected the availability of the sand and thereby the ASI storm-proxy used in this study. The main aims of this thesis are therefore to;

- reconstruct storminess and humidity variations during the past 6500 years in south-west Sweden,
- reconstruct and explain vegetation and land use changes in this region,
- use the climatic reconstructions to infer atmospheric circulation changes in north-western Europe.

To clarify the interpretation of the climatic parameters reconstructed in this thesis, a general description of large scale atmospheric circulation and major meteorological features in the North Atlantic region is provided in the next section.

1.5 Atmospheric circulation patterns in the North Atlantic region

Rossby waves, the Polar Front and the Polar Front Jet

An important atmospheric feature in the northern hemisphere is the pattern of the upper westerly air flow, also known as 'Rossby waves'. Rossby waves reflect the motion of the upper westerly air stream on a horizontal plain above the earth surface. Rossby waves determine the position of the zone where two air masses meet; Atlantic moist and warm air in the south, and cold and dry polar air in the north (Henderson-Sellers and Robinson, 1996). Due to the temperature and pressure contrast between these two air masses, the Polar Front is formed. Since these contrasts are largest in winter, this is the season when the Polar Front is most pronounced.

The Polar Front is a nearly continuous global frontier that separates cold polar air from warm and moist subtropical air (Ahrens, 1991) and extends from sea level to the tropopause (at 10-15 km height). Due to the large temperature and pressure differences between these two air masses, strong westerly winds develop at or just below the tropopause, referred to as the Polar Front Jet (Ackerman and Knox, 2003). In general, an increase of the pressure gradient along the Polar Front leads to increased vigour of westerly flow. The characteristics and position of the Polar Front and the associated jet is related to the pattern of Rossby waves. If the pattern of Rossby waves is constricted to a narrow zonal band ('zonal flow'), westerly flow is enhanced. If the upper air flow meanders over a wider zonal band (meridional flow) loops of cold polar air can extend far south, whereas warm maritime air can extend to the north. In such situations high pressure cells of cold polar air extend far south and can be cut off from the main circulation, thereby blocking westerly air flow. This is called a 'blocking situation', since the westerly flow is diverted north-eastwards towards the Norwegian Sea or south-eastwards into southern Europe (Barry and Chorley, 1998). A major area of blocking is Scandinavia. Along the southern margin of the high pressure cell strong easterly flow occurs, producing severe winter weather in a larger region in northern Europe (Barry and Chorley, 1998) and strong easterly winds in south-west Sweden (Jönsson, 1994).

Extratropical cyclones and anticyclones

Extratropical cyclones (and anticyclones) are formed near the Polar Front along the Polar Front Jet. Westerly winds are strongest near the core of the jet, and as air approaches this core, it is accelerated. As winds move away from the core area, wind speeds decrease (Ahrens, 1991). As a result, air is 'piled up' or stretched out, leading to high pressure (anticylones) and low pressure (cyclones) areas respectively. Low surface pressure and cyclones are mostly maintained at the cold polar-side of the main air flow (the so-called 'cyclone track'), whereas anticyclones prevail at the warm side (Lamb, 1985). The character and position of cyclones and anticyclones is therefore determined by the behaviour of Rossby waves and the Polar Front Jet. Changes in the flow type (zonal or meridional) or in the position of the Polar Front therefore have a direct control on the position of the cyclone track and the characteristics of the associated weather patterns.

Cyclones bring moist oceanic air to the continent, thereby moderating summer and winter temperatures. Cyclones are also associated with precipitation and westerly storms (Jönsson, 1994). High pressure cells or anticyclones, on the other hand, lead to a completely different weather pattern. Blocking situations may persist for weeks or even months (Barry and Chorley, 1998) and therefore they may also form an important element in the climate of Scandinavia.

Air pressure at sea-level; North Atlantic Oscillation

When referring to air pressure patterns at sea-level, the atmospheric circulation in the North Atlantic region is frequently expressed in terms of North Atlantic Oscillation (NAO) modes. The NAO mode is defined as the air pressure difference between Iceland (Stykkisholmur) and the Azores (measured in Lisbon) and is most clearly expressed in winter (Hurrell, 1995, measurement data from 1935 – 1999). For weather and climate in Europe, the Icelandic Low and Azores High are dominant features, although it should be noted that these are not the only centres of action that affect European climate (Wanner *et al.*, 2001). In its positive phase (NAO+), the Icelandic Low and Azores High are intensified. As a result, the pressure gradient is large, which is associated with strong westerly storms in north-west Europe. During the negative extreme of NAO (NAO-), the Azores High is weakened, whereas the Icelandic Low is not well developed and shifted eastward. Air pressure differences are subsequently smaller and the storm track is weaker and situated further south, over Spain and Portugal. Extreme reversals of the pressure distribution, with higher air pressure over Iceland than the Azores, are very rare but possible (extreme NAO-). This situation is associated with strong easterly flow in the eastern North Atlantic (Wanner *et al.*, 2001). It is important to realize that the pressure distribution in the North Atlantic does not 'switch' between a positive and a negative state of the NAO, but can take the form of the entire scale of possibilities in between the extremes.

It is thus suggested that periods of high westerly storm activity in north-west European winters are associated with a positive state of the NAO, which is in turn related to a strong atmospheric contrast between Iceland and the Azores. However, Dawson *et al.* (2002) found, that increased storm activity in the late 19th century (1885-1898) could not be correlated to a positive state of the NAO; NAO values were either negative or slightly positive. Instead they found a correlation to the extent of sea-ice in the Greenland Sea. This sea-ice caused increased air pressure near Iceland and a southward shift of the Polar Front (Dawson *et al.*, 2002). As a result, the Polar Front Jet and the associated cyclone track shifted southwards, thereby bringing frequent storms to the British Isles. An extreme southern extension of the Polar Front and sea-ice may be associated with meridional upper air flow or a southward shift of the entire associated system of Rossby (long) waves, the Polar Front and the Jet Stream.

Thus, it seems that increased storminess in north-west Europe may be associated with two different atmospheric situations; an NAO+ state, or an extreme southerly extension of the Polar Front. In both cases atmospheric contrasts are enhanced. Reconstructing atmospheric flow patterns based on storminess reconstructions alone is therefore not possible; knowledge on additional parameters such as humidity and temperature are required. This also implies that reconstructed variations in storminess cannot be interpreted directly in terms of NAO modes.

2. Study area

2.1 Geological setting

Both study sites, Undarsmosse bog and Store Mosse bog, are situated on the coastal plain of the province of Halland (Figure 1). The coastal plain north of the Laholm Bay is generally 10-20 km wide and the elevation is 10-25 m above sea level (a.s.l.). The coastline is characterised by a mix of beach ridges and extensive dune areas, (marine) reworked tills, moraine ridges and bedrock outcrops (Påsse, 1987; 1989). The coastal plain is characterized by sand- and silt-rich wave-reworked glacial sediments. Bedrock hills reaching up to 140 m a.s.l. are found close to the present coastline in central and northern Halland. These hills, as well as the bedrock underlying the coastal plain, predominantly consist of gneisses and gabbros (Påsse, 1987a). In the east the terrain rises up to 200 m a.s.l.

Lundqvist and Wohlfarth (2001) dated the deglaciation of the Halland coastal plain to 16,000 cal. yrs BP. However, after initial deglaciation the ice margin fluctuated strongly, resulting in the formation of a successive series of north-west to south-east running moraine ridges and thick glaciofluvial and glaciomarine deposits west of the ice margin (Berglund, 1995). The relative sea-level changes have been substantial in this region; the marine limit is situated 50-80 m a.s.l (von Post, 1947; Berglund, 1995). Around 10,000 to 10,500 cal. yr BP a regression maximum to 20 m below present sea level took place, followed by a transgression around 7000-6000 cal. yr BP to 8 m above present sea level (Björck, 1987). This maximum was followed by an oscillating, but gradually falling sea level (Mörner, 1969; Påsse, 1987b). Consequently, the glacial sediments on the low lying coastal plain where reworked considerably by wave action, whereas the bedrock hills close to the coastline were islands during the time of maximum sea level.

2.2 Climatological setting

The province of Halland lies in the path of the westerlies, producing a mild coastal climate with cool summers (16° C July average temperature) and relatively mild winters (-4° C January average temperature)(Raab and Vedin, 1995). Precipitation in Halland is highest in the upland region, up to 1200 mm yr-1, whereas the narrow zone along the coastline is less humid with annual precipitation around 800-900 mm. The mean number of days with snow cover varies between 75 and 100 days (Raab and Vedin, 1995). The weather in all seasons is extremely variable, being controlled by the frequency, intensity and position of the passing cyclones. Analysis of geostrophic wind speeds in southern Sweden from 1881 to 1997 shows that winds from a westerly direction strongly dominate the wind spectrum and the relative storm frequency was highest between October and March (Alexandersson *et al.*, 1998; 2000; Nilsson *et al.*, 2004). These westerly storm winds are caused by cyclones passing north of Halland towards the east (Jönsson, 1994). Easterly winds of storm force occur when cyclones pass south of Halland, and are associated with a high pressure field situated over northern Scandinavia. However, during the past century easterly storm winds (geostrophic wind speed >20 m/s) have been rare (Nilsson *et al.*, 2004).

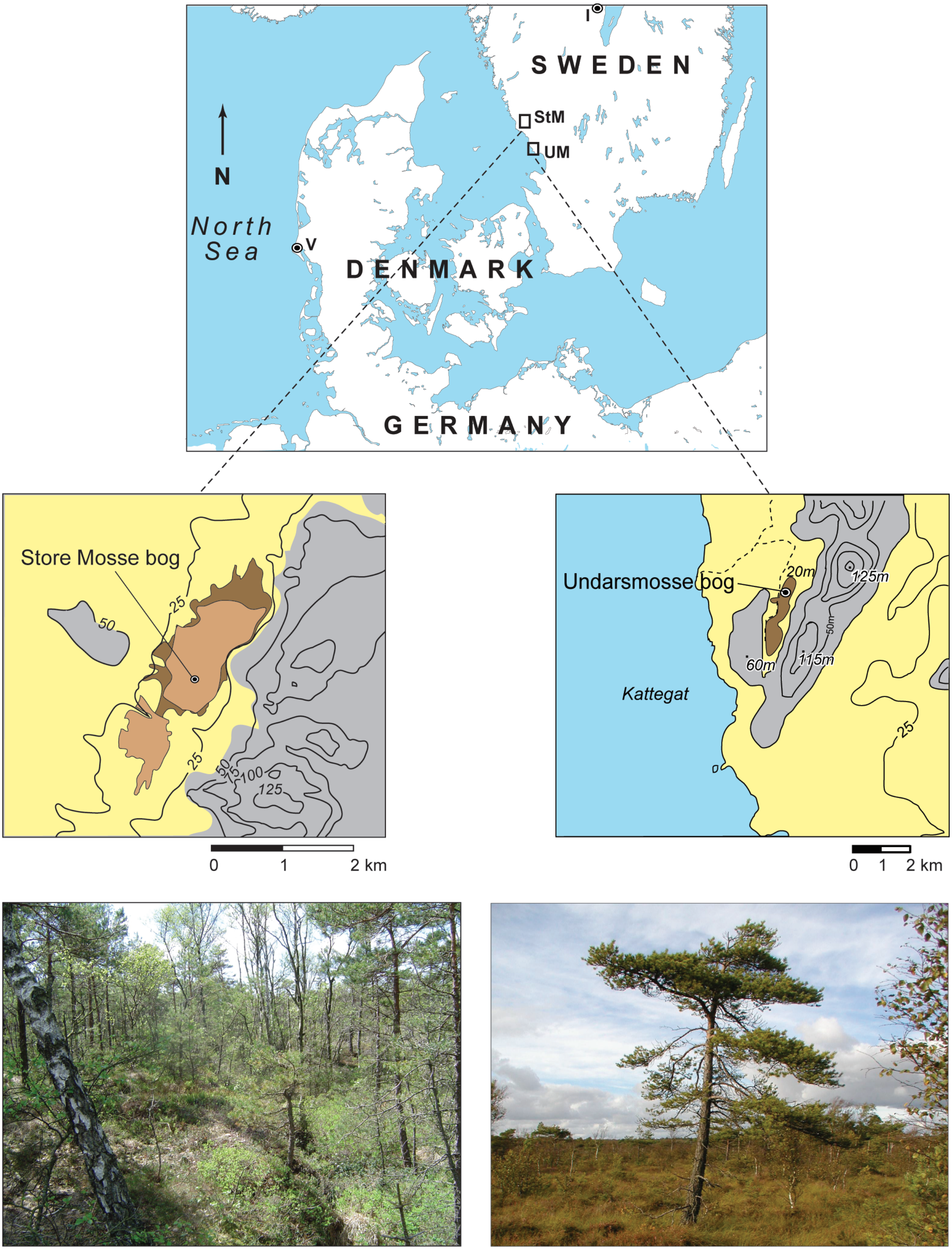

Figure 1 Site map showing the position of the two study sites (UM: Undarsmosse bog, StM; Store Mosse bog). Also shown are the locations of Lake Igelsjön (I; south-central Sweden) and Vejers dunefield (V; west Denmark), which are mentioned in the text. Pictures were taken from each coring site. (photo's; Rixt de Jong)

2.3 Plant geography

The province of Halland lies at the boundary between two plant geographical zones; the western part belongs to the nemoral forest region, whereas the eastern part lies at the transition to the boreo-nemoral zone (according to Sjörs, 1965). The nemoral zone in the west is dominated by broadleaved (deciduous) forest trees, whereas forests in the boreo-nemoral region are mixed deciduous-coniferous, with a dominance of coniferous trees. For *Fagus* (beech) and *Picea* (spruce), Halland lies at the northern respectively southern limit of their natural occurrence, with beech immigrating from the south and spruce from the north-east (Björkman and Bradshaw, 1996). However, due to large scale spruce and pine plantations, coniferous trees are currently common in the entire region.

The geological contrast between the coastal plain in the west, with thick deposits of glacial sand, silts and clays, and the glacial till in the east (often with the underlying acidic bedrock exposed), may be at the basis for a distinct difference between the types of vegetation in each area and the possibilities for agriculture. This contrast is likely to have existed throughout the study period. At present, the coastal plain is dominated by cultivated fields, whereas the upland area is mainly used for forestry, although both land use types occur in the entire region. It is likely that, also in the past, agriculture was more widespread in the coastal area than in the upland regions.

2.4 Local setting; Undarsmosse bog

At present, Undarsmosse bog (Figure 1) is an ombrotrophic bog situated at 20 m a.s.l. The distance to the modern coastline is only *ca.* 1.5 km, which places the bog in the relatively dry zone where precipitation varies between 800 – 900 mm yr^{-1}. The areal extent of fen and peat deposits is *ca.* 120 ha. The bog is situated in a basin with a threshold in the northern part at 16-17 m a.s.l. (Påsse, 1989). Low bedrock hills, partially covered by silty tills, flank the basin to the east and west. Cores were taken in the northern part of the basin at approximately 100 m from the western edge of the modern bog surface, where the surrounding hills are lowest. The terrain to the north and south is flat. The Undarsmosse basin was isolated from the sea at *ca.* 12,000 cal. yr BP (Berglund, 1995).

Sandy sediments are found immediately west and east on the northern flanks of the basin at a minimum distance of 600 m to the coring location (Påsse, 1988). North-west and west of the site, small active dune areas are present. The vegetation on the hills is dominated by pine plantations. The bog is surrounded by a narrow rim of birch and pine trees, growing on the relatively dry areas where extensive drainage and peat cutting have taken place. On the peaty soils outside this area crop cultivation takes place. The bog vegetation is dominated by *Calluna vulgaris* and several other Ericaceae species in the field layer, whereas the bottom layer is dominated by *Sphagnum* spp. Low pine and birch trees occur in small groups. The bog is still growing today.

2.5 Local setting; Store Mosse bog

The Store Mosse bog is situated on the eastern limit of the coastal plain at the transition to the upland area. Because of the position at a topographical transition zone, precipitation is high, between 1000-1200 mm yr^{-1} (Raab and Vedin, 1995). The coastal plain is approximately 12 km wide here and is characterised by sand- and silt-rich wave-reworked glacial sediments. The bedrock area in the east reaches up to 130 m a.s.l. and is composed of acidic igneous rocks. Sandy sediments are found in the immediate vicinity of the bog in all directions; sandy tills predominantly in the east, and fine sand to gravel to the south and west of the basin. North of the bog glacial clay is found at the surface, together with sandy glacial deposits. Active sand dune areas are found at a distance of *ca.* 6 km to the west and south-west.

The basin in which the Store Mosse bog has developed is *ca.* 750 m wide and 3250 m long. The bog is divided into a large northern part and a smaller southern part, separated by an east-west running moraine ridge. The total area covered by fen and peat deposits is *ca.* 240 ha (Påsse, 1989). The modern surface of the bog is situated at 23 m a.s.l. Drainage occurs to the northeast. The basin is wide and open to winds from all directions, except along the eastern side of the basin where the surface rises steeply to 140 m. a.s.l. Cores were taken from the central northern part of the bog (Figure 1). Immediately west of the coring location the basin is confined by a slightly elevated plateau (70 m. a.s.l.) of terminal glaciofluvial deposits. In the south the basin is dammed up by the Spannarp Moraine, a terminal moraine system (Påsse, 1989; 1990).

Today, Store Mosse is an ombrotrophic bog. However, the entire bog surface has been subjected to drainage and peat cutting, which is clearly visible at the surface and on aerial photographs. Drainage channels were dug around AD 1930, after which large scale peat cutting was possible. Cutting was carried out in elongated ditches separated by high and narrow ridges of peat. The cores in this study were taken from such a ridge, where disturbance of the peat stratigraphy was assumed to be smaller than elsewhere in the bog area.

Due to the dry conditions on the drained bog, vegetation on the remaining ridges is relatively dense and dominated by birch and pine trees. The under-storey at the coring site is composed of heath vegetation with a dominance of *Calluna vulgaris*, *Vaccinium myrtillus* and *Empetrum nigrum*. The vegetation in the ditches is characterised by *Eriophorum*. The areas west, north and south of the bog are mainly used for cultivation and pasture. The steep slope and hills bordering the eastern side of the study site are dominated by pine plantations.

3 Methods

3.1 Fieldwork and sampling

Cores were taken from the central part of the bogs using a Russian peat sampler (7.5 cm diameter). To ensure full stratigraphic recovery, corings were done in two parallel holes with considerable overlapping. Core stratigraphies were described in detail in the field. The cores were subsequently wrapped in plastic foil and stored in a deep freezer to prevent water loss. Next, the frozen cores were cut in 1 cm pieces, with the exception of the upper 1 m of the Undarsmosse core, which was cut in 2 cm pieces. Each piece was sampled for organic bulk density (OBD), ignition residue (IR) and aeolian sediment influx (ASI). At larger intervals samples were taken for pollen analysis, radiocarbon dating and testate amoebae analysis (the latter only in the Undarsmosse cores). Author contributions to the different methods described below are summarized in Table 1.

3.2 Radiocarbon dating and chronologies

The age models of both Undarsmosse and Store Mosse bog were based on AMS radiocarbon dates of bulk peat samples. Where possible, remains other than *Sphagnum* were removed. At one level in the Undarsmosse core birch twigs were dated. The radiocarbon dates were calibrated using the IntCal04 calibration curve (Reimer *et al.*, 2004) as implemented in the OxCal 3.10 program (Bronk Ramsey, 1995; Bronk Ramsey, 2001). The Undarsmosse chronology was based on 14 dates. The age-depth model was constructed using a combination of a 7th and 10th degree polynomial fit, taking into account the stratigraphy of the core; changes in the lithology were associated with changes in the accumulation rate. The chronology of the Store Mosse site was based on 12 radiocarbon dates. The model is a combination of two linear segments and one 9th degree polynomial function connecting the two linear sections. Lithological shifts were taken into account.

3.5 Pollen sampling and preparation

Pollen preparations were carried out on 2 cm^3 samples from the central part of each segment. Pollen preparation was carried out according to standard methods as described by Berglund and Ralska-Jasiewiczowa (1986) and Moore *et al.*(1991) with an overnight cold HF treatment to ensure that all quartz particles were dissolved. *Lycopodium* tablets were added prior to further treatment to enable the reconstruction of pollen concentrations and influx values (Stockmarr, 1971). Samples were sieved with a 125 µm mesh. Pollen, *Sphagnum* spores and charcoal particles >25 µm were counted under the microscope at 400 x magnification. The pollen keys in Moore *et al.* (1991) were used for determination of critical pollen types. The reference collection at the Quaternary Sciences pollen laboratory at Lund University was used to check pollen determinations. The program TILIA (Grimm, 1992) was used for the calculation of percentages and concentrations and for the construction of the pollen diagram. The pollen diagram from the Undarsmosse bog was divided into six local pollen zones based on visual inspection and cluster analysis of the data (Johnson and Wichern, 1998). A stratigraphically constrained cluster analysis (CONISS; Grimm, 1987) was used for zonation of the pollen diagram from Store Mosse, applying a square root transformation to give higher importance to rare pollen types. At most levels more than 500 arboreal pollen grains were counted. At levels with low pollen concentrations between 300 and 500 grains were counted.

3.3 Organic Bulk Density (OBD) and Ignition Residue (IR)

Samples from each frozen peat slice were weighed and the wet volume was estimated by water displacement. The samples were then dried overnight at 105 °C and weighed again to determine water loss, giving the water content. From these values both the wet weight and dry weight could be calculated in grams. Subsequently, each sample was burnt at 550 °C for 4.5 hours. The ignition residue was weighed, providing the percentage of non-organic matter (ignition residue; IR) and the ash weight (grams). To calculate the ash-free OBD, the weight of the minerogenic (IR) matter was subtracted from the weight of the dry organic matter and then divided by the volume of the sample, thus

$$(dry\ weight_{105^oC} - ash\ weight_{550^oC})/volume\ (cm^{3)}$$

The ignition residue was subsequently rinsed with 10% HCl and the remaining mineral grains were used for ASI analysis.

3.4 Aeolian Sediment Influx (ASI)

The mineral grains were analysed under a 50x zoom stereomicroscope. Samples with very high fine particle content were sieved at 63 µm before further analysis. Grains were counted and divided in three or four grain-size classes; 80-125 µm (Store Mosse samples only), 125-250 µm, 250-350 µm and >350 µm. Furthermore the maximum grainsize in each sample was measured. OBD, IR and ASI analysis were carried out on 276 and 302 levels for the Undarsmosse and Store Mosse cores, respectively.

3.5 Sediment traps

In September 2003 traps were placed on the Undarsmosse bog to monitor seasonal sand influx. Since then the traps have been emptied every three months. Each trap consists of a plastic box (20 x 36 cm) covered by a mesh. The traps were filled with a thin layer of glycerine, ethanol and thymol. Hereby algae growth was slowed down and a complete drying up of the sample was prevented so that once deposited, sand grains would be stuck in the trap.

All samples were dried overnight and burnt at 550 °C. Next, the ash residues were sieved using a 90 µm sieve. The mineral residue was analyzed using a stereomicroscope with 50x zoom. The grains were counted and divided into 4 grain-size classes (80-125, 125-250, 250-350 and >350 µm. The maximum grain-size per sample was also measured.

Table 1 Summary of contributors to analyses and fieldwork for each study site

	Undarsmosse bog	**Store Mosse bog**
Fieldwork and stratigraphical description	*R. de Jong,* *S. Björck,* *L. Björkman,* *R. Liljegren* *L.B. Clemmensen*	*R. de Jong,* *S. Björck,* *L. Björkman,* *L.B. Clemmensen* *A. Schomacker*
Core correlation and sample preparation	*R. de Jong*	*R. de Jong*
^{14}C sampling and age model construction	*R. de Jong* *S. Björck*	*R. de Jong* *S. Björck*
Organic bulk density, loss on ignition	*R. de Jong*	*R. de Jong*
Aeolian sediment influx and sediment trap influx monitoring	*R. de Jong*	*R. de Jong*
Pollen analysis	*R. de Jong*	*R. de Jong*
Testate amoebae analysis	*K. Schoning*	-
REVEALS modelling	-	*R. de Jong,* *S. Hellman,* *A. Broström,* *M.-J. Gaillard*
vegetation maps	-	*A. Broström*

4 Summary of papers

Appendix I

De Jong, R., Björck, S., Björkman, L. and Clemmensen, L.B. 2006. Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, SW Sweden. Journal of Quaternary Science 21(8), 905-919.

In this study ASI, OBD, LOI and pollen analysis were carried out on cores from the Undarsmosse bog. The ASI record shows a distinct pattern of long periods with little aeolian activity, interrupted by shorter time periods with strongly increased sand influx to the bog. After *ca.* 2800 cal. yrs BP a distinct increase in both ASI peak amplitudes and the level of noise is seen, which may be related to both higher sample resolution and increased sediment availability due to landscape opening. Comparisons to the dune development record from Vejers dunefield (west Denmark, Clemmensen *et al*, 2001; 2006), a grainsize record from the Skagerrak (Hass, 1996) and ASI records from Halland (Björck and Clemmensen, 2004), show that many of the recorded events appear to be simultaneous with ASI peaks at Undarsmosse bog. This suggests that the ASI record reflects changes on a larger spatial scale, and can be used to infer atmospheric circulation changes in the wider region. Pollen analysis shows relatively little human influence in the near vicinity of the bog and a potential link between the ASI record and human impact can not be seen until after 1500 cal. yrs BP.

Many of the reconstructed peak events apparently coincide with well-known cold phases in the North Atlantic region, suggesting a link to large-scale fluctuations in atmospheric circulation patterns. The tentative correlation to these climatic set-backs may suggest a link to reduced solar irradiance, and feedbacks through atmospheric and oceanic circulation, causing strongly increased storm activity in south-west Scandinavia.

Appendix II

De Jong. R., Broström, A., Gaillard-Lemdahl, M-J., Hellman, S., Sugita, S. Late Holocene vegetation, land-use and land cover changes in Halland, south-west Sweden; a quantitative reconstruction using the REVEALS model. Submitted to the Holocene

To reconstruct vegetation development and landscape openness in the region around the Store Mosse bog, pollen analysis was combined with a quantitative vegetation reconstruction for 24 taxa. The REVEALS model was used to calculate the abundance of each of these taxa in a 100 x 100 km area. This model corrects for bias in the traditionally used pollen percentage values, caused by species-specific differences in pollen productivity and pollen dispersal mechanisms. Because the Store Mosse bog is a large site according to the definition by Sugita (2007), the pollen record is assumed to reflect regional vegetation changes.

The results clearly show a step-wise opening of the landscape and a gradual change in forest composition. Furthermore, the development of pasture and cultivation is reconstructed, showing the gradually increasing importance of crop cultivation. These results can be used to study the role of humans for the observed vegetation changes, and a link to population density changes is seen after *ca.* 700 cal. yrs BP (1350 AD). At this time a complete disappearance of cultivated fields is tentatively related to the steep population decrease caused by the Black Death.

Appendix III

De Jong, R., Schoning, K., Björck, S. 2007. Increased aeolian activity during climatic regime shifts as recorded in a raised bog in south-west Sweden during the past 1700 years. Climate of the Past Discussions 3, 383-408 (SRef-ID: 1814-9359/ cpd/2007-3-383) Climate of the Past Discussions is the access reviewed discussion forum of Climate of the Past.

To reconstruct atmospheric circulation changes and to improve the understanding of the climatological set-up during stormy periods during the past 1700 years, ASI reconstructions were combined with testate amoebae analysis on cores from Undarsmosse bog. Thus, aeolian activity and bog surface humidity were reconstructed using material from the same peat core, which allows for a direct comparison between both parameters. The testate amoebae analysis reveals a pattern of alternating predominantly wet and dry conditions, separated by transitional phases characterized by a major shift in the testate amoebae assemblages. Variations in the water table were reconstructed using the indicator-species approach as proposed by Charman *et al.* (2007).

The results show that ASI peaks occurred during the transitional phases of bog surface humidity, both during wet-dry transitions and dry-wet transitions. The wet and dry phases can be correlated to well-known climatic time periods and were interpreted as reflecting the dominance of zonal flow conditions and meridional flow conditions, respectively. The causes for the ASI peaks, however, remain enigmatic. A detailed comparison between the watertable reconstruction and the ASI peaks shows, that increased storminess coincided with temporarily higher levels of the watertable, suggesting a link to increased humidity. A possible causal link to the climatic regime shifts recorded in the testate amoebae was suggested. An alternative explanation may be that increased storminess in the study area was caused by a southerly expansion of sea-ice in the Greenland Sea, which could lead to a southward shift of the Polar Front and the associated cyclone belt. In addition, some ASI peaks apparently coincide with reduced solar activity, possibly suggesting a solar cause for some of the observed events.

5 Exploring the causes of land use changes

The causes of vegetation and land use changes have been the topic of debate during a long time. Climatic change is recognised as an important factor controlling land use changes (e.g. Berglund, 2003), but the extent of the forcing is thought to depend on the vulnerability of a society; marginal areas are affected more severely (Messerli *et al.*, 2000). Nevertheless, Berglund (2003) reconstructed seven time periods of seemingly synchronous changes in human impact in north-west Europe and tentatively linked these changes to climatic events recorded in the North Atlantic region, suggesting a causal link. In this chapter this suggested causal link will be analyzed by comparing climatic proxy with human impact indicators from the Undarsmosse and Store Mosse bogs. The records of ASI and agricultural indicator pollen can be compared directly, since samples were taken from the same cores. In addition, this comparison is important for a correct interpretation of the ASI record; the potential control of landscape opening on sediment availability, and thus the ASI record, will be evaluated.

5.1 The development of cultivated fields and pastures

Cultivated crops and pastures are two important types of vegetation that indicate human land use. In this section pasture on grassland and in woodlands will be taken into account, but grazing on heathlands is not discussed; heath vegetation is common on both bog sites. Therefore it is very difficult to separate the 'local' bog heath signal from the 'dry grazing heathlands' signal (see discussion in appendix II).

At the Store Mosse site, both pollen percentage data and modelled quantitative vegetation

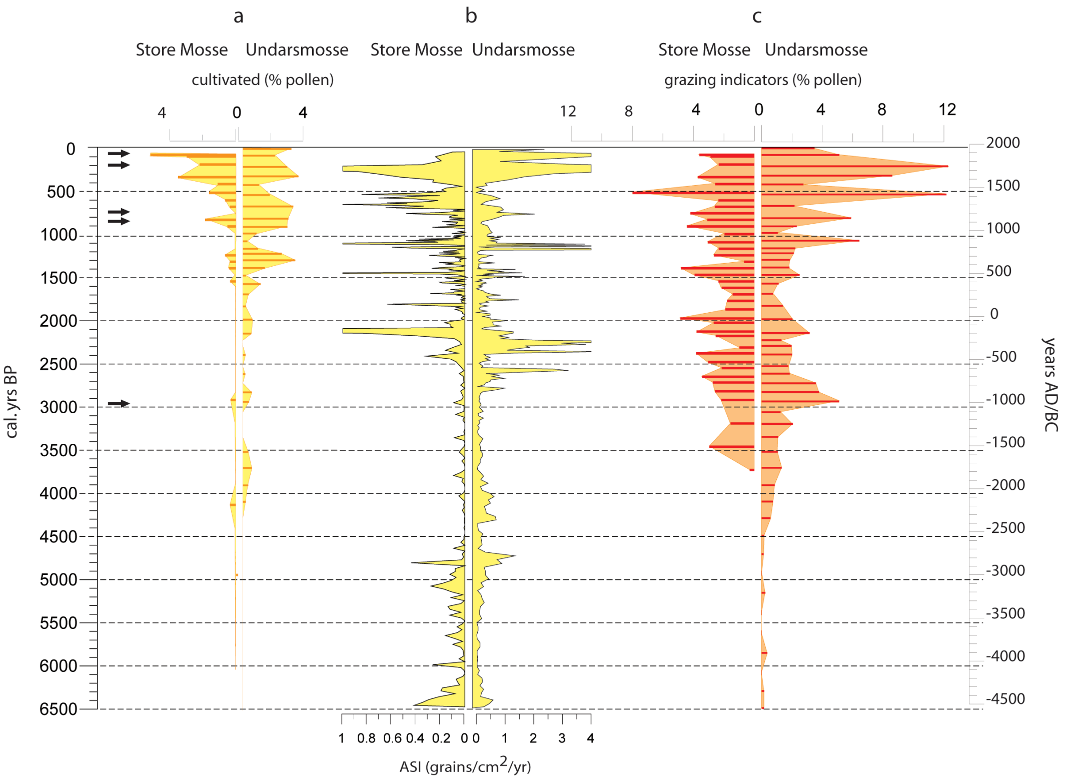

Figure 2 Overall comparison between the records from Store Mosse and Undarsmosse bogs, showing: a) cumulative pollen percentage values indicating cultivated fields (Secale, Cerealia), b) ASI values of sand grains > 125 µm (note that the maximum values are clipped at 1 and 4 grains/cm²/yr respectively) and c) cumulative pollen percentage values indicating grazing (Poaceae< 40 µm, Asteraceae (Taraxacum), P. lanceolata, Potentilla, Rubiaceae (Galium), R. acetosa/acetosella)

proportions were used to reconstruct the openness of the landscape. The modelled vegetation data give reliable values for the proportion of land use areas. Although the values for heath land and wetland may be overestimated in the REVEALS reconstruction (appendix II), the values for cultivated fields are thought to be a reliable minimum estimate. However, before ca. 3500 cal. yrs BP grass was abundant on the Store Mosse site, which was minerotrophic at that time, and values for 'grassland' during this time period are therefore highly overestimated. This is also a problem in the pollen percentage values used in Figure 2 and for this reason the percentage of grassland indicator pollen around Store Mosse bog is shown only from 3500 cal. yrs BP onwards. In addition to the pollen percentages used in Figure 2, hypothetical vegetation maps were reconstructed for the region around Store Mosse bog for five time slices, based on the REVEALS modelling values (Figure 3). The basic assumptions and methods for map construction are described in the next section. For the Undarsmosse site only pollen percentage data are available. Although these do not provide a corrected measure for landscape openness, the timing of the development of agriculture and pasture can be derived from it. In Figure 2 the pollen percentage results from Undarsmosse and Storemosse bog are compared, showing the total sum of pollen types indicating cultivation (*Secale*, other Cerealia (Poaceae > 40 µm) (Figure 2a) and grassland (Poaceae < 40 µm, Asteraceae (*Taraxacum*), *Plantago lanceolata*, *Potentilla*, Rubiaceae (*Galium*), *Rumex acetosa/acetosella* (Figure 2c). In section 5.1.2 and 5.1.3 the pollen percentage data from both study sites will be compared to study regional scale changes in cultivation and grazing areas.

Hypothetical vegetation maps; construction and results

Five time windows within the last 3000 years were selected to produce hypothetical vegetation maps for a 50 km x 50 km area around Store Mosse using the REVEALS estimates of plant abundance: 1) 2930 +/- 50 cal. yrs BP, 2) 840 +/- 80 cal yrs. BP, 3) 770 +/- 60 cal. yrs BP, 4) 200 +/- 60 cal. yrs BP and 5) 50 +/- 60 cal. yrs BP. These time periods were chosen because they reflect important stages in vegetation development that occurred in the Store Mosse region since the introduction of crop cultivation. The basic assumptions for application of the REVEALS model and the interpretation of the results are discussed in Appendix II.

The MOSAIC v1.3 software (Middelton and Bunting, 2004) was used to draw the maps (Figure 3a-e). For a given composition of vegetation types (in percentages), the program randomly places vegetation patches of various sizes in a homogenous vegetation matrix. To provide a rough spatial picture of vegetation development and relative abundances of land-use through time, the taxa used in REVEALS were divided into six groups. Each group of taxa is characteristic of a vegetation or land-use type. The groups are 'coniferous forest'(*Pinus, Picea*), 'broadleaved deciduous forest' (*Corylus, Carpinus, Fagus, Fraxinus, Quercus, Tilia* and *Ulmus*), 'trivial deciduous forest' (*Betula, Alnus* and *Salix*), 'heath land' (*Calluna, Juniperus*), 'grassland' (Poaceae < 40 µm, Asteraceae (*Taraxacum*), *P. lanceolata*, *Potentilla*, Rubiaceae (*Galium*), *R. acetosa/acetosella*), 'cultivated land' (Cerealia (Poaceae > 40 µm) and *Secale*) and 'wetlands' (Cyperaceae, *Filipendula*) (Figure 5). The REVEALS-estimated proportions for each taxa group were used to construct the hypothetical vegetation maps.

The maps were designed as follows:

- because of the distinct geological and topographical division of the landscape in a western lowland and eastern upland area, the vegetation composition was assumed to have differed between these two regions in the past. Therefore, a western and an eastern version were produced for each map.
- patches of 'coniferous' (500 m radius circle), ' trivial deciduous' (300 m radius circle), 'heath land' (200 m x 200 m square), 'grassland' (200 m x 200 m square), 'cultivated crops' (100 m x 100 m square) and 'wetland areas' (100 m x 100 m square) were randomly placed in a homogenous matrix of 'broadleaved deciduous', with the constraint that 'grassland' and 'cultivated crops' were placed only in the western part of the map

(lowland area), whereas ’coniferous forests’ were positioned only in the eastern part of the map (upland area). The final layout of the maps was produced in ArcGIS 9.1.

The resulting maps are shown in Figure 3a-e. The results will be interpreted parallel with the pollen percentage values from the Store Mosse and Undarsmosse bogs in the next sections. The maps provide visual information on the proportion of open land versus forested land and of cultivated land versus other open vegetation types, using quantitative estimates of vegetation abundance. However, the maps in themselves are speculative, which should be kept in mind when interpreting the results. The main uncertainties in the map reconstructions are;

- The REVEALS model assumes heterogeneity in vegetation, which is simulated in the maps by the random distribution of vegetation patches of different sizes. However, vegetation heterogeneity can only be reconstructed with estimates from several sites of different size, using both local and regional scale pollen assemblages. The ‘patchiness’ of vegetation in the maps is thus entirely hypothetical. Large stretches of for example forest may have existed during all time slices shown in Figure 3.
- The choice of patch sizes for each vegetation group is arbitrary; patch sizes for each vegetation group may have varied on a spatial scale as well as through time.
- The basic assumptions for constructing the maps are a simplification of reality. For example, it is known that the forested upland areas of south Sweden were colonised at least from Medieval Times or earlier (Iron Age; e.g. Lagerås, 2007), and agricultural land did exist in such areas, whereas in the vegetation maps agricultural land was assigned to the lowland coastal zone only.

Future improvements of the maps should therefore include a non-random distribution of vegetation patches based on the spatial distribution of soil types, hydrology, archaeological findings and past population density. Despite these problems, the maps and associated pie charts are thought to give the best available spatial representation of the extent of vegetation changes in this region, which is highly underestimated in the pollen percentage values shown in Figure 2. They can be used to visualize the land use changes discussed in the next section.

Crop cultivation

In Figure 2 the summarized pollen percentages indicating cultivated fields are shown for both study sites on an age scale. The error margins for both age-depth models, as presented in appendix I and II, should be noted. The levels for which a vegetation map has been constructed are indicated with arrows in Figure 2. Both sites show development of cultivated fields around 4100 and 2900 cal. yrs BP, the latter time period with a modelled extent of cultivated fields of 3% (Figure 2a, 3a). After a long period with low values, agricultural expansions were recorded at 1550, 1300, 840 (Figure 3b) and after 350 cal. yrs BP (Figures 3d,e; 200 and 50 cal. yrs BP) at both sites, but with an early expansion at 2200 cal. yrs BP at Undarsmosse, whereas strong decreases are seen at 1450, 1100 and 400 cal. yrs BP. The main difference between the two records is seen between 750 and 550 cal. yrs BP. This could reflect site specific developments, but on the other hand a dating offset may exist between Store Mosse and Undarsmosse bog. As discussed in appendix II, it is possible that the strong decline of cultivated fields from *ca.* 17 to 0 % recorded at Store Mosse bog shortly after 780 cal. yrs BP (Figure 3b, c) is too old.

However, the overall pattern of expansion and decline of cultivated land is similar between the two sites and both records show a general increase of cultivation after 3000 cal. yrs BP. Moreover, comparison to the results of Berglund (2003) shows that the reconstructions of cultivation from west Halland concur with the overall development in north-west Europe, with expansion phases shortly before 4000 and around 2800 cal. yrs BP,

Figure 3 Hypothetical vegetation maps showing the modelled (REVEALS) vegetation abundance for 6 vegetation groups; coniferous forest, broadleaved deciduous forest, trivial deciduous forest, heath land, cultivated crops, grassland and wetland areas for five time intervals; 2900 cal. yrs BP, the time period of the first appearance of cultivated crops in the pollen record from Store Mosse bog; 850 cal. yrs BP, during a period with a large expansion of cultivated fields; 750 cal. yrs BP, just after a strong decline in cultivated areas. Grassland is very extensive, an effect that may be caused by grasses thriving on the abandoned cultivated fields; 200 cal. yrs BP, reflecting the major heath expansions that took place in large parts of western Europe around this time and; 50 cal. yrs BP, the most recent time period available from the Store Mosse bog records, showing the increased importance of forestry (coniferous trees)

and decreasing values around 1450 cal. yrs BP. An exception is the reduction of cultivated fields at the two study sites around 1100 cal. yrs BP; this is a phase of expansion in the reconstructions by Berglund (2003). However, other local studies in the south Swedish upland (Lagerås, 2007) record a similar development as shown in Figure 2 around this time period.

The extent of the vegetation and landscape changes as modelled by REVEALS during the recorded expansions and reductions of agricultural land can be seen in Appendix II (Figure 6); for example the peak of cultivation indicators around 800 cal. yrs BP of 2% (Figure 2a) corresponds to a modelled proportion of 18 % of cultivated fields in the regional vegetation. The changes shown in Figure 2a, with cultivation indicators ranging only between 0 and 4% of pollen, thus correspond to fairly large-scale changes in the landscape (Figure 3).

Grassland areas

The total sum of grazing indicators for the Store Mosse and Undarsmosse bogs are shown in Figure 2c. For both localities the pattern is very irregular, although at Undarsmosse a generally increasing trend is recorded from 4500 cal. yrs BP and onwards. The comparison between the records from both sites shows many differences, although during some time periods (1700, 1000, 700 and 400 cal. yrs BP) an apparently simultaneous short-lived decrease of grazing indicators is indicated. Simultaneously high values are, for example, recorded at 500 cal. yrs BP, but due to the irregular patterns the records are difficult to interpret. It has to be kept in mind, that according to Sugita (2007) the pollen spectra from both sites reflect a very different spatial scale; the record from Store Mosse represents changes on a regional scale, whereas at Undarsmosse the local, nearby changes are recorded. As a result the record from Store Mosse appears 'smoothed' in comparison, since it reflects a large region comprising both the coastal plain and the upland forested regions.

An additional difficulty is that increases in grassland indicators can be caused by different land use changes; 1) an expansion of grazing areas, 2) the overgrowing of abandoned cultivated fields (resulting in a short phase of grass blooming, followed by an increase in shrubs such as birch), and 3) the abandonment of a grazing area (if a heavily grazed pasture is abandoned, the grasses can flower and produce high amounts of pollen). A straightforward interpretation of the grazing records is thus not possible, although grassland indicators are in general interpreted as an expansion of grazing areas.

5.2 Land use changes and the ASI record; did land use changes cause ASI peaks?

An overall comparison of the land use records (Figure 2a,c) and the ASI record (Figure 2b) shows, that as agricultural areas expanded after ca. 3000 cal. yrs BP, the amplitude of ASI peaks increased. This suggests that as the landscape gradually became more open, sediment availability increased, thereby amplifying sand influx values. The overall long term pattern of the ASI record may thus be related to a general increase in human land use in the region.

However, when comparing the records for cultivated pollen indicators and ASI influx directly for each ASI peak event, a clear pattern emerges; ASI peaks occur when pollen types indicating cultivated fields are low. This can be seen at both study sites during each of the reconstructed ASI peaks occurring before 1000 cal. yrs BP (Figure 2). After that time, the only exception is the ASI peak at Undarsmosse occurring at 800 cal. yrs BP, which coincides with a generally high sum of cultivated field indicator pollen. The ASI peaks after 400 cal. yrs BP also coincide with small, short-lived decreases in crop indicators.

Thus, with one exception, sand influx peaks are greatest when crop cultivation is limited. The pattern is less clear for grazing indicators, but there is no clear and consistent pattern suggesting a causal link between these two proxies. High grassland values frequently occur *after* ASI peaks, around 2000, 1350 and 500 cal yrs BP at Store Mosse, and around 1100, 800 and 500 cal. yrs BP at Undarsmosse. In addition, high grassland values such as those recorded around 3500 cal. yrs BP (Store Mosse) and 2800 cal. yrs BP (Undarsmosse), occurred during a prolonged phase of very low ASI values. These findings imply that individual ASI peaks are not causally related to increased land use, thus providing evidence that the ASI peak events are caused by climatic factors.

5.3 A causal link between climate and land use changes?

As discussed in appendix II, the agricultural changes during recent time may be ascribed to demographic changes, such as the occurrence of the bubonic and pneumonic plagues in Sweden at 1349 AD and the associated severe population decline. At both sites, a reduction of the cultivated fields is seen around this time, although at Store Mosse there seems to be an offset in the exact timing; the causal link between the Black Death and the disappearance of cultivated fields around Store Mosse thus remains tentative (appendix II, Figure 6). The increase of agricultural land areas after AD 1349 is most likely caused by an increase in population. Recent landscape and vegetation changes may thus be attributed to demographic changes, but for the largest part of the record population data are not available.

Berglund's (2003) hypothesis can now be tested on the results presented here. The general occurrence of ASI peaks during periods of low or absent agricultural indicators may imply that climatic changes have affected regional land use. However, ASI peaks generally occur in the middle of a time period with reduced agriculture and not during the agricultural decline, which suggests that the ASI peaks and associated climatic events did no cause the declines. However, as shown in appendix III (Figure 3), the ASI peaks occur at the end of climatic transitions and continue for a short while during the next climatic phase. This implies that the onset of the overall climatic changes precedes the ASI peaks by 50-100 years, and may therefore approximately coincide with the agricultural declines. However, due to the low sampling resolution in the testate amoebae record and partly also in the pollen records, this link cannot be analysed in detail. Nevertheless, the overall pattern suggests a causal link between changes in the dominant climatic regime and vegetation change. Furthermore, as in Berglund's (2003) studies, the climatic changes and ASI peaks recorded here generally coincide with well-known climatic coolings in the North Atlantic region (Appendix I).

6 Long-term reconstructions of storminess and humidity; a clue to atmospheric circulation patterns?

To reconstruct atmospheric circulation changes in the past, information on different climatic proxies is needed. Below the reconstructions of humidity and storminess from this study will be discussed and compared to other records from southern Sweden, and a regional model for climatic changes is suggested.

6.1 Humidity reconstructions

In this section two different proxies are used for a long term reconstruction of humidity variations; OBD from Store Mosse and Undarsmosse bog and δ^{18}O from lake Igelsjön (Hammarlund *et al.*, 2003; Seppä *et al.*, 2005). The shorter-term variations between *ca*. 1700 and 50 cal. yrs BP from testate amoebae based wetness and water-table reconstructions are discussed in appendix III. All these proxies reflect humidity changes in different ways and should therefore be interpreted with care.

OBD as a proxy for humidity changes

OBD values were used as a proxy for humidity changes at the peat surface. The OBD values from Store Mosse and Undarsmosse bog are shown in Figure 4b and c and will be discussed in section 6.1.2. The interpretation of OBD values in general, however, needs to be assessed first.

Ash-free organic bulk density is a measure for the amount of dry organic carbon per cm^3. The amount of non-organic carbon was thought to be negligible since both sampling sites are situated in granitic bedrock basins. OBD values reflect the degree of peat decomposition (Björck and Clemmensen, 2004); high decomposition results in fine organic particles, giving a higher value for the amount of carbon per volume unit and thus a high OBD value. Low decomposed peat consists of larger plant remains and a relatively high proportion of water, thus resulting in low OBD values. Low OBD values indicate that peat growth was rapid and surface conditions were wet during the growing season of *Sphagnum*. High values indicate that surface conditions were relatively dry and peat decomposition was high, and/or that the accumulation rate was low.

A weakness of this proxy is that the OBD signal may have a delayed response to humidity changes; peat humification can take place a long time after peat formation. However, as a result the age assigned to the dry conditions may be too old due to secondary peat humification. This is especially important at transitions from wet to dry phases, because secondary humification of peat may take place as the water level falls (Borgmark and Schoning, 2006). In addition, OBD is not necessarily a very sensitive proxy for humidity changes; the OBD record from Undarsmosse bog does not show the humidity changes reconstructed by testate amoebae analysis (Appendix III). The sensitivity of the proxy may also be time-dependent as the ecological setting of a site changes from a minerotrophic fen to an ombrotrophic bog. Short term OBD variations can also be local due to hummock and hollow micro-topography on the bog surface.

Another drawback in the interpretation of OBD records is that it is not possible to determine which climatic parameter controls the main signal; OBD values are a measure for bog surface humidity, which is controlled mainly by precipitation and evapotranspiration (thus temperature). In addition, since these parameters vary on very long time scales as well as throughout the year, it is not possible to determine which season is mainly reflected by the OBD records. This prohibits detailed climatic reconstructions based on OBD values alone.

Regional scale humidity changes

In Figure 4 the OBD records are plotted next to the stratigraphies from the Undarsmosse and Store Mosse bogs, which have been adjusted to match the age scale. Figure 4d shows the δ^{18}O values from Lake

Igelsjön. The OBD records from the Store Mosse and Undarsmosse bogs (Figure 4b and 4c) show a very similar long-term pattern; relatively dry conditions from 6500 to 2000-1700 cal. yrs BP, interrupted by a short, very dry period around 4700-4500 cal. yrs BP. After ca. 2000 cal. yrs BP, OBD values decreased strongly at both sites, reaching low values around 1500 cal. yrs BP. The slightly higher OBD values at Store Mosse between 1300 and 1100 cal. yrs BP may indicate drier local conditions. From 400-100 cal. yrs BP both sites record high OBD values. Although the long term trends are very similar at both sites, several important differences exist; 1) the average OBD values at Store Mosse bog are much lower than at Undarsmosse bog, 2) the onset of the transition to low OBD values at Store Mosse (2000 cal. yrs BP) precedes the transition at Undarsmosse bog (1750 cal. yrs BP) and 3) OBD fluctuations at Store Mosse after this transition are larger than at the Undarsmosse bog.

The overall lower OBD values at Store Mosse bog are most probably related to the generally higher annual precipitation at this site, located at the transition to the upland region (section 2.5). It is thus likely that the average water-table at Undarsmosse bog has been lower than at Store Mosse bog, especially during summer, leading to generally higher peat humification. The transitions to lower OBD values after 2000 cal. yrs BP is interpreted as the onset of ombrotrophic conditions. This was confirmed by testate amoebae analysis at the Undarsmosse site, and is recorded in the peat stratigraphy (Figure 4a) by a shift to low humified (*Sphagnum*) peat at both sites. Influx and concentration values of *Sphagnum*

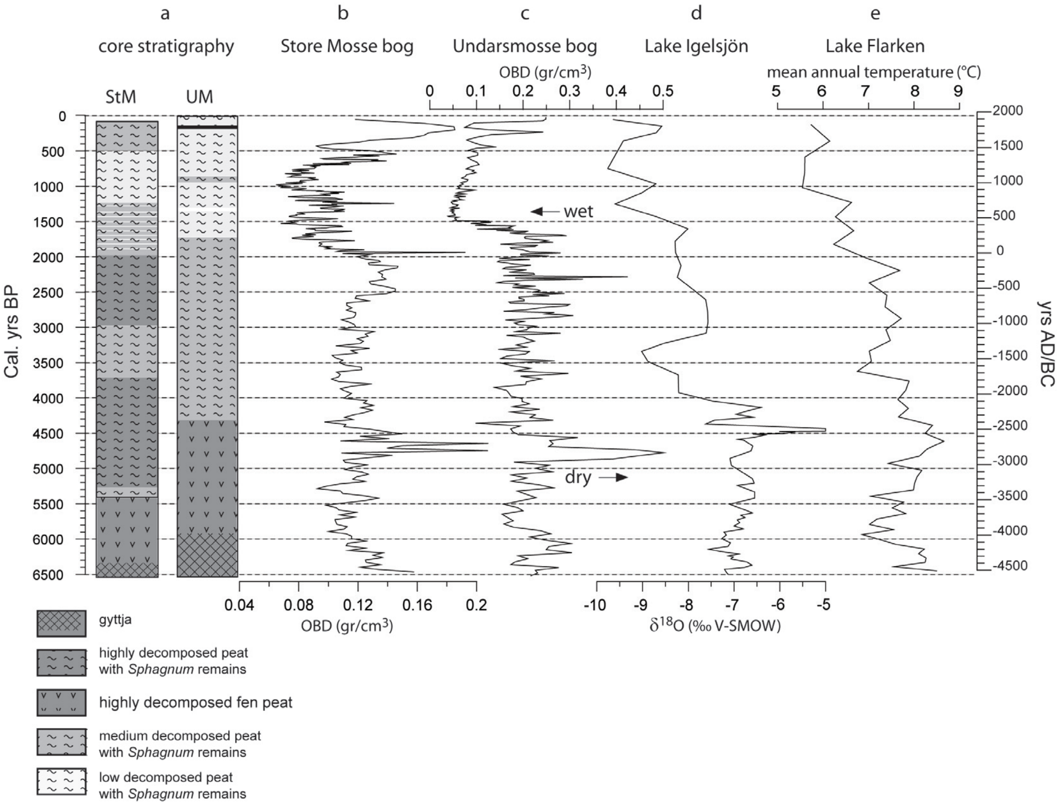

Figure 4 a) Core stratigraphies from both the Store Mosse bog (StM) and Undarsmosse bog (UM) adjusted to match an age-scale, b) Organic Bulk Density (OBD) values from the Store Mosse bog; high OBD values indicate high peat humification reflecting dry bog surface conditions, whereas low values are interpreted as wet conditions, c) Organic Bulk Density (OBD) values from the Undarsmosse bog (note the different scale on the horizontal axis between b and c!), d) $\delta^{18}O$ *values measured on bulk carbonates in Lake Igelsjön, south-central Sweden (Hammarlund et al., 2003; Seppä et al., 2005). Strongly negative values indicate high lake levels and humid and/or cold climatic conditions, e) Mean annual temperature reconstruction based in pollen-climate transfer functions and pollen data from lake Flarken, south-central Sweden (Seppä et al., 2005)* spores increase strongly at both sites at the time of the transition (appendix I and III). The earlier transition to ombrotrophic conditions at the Store Mosse site is probably also caused by the higher annual precipitation here.

The $\delta^{18}O$ record from Lake Igelsjön (Figure 1) is shown in Figure 4d. This record is based on a detailed chronology before *ca.* 3000 cal. yrs BP (Hammarlund *et al.*, 2003; Jessen *et al.*, 2005), whereas the age model from 3000 cal. yrs BP to modern time was based on only two ^{14}C dates. Sampling density after 3000 cal. yrs BP is also low. The $\delta^{18}O$ values were measured on bulk carbonates, precipitated mainly by *Chara* algae (Hammarlund *et al.*, 2003). Since the turnover time of the lake is in the range of weeks to months, there is no delayed response in the proxy record as is the case for OBD values. The $\delta^{18}O$ values were interpreted as a proxy for effective precipitation, which is determined by the ratio precipitation/evaporation (Hammarlund *et al.*, 2003). Also shown is the annual mean temperature reconstruction based on pollen-climate transfer functions and pollen stratigraphical data from Lake Flarken, situated just 10 km north of lake Igelsjön (Seppa *et al.*, 2005)(Figure 4e). This record has a high sampling density before 4000 cal. yrs BP, but after this time both the sampling density and the chronological control decrease.

The $\delta^{18}O$ values and the OBD records from this study are generally in good agreement, although the variation in the lake record is larger than in the bogs before 2500 cal. yrs BP. This difference is thought to be mainly due to the ecological setting of the bogs during this time; increases of the water-table in a minerotrophic mire would have a less strong effect on the humification of the sediment, whereas the $\delta^{18}O$ record is sensitive to such changes during the entire time period. Dry conditions, on the other hand, would affect peat humification in a mire, which is clearly seen around 4700-4400 cal. yrs BP when all three records show exceptionally high values, indicating dry conditions. In the temperature reconstruction, this time period is characterized by a small peak of annual temperatures, followed by steadily decreasing values. The suggestion of higher temperatures around this time is corroborated by analysis of organic carbon and calcium carbonate production in Lake Igelsjön (Jessen *et al.*, 2005), which show a strong increase and decline respectively. This was interpreted by the authors as a possible intensification of the warm and dry conditions that existed before this peak, causing an increase of productivity by the organic carbon producing algae at the expense of calcite producing algae (Jessen *et al.*, 2005).

The dry peaks recorded at the Store Mosse and Undarsmosse bogs and Lake Igelsjön are interpreted as a true signal; at all three sites the peak values around 4700-4500 cal. yrs BP are based on multiple measurement points. The maximum values at these three sites may have occurred synchronously, which is possible when the chronological control and error margins are taken into account. The dating around this time is probably most secure at Lake Igelsjön where 5 ^{14}C dates on macrofossils were performed between 3500 and 4500 cal. yrs BP (Jessen *et al.*, 2005). At Store Mosse only one date is available around this time, 4280 +/- 135 cal. yrs BP, whereas at Undarsmosse the nearest date is 4795 +/- 185 cal. years BP (appendix I and II). It is thus possible that the peaks at the Store Mosse and Undarsmosse bogs are too old and are synchronous with the very low effective precipitation minimum recorded in Lake Igelsjön.

Between 2000 and 1700 cal. yrs BP the OBD and $\delta^{18}O$ lake records show a shift to increasingly wet conditions. As discussed earlier, this represents the transition to ombrotrophic bog conditions at the Store Mosse and Undarsmosse bogs, but the increase in effective humidity around the same time at Lake Igelsjön may suggest that this ecological shift was favoured by a regional scale climatic change to more humid conditions, with increased precipitation and/or decreased evapotranspiration. The temperature reconstruction shows a rapid temperature decline starting around 2300 cal. yrs

BP, although due to the low resolution of the Lake Flarken record after 4000 cal. yrs BP the exact timing of this change is not certain. However, this generally decreasing temperature trend suggests that the increased humidity after this time was –at least partially- due to decreased evaporation.

The period from 400 to ca. 100 cal. yrs BP is again characterized by dry conditions in the OBD records. Although the age-control for Lake Igelsjön is poor in this recent part, the top section appears to show a similar trend of decreased effective precipitation. The resolution and age control of the Lake Flarken record are too unreliable to interpret the temperature record during this time period. Thus, the most important features that can be seen in these records are; 1) extremely dry and possibly warm conditions between 4700 and 4450 cal. yrs BP, 2) transitions to wetter and cooler conditions after 4400 and 2000 cal. yrs BP, and 3) dry conditions from 400-100 cal. yrs BP. The latter period is also recognised in the testate amoebae reconstructions from Undarsmosse bog (Appendix III). Based on the comparison in Figure 4 it becomes clear that;

- The hydrological trends indicated above appear to have occurred more or less simultaneously, and therefore these trends are thought to reflect regional scale climatic changes. The causes of these changes and a comparison to records from the North Atlantic region will be discussed in section 6.3.
- The dry conditions around 4700-4450 cal. yrs BP appear to coincide with increased temperature, which is supported by chemical analysis of the sediments from Lake Igelsjön (Jessen *et al.*, 2005).
- The transition to ombrotrophic conditions after *ca.* 2000 cal. yrs BP coincides with increased effective humidity at Lake Igelsjön and with decreasing temperatures, as reconstructed from the pollen data from Lake Flärken (Seppä *et al.*, 2005). Although it cannot be excluded that this ecological shift was the result of long-term natural succession from a minerotrophic mire to a raised bog, the climatic conditions around this time favoured ombrotrophic bog formation.
- The dry conditions from 400-100 cal. yrs BP are recorded in the OBD, $\delta^{18}O$ and testate amoebae reconstructions and appear to be a regionally synchronous climatic signal.

To interpret these changes and to infer atmospheric circulation changes, a comparison to other records in the North Atlantic region is needed. This will be done in section 6.3. The ASI records from the Undarsmosse and Store Mosse bogs also provide information on atmospheric circulation that can be compared to the OBD records, and therefore the reconstruction of storminess based on sand influx will be discussed first.

6.2 Aeolian activity reconstructions

ASI as a proxy for –winter?- storminess

In this section ASI reconstructions from the Undarsmosse and Store Mosse bogs are used for a reconstruction of aeolian activity. ASI is a measure of the number of sand grains deposited per cm^2/year. The amount of sand that is transported depends on two factors; sediment availability and transport capacity. As shown in chapter 5, sediment availability increased after ca. 3000 cal. yrs BP due to increased human land-use and landscape opening. In addition increased sample resolution and possibly also a sea-level increase could have caused increased sediment availability. Individual ASI peaks, however, could not be linked causally to increased land-use and therefore the ASI peaks are interpreted as climatic signals, indicating increased storm frequency and/or intensity.

In both study areas, cores were taken in the central part of the bogs and therefore it is unlikely that even during the mire phase sand was transported by other processes than wind action, since there are no inlets into the bogs. As mentioned in section 1.2, Björck and Clemmensen (2004) tentatively interpreted the ASI record as a proxy for winter snow storms. To study the suggested seasonality of the ASI signal, modern sand transport was monitored for three month periods from September 2003 to September 2006.

Modern ASI from sand traps

In Figure 5a the total seasonal sand influx is shown for four grain-size classes for the three year measurement period. In general ASI is highest during autumn (son) and winter (djf). The ASI of fine-medium sand was highest during autumn, (in particular son 2004), whereas ASI of the largest grain-size (>350 µm) shows the highest values during winter, in particular winter (djf) 2003-2004. The grain-size groups thus appear to indicate different conditions. The cause for this difference is not known; it may be related to different dominant wind directions and thus different sediment source area characteristics, different distances to these source areas, more extreme winter storms, or perhaps most likely, the presence of snow/ice in winter favours long transport of coarser particles through saltation processes. The maximum grain-size measurements appear to confirm the trend of high values during autumn and winter; in Figure 4b the stacked maximum grain-size for two trap series shows that the largest particles were deposited during the winter season. The second highest values are seen in the autumn samples. Although the time series are much too short to draw any conclusions, the results appear to confirm the dominance of a cold-season signal in the ASI values. However, the data also reveal that a few large grains (up to 480 µm) were deposited during summer (jja, 2004). The mechanism for the transport of such large sand grains in summer is as of yet not well understood.

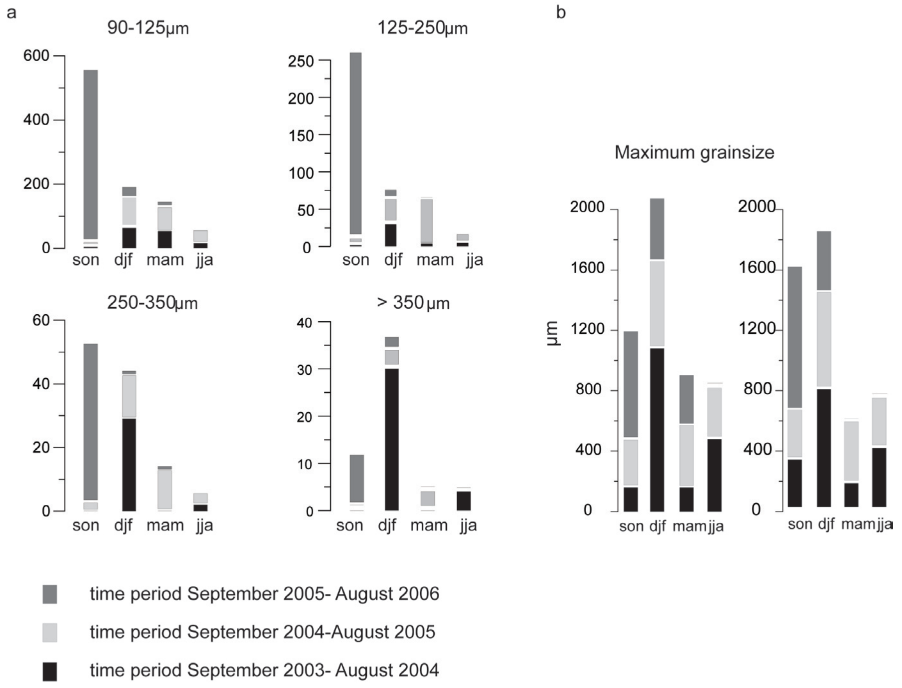

Figure 5 Modern trap influx measurement data for the time period September 2003 –August 2006, showing a) the influx of grains for four grainsize classes per season, and b) the accumulated maximum grainsize per season, shown for two trap measurement series, situated 50 m apart.

Aeolian activity phases in south-west Scandinavia

Aeolian activity as reflected by sand influx values is shown in Figure 6 for both study sites. The comparison shows that the timing of ASI peak events is remarkably similar at both sites, despite the 60 km distance between them and the different character of the surrounding area; Undarsmosse is situated in the close proximity of beaches and dune areas, whereas Store Mosse bog is surrounded by agricultural land on sandy-silty soils, but at a considerable distance to the nearest sand dune deposits (*ca.* 6 km). The close correlation between the two records is a strong indication that the ASI records reflect regional scale changes in aeolian activity. This is further confirmed by the many coinciding dune re-activation phases reconstructed at the west coast of Denmark (Clemmensen *et al*, 2001; 2006) (Figure 6c), and similarities in timing of increase storminess as recorded in ASI records from Boarps Mosse and Hyltemossen (Björck and Clemmensen, 2004) and grain-size analysis from the Skagerrak (Hass, 1996) during some of the ASI peaks recorded in this study (appendix I, Figure 6).

However, a few points have to be considered in connection with the interpretation of ASI records;

- ASI peaks may be caused by a limited number of extreme storms. Peaks are usually composed of more than one sample with high ASI values, but the ASI peaks should not be seen as time periods with a continuously high storm activity. The number of storms causing these peaks cannot be reconstructed. Dune records on the other hand do not generally record single storm events, but imply a general climatic change to more stormy conditions.
- In comparison to dune development phases, ASI values are thought to respond quickly to climatic changes. Dune re-activation may be delayed, but once activated dune activity may continue for a long time even under less stormy conditions.
- ASI records are tentatively interpreted as a proxy for winter storms (Björck and Clemmensen, 2004), which is partly supported by the results

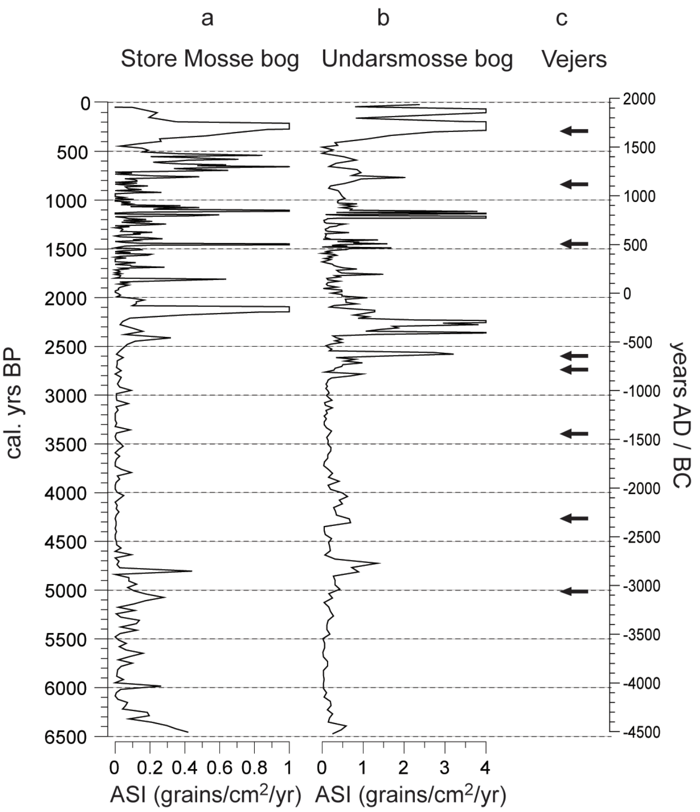

Figure 6 Aeolian activity reconstructions as reconstructed from; a) ASI values from the Store Mosse bog, b) ASI values from the Undarsmosse bog and c) dune re-activation phases reconstructed at Vejers dunefield, Denmark (Figure 1; Clemmensen et al., 2001; 2006). ASI maximum values are clipped at 1 and 4 grains/cm^2/yr respectively

from the sand traps as described above. Dune development is, however, interpreted differently by different authors; Clarke and Rendell (2006) interpret dune activity in France and Portugal as winter signals, whereas Clemmensen and Murray (2006) interpret the dune re-activation phases as a proxy for increased spring and summer storminess.

Figure 6 shows that during seven time periods ASI influx values show apparently simultaneous increases at the two bogs; 4600, 2800-2100, 1700, 1450, 1100, 800-600 and 400-100 cal. yrs BP. At Vejers dunefield dune re-activation (indicated by arrows in figure 6c) appears to coincide with increased ASI around 5000, 2800, 2600, 1450, 800 and 400 cal. yrs BP (Clemmensen *et al.*, 2001; 2006). The causes for these often simultaneous increases in aeolian activity will be discussed in the next section, together with the reconstructed humidity variations described in the previous section.

6.3 *Atmospheric circulation reconstructions*

Figure 7 summarizes the results from the ASI-based storminess reconstructions, the long term humidity reconstructions based on OBD values from both study sites, $\delta^{18}O$ values from Lake Igelsjön and the humidity reconstructions during the past 1700 years based on testate amoebae reconstructions from Undarsmosse bog (Appendix III). The temperature reconstruction from Lake Flarken (Seppä *et al.*, 2005) is also shown (Figure 7b). Together these records can be used to obtain a climatic reconstruction for south-west and south-central Sweden, as indicated in Figure 7c and d; thick lines indicate the approximate timing of major changes in temperature and humidity as reconstructed at all four sites. Dotted lines indicate the humidity transitions recorded after 1700 cal. yrs BP in the testate amoebae record from Undarsmosse bog only.

In the right hand side of Figure 7, the time periods of rapid climatic change (RCC) as reconstructed by Mayewski *et al.* (2004) are shown. This reconstruction was based on the scheme of glacier fluctuations as proposed by Denton and Karlén (1973), which was then compared to *ca.* 50 palaeoclimate records from the northern and southern hemispheres by Mayewski *et al.* (2004). Although not all sites respond simultaneously or equally during these time periods, the general scheme of RCC's is useful to interpret climatic records from a relatively small region (such as in this study) in the light of global-scale climatic changes. In addition to the RCC's from Mayewski *et al.* (2004) two periods of change recorded in many records in the Northern Hemisphere (NH, Figure 7f) are also shown (Mayewski *et al.*, 2004 and references therein); 2800 – 2000 and 1500 cal. yrs BP. The climatic changes recorded in south-west and south-central Sweden will now be discussed in the light of these large-scale RCC's and NH records.

4800 -4500 cal. yrs BP

Between 4800 and 4500 the first major climatic change was recorded in the sediments in this study; sand influx increased slightly around 5000-4800 cal. yrs BP, whereas humidity indicators show a distinct dry peak around this time and temperature increased. These results indicate dry and warm conditions in the study region, possibly with a short-lived increase in storm activity. Although this time period is not reflected in the global RCC's (Figure 7e), marine records from the north Atlantic region (Bond *et al.*, 1997; 2001) also show a distinct change around this time period with increased ice rafting, indicating a strong southward advection of polar waters. Together these records may indicate a frequent occurrence of blocking situations over Scandinavia in summer during a period with generally weakened westerly flow, which could indicate meridional flow conditions. However, since these changes are not reflected in the majority of sites used in Mayewski *et al.* (2004), the climatic changes reconstructed in southern Sweden between 4800-4500 cal. yrs BP may be of a regional character.

4400 cal. yrs BP

Immediately after the peak in temperature and dry conditions, a rapid transition to cooler and wetter conditions took place. This transition was interpreted as the onset of Neoglaciation by e.g. Hammarlund *et al.* (2003) and Jessen *et al.* (2005) and the time period of climatic instability lasted from *ca*. 4500 to 3400 cal. yrs BP according to Jessen *et al.* (2005). During the transition to cooler and wetter conditions, storminess appears to have been slightly higher between 4300 and 4000 cal. yrs BP, although this was not recorded at the Store Mosse bog (Figure 6). The timing of the onset of 'Neoglaciation' differs greatly between sites (e.g. Jessen *et al.*, 2005; Jessen, 2006). This time period appears to coincide broadly with the RCC from 4200-3800 cal. yrs BP (Figure 7), but the climatic signal during this RCC is not very strong and different in character between sites (Mayewski *et al.*, 2004). The climatic reconstructions from southern Sweden however, appear to indicate an increasing dominance and strength of westerly flow over this region after 4400 cal. yrs BP.

2800- 2000 cal. yrs BP

Around 2000 cal. yrs BP a second major shift in temperature and humidity took place in southern Sweden; humidity increased strongly around this time, whereas the annual temperature decreased already around 2300 cal. yrs BP (Figure 7b). The timing of this change is difficult to determine based on the records from southern Sweden; the OBD record may show a delayed response because it reflects the transition to ombrotrophic bog conditions, and the dating of the lake records is not very secure around this time. The most important change in storminess, however, took place before 2000 cal. yrs BP; between 2800 and 2000 cal. yrs BP several peaks in aeolian activity were recorded at both bog sites and at Vejers dunefield (Figure 6, 7a). This increase is synchronous with the climatic changes recorded in the Northern Hemisphere (NH, Figure 7e) in particular, but also with the global RCC from 3500 to 2500 cal. yrs BP. Around this time ice rafting increased, alpine glaciers advanced, the Scandinavian tree-limit decreased and westerlies were strengthened over the North Atlantic and Siberia (Mayewski *et al.*, 2004 and references therein). The results from this study may indicate that the Polar Front shifted southward, an effect that would have been most pronounced in winter, and would cause a strong increase in the atmospheric contrasts over the North Atlantic and cooling in northern Scandinavia in winter. The RCC is also clearly reflected in records from outside the northern hemisphere, indicating the global extent of this period of climatic change. The regional increase in humidity and decreased annual temperatures after 2000 cal. yrs BP could be explained by intense westerly airflow over the region, which may indicate a dominance of zonal flow conditions.

2000-500 cal. yrs BP

After 2000 cal. yrs BP the climatic reconstructions become increasingly complex, with relatively rapid humidity changes accompanied by increased aeolian activity during these transitions, as described in Appendix III. Although this increased complexity may in part be an artefact of improved resolution of the Store Mosse and Undarsmosse records and increased sensitivity of the bog basins, two short events around 1500 and 1100 cal. yrs BP are also seen in the RCC and NH records in Figure 7. The former time period is characterized by increased ice rafted debris in the North Atlantic (Bond *et al.*, 1997), whereas between 1200 and 1000 cal. yrs BP glaciers in northern Scandinavia expanded and conditions became generally cooler here (Mayewski *et al.*, 2004). More detailed interpretations of the aeolian and humidity records during these time periods are provided in Appendix III.

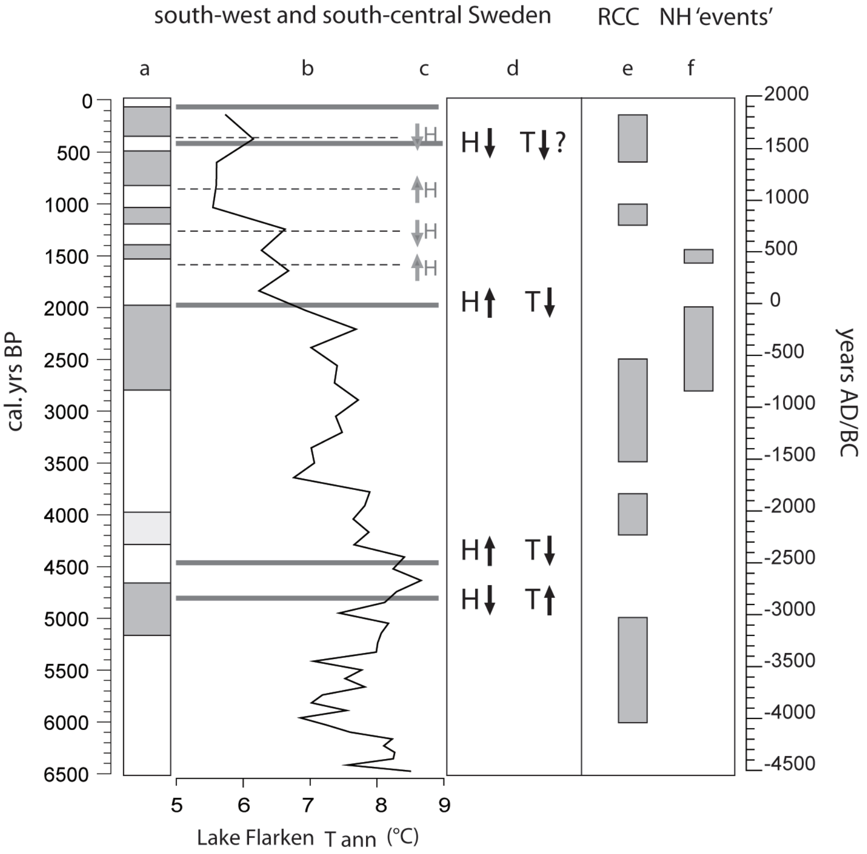

Figure 7 Summary of climatic data from south-west and south-central Sweden and a comparison to global scale events of Rapid Climatic Change (RCC, Mayewski et al., 2004) and time periods of major climatic change in the Northern Hemisphere (NH), as summarized by Mayewski et al. (2004). The figure summarizes a) time periods of major changes in aeolian activity, based on ASI data from both the Store Mosse and Undarsmosse bog. The light grey band just before 4000 cal. yrs BP reflects a time period when increased aeolian activity was not seen in the Store Mosse record. b) Mean annual temperature reconstruction from lake Flarken (Seppä et al., 2005) c) Summary of results from testate amoebae analysis on humidity variations at the Undarsmosse bog (Appendix III), d) Summary of humidity reconstructions from OBD records from this study, the $\delta^{18}O$ *values from Lake Igelsjön and the temperature changes recorded in b (Hammarlund et al., 2003; Seppä et al., 2005), showing the approximate timing of phases of major humidity and temperature changes in south-west and south-central Sweden, e) Timing of global cale periods of rapid climate change (RCC; Mayewski et al., 2004), f) Timing of important climatic changes recorded in the Northern Hemisphere, as summarized by Mayewski et al. (2004)*

400 cal. yrs BP

Shortly after 400 cal. yrs BP a change to dry conditions was reflected in all records, whereas at the same time aeolian activity increased strongly. The temperature reconstruction from Lake Flarken may not be very reliable in this recent period due to low sampling density and poor chronological control, but generally conditions around this time are thought to have been much colder than previously, especially in winter (e.g. Lamb, 1985; Grove, 2001). Again, the changes recorded in southern Sweden occur during a period of global scale climatic changes, as shown by Mayewski *et al.* (2004; Figure 7). In the northern hemisphere glaciers advanced and westerlies over the North Atlantic and Siberia increased strongly, suggesting very fast and strong climatic changes during this time period (Mayewski *et al.*, 2004). The dry conditions recorded in southern Sweden may indicate the frequent occurrence of blocking situations in all seasons; this would lead to very dry conditions, with cold and dry winters and/or dry and possibly slightly warmer summers. This may point to meridional flow conditions, or a southward shift of the entire circumpolar vortex, as suggested by e.g. O'Brien *et al.* (1995).

6.4 Causes of climatic changes; a solar link?

Changes in solar irradiance are frequently mentioned as an important cause for apparently simultaneous climatic changes (e.g. Denton and Karlén, 1973; Van Geel *et al.*, 1996; Bond *et al.*, 2001; Mayewski *et al.*, 2004), although the topic is debated; not all climatic changes occur during altered solar irradiance and the mechanism causing the actual climatic change is not clear, although different mechanisms have been proposed (e.g. Van Geel *et al.,* 1999). A comparison between the reconstructed RCC's in Mayewski *et al.* (2004) to several different possible forcing factors – volcanism, CO_2 content of the atmosphere, atmospheric methane concentrations, insolation changes and solar irradiance variations - shows that for several RCC's reduced solar irradiance appears to be a possible cause for the observed global events. In numerous studies based on peat bog wetness variations (e.g. Van Geel *et al.*, 1996; Mauquoy *et al.*, 2002, Chambers *et al.*, 2006) solar irradiance variations have been put forward to explain the observed humidity shifts. The timing of several large climatic shifts reconstructed in this study may also suggest a link to reduced solar irradiance; 'solar lows' are particularly strong around 4800, 2700 and between 600-275 cal. yrs BP as reconstructed from ^{14}C and ^{10}Be variations (Stuiver *et al.*, 1998; Bond *et al.*, 2001). Figures 4 and 6 show, that climatic changes were recorded around these time periods in this study as well. However, the chronological control in this project does not allow for a more detailed study between solar forcing and the climatic responses. Furthermore the absence of solar irradiance changes during several of the other reconstructed climatic changes indicates that other processes are also important for the climatic developments in southern Sweden.

7 Conclusions and recommendations

The reconstructions of vegetation and land use changes, humidity variations and storminess throughout the past 6500 cal. yrs BP have provided detailed yet complex information on the magnitude and timing of both vegetation changes and climatic change in the coastal zone of Halland, south-west Sweden. A comparison to pollen studies from other areas has shown that the land use changes recorded in this study concur with records from southern Sweden and also follow the general trends of deforestation and forest regeneration in north-west Europe. Modelling of the regional vegetation based on pollen productivity and dispersal values indicates that these vegetation changes were substantial and much larger than suggested by pollen percentage values. A strong increase in landscape openness was recorded at both study sites after 3000 cal. yrs BP, at the Bronze Age – Iron Age transition. The causes for landuse changes are debatable, but after 1300 cal. yrs BP demographic changes appear to have had an important control on the extent and intensity of land use. A direct comparison to climatic reconstructions of storminess and humidity changes shows, however, that climatic changes preceded changes in the extent of cultivated fields – thus suggesting a climatic control on land use changes.

Storminess reconstructions based on the ASI method were shown to be largely independent of sediment availability as controlled by vegetation disturbances, although the increase of ASI peak amplitude after 3000 cal. yrs BP may be linked to a more open landscape and increased sediment availability. ASI and dune re-activation appear to have been largely synchronous during many of the events reconstructed in this study, implying a regional significance of the ASI reconstructions as a proxy for storminess. However, differences in the interpretation of the used proxies should be kept in mind, as well as chronological uncertainties. Humidity reconstructions from the Store Mosse and Undarsmosse bogs generally concur with humidity reconstructions from lakes in southern Sweden, indicating that these reconstructions also reflect regional scale climatic changes. A detailed comparison between humidity variations and ASI at Undarsmosse bog after 1700 cal. yrs BP reveals an enigmatic pattern of increased storminess during climatic shifts, which can be used to infer changes in atmospheric circulation.

The overall comparison of humidity, storminess and temperature changes in south-west and south-central Sweden has revealed five important time periods of climatic change; 4800, 4400, 2800, 2000 and 400 cal. yrs BP. Around these time periods major changes in humidity, temperature and/or storminess were reconstructed. Based on these results a general reconstruction of atmospheric circulation changes was proposed; predominantly meridional flow before 4800 cal. yrs BP, an intensification of this situation until *ca.* 4400 cal. yrs BP; a stepwise shift to more oceanic/zonal flow conditions around 4400 and 2000 cal. yrs BP, with a strong intensification of atmospheric contrasts between 2800 and 2000 cal. yrs BP. After 1700 cal. yrs BP the climatic patterns become increasingly complex, with shorter term shifts between the dominant atmospheric circulation regimes. A comparison of these results to climatic records from the North Atlantic region and to global records apparently suggests large scale synchronicity of climatic changes during certain time periods. Important climatic changes, in particular around 4700, 2800, 2300 and between 600-200 cal. yrs BP, appear to be linked to time periods of increased ^{14}C production, suggesting a causal link to solar irradiance variations.

To test the suggested link between solar irradiance changes and climate, a more detailed chronology is suggested for future studies. This could be obtained by ^{14}C wiggle-match dating. In addition a more detailed reconstruction of humidity changes is required, especially for the time period older than 1700 cal. yrs BP, because the OBD records used in this study are affected by many factors other than climate. For the younger time period, testate amoebae analysis on the Store Mosse site would be highly usefull to test the validity of the link discussed in Appendix III; increased storminess during climatic regime shifts.

The reconstruction of vegetation changes would greatly benefit from additional pollen analysis in the region, preferentially from a large lake. If reconstructed vegetation data from a lake in this region could be compared to the data from Store Mosse bog presented in Appendix II, the importance of bog vegetation could be established and the regional vegetation reconstruction would be more secure. Macrofossil analysis would also be usefull in this context. In addition, pollen records from small sites could be used to model local scale vegetation changes, which could be implemented in the regional scale reconstructions.

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My time at the office would not have been as pleasant without the continuous support from the PhD (and post doc) group at our department. I want to give special thanks to the ‘thursday-lunch’ club people, with whom I shared all the fun and most of the suffering. Furthermore, I owe a big ‘thank you’ to Sofie Hellman, Marie-Jose Gaillard (both Kalmar University) and Anna Broström, for giving me the warmest of welcomes in Kalmar and for showing great interest in my work. I also want to thank Kristian Schoning (Stockholm University) for giving me the chance to develop the hydrological part of this thesis, which would not have been possible without his work. I greatly enjoyed discussing storms and other meteorological issues with Carin Nilsson (Physical Geography, Lund University). Karin Holmgren from the Länsstyrelse in Halmstad has kindly provided important background information on both study sites. I also enjoyed working together with Wim Hoek in supervising Femke Davids and Nadinja Hettinga (Utrecht University) during their masters’ fieldwork in Haverdal, Halland.

Last (but not least!) I want to thank my friends in Sweden and in the Netherlands; we have had dinners and parties, camping trips in the snow, skiing trips in the sun, climbing trips in the rain and swimming adventures in the night. It was fun! So let’s continue our journeys in another part of Europe...

Nederlandse samenvatting

Klimaatverandering en landschapsdynamiek in zuidwest Zweden tijdens de laatste 6500 jaar; een reconstructie van stormactiviteit en vegetatie op basis van veenkernen.

Het klimaat in de Noord Atlantische regio is gedurende het Holoceen sterk variabel geweest. en daardoor is ook het regionale klimaat in zuidwest Zweden beïnvloed. Een belangrijke factor voor globale en regionale klimaatveranderingen is het karakter van de atmosferische circulatie, ofwel het dominante patroon van luchtstroming in de hogere luchtlagen. Om deze circulatiepatronen te reconstrueren is gedetailleerde informatie over temperatuur, neerslag en stormintensiteit en - frequentie noodzakelijk. Eén van de belangrijkste doelstellingen in deze thesis is het reconstrueren van stormactiviteit en hydrologische veranderingen in zuidwest Zweden. Daarnaast zijn de veranderingen in landschap en vegetatie onderzocht, alsmede de oorzaken voor deze veranderingen. Vegetatiedynamiek kan deels verklaard worden door klimaatveranderingen maar sinds ongeveer 6000 jaar is menselijk ingrijpen in toenemende mate een oorzaak van veranderingen in de samenstelling van soorten en dichtheid van de vegetatie in dit gebied. Anderzijds hebben meerdere studies in noordwest Europa aangetoond dat het klimaat invloed kan hebben gehad op de variaties van het landbouwareaal en de intensiteit en het karakter van de landbouw.

De kustvlakte in de provincie Halland, zuidwest Zweden, ligt in een regio die sterk beïnvloed wordt door de frequentie en intensiteit van passerende lagedrukgebieden en de daarmee geassocieerde stormen en dominante luchtstroom vanuit het westen. In dit gebied valt daardoor de meeste neerslag van zuid Zweden en de dominante windrichting is in alle seizoenen westelijk. De intensiteit en 'route' die deze lagedrukcellen volgen is afhankelijk van de luchtdrukverschillen in de Noord Atlantische regio en de positie van het polaire front. Hoewel de meeste stormen in dit gebied vanuit het westen komen, komen ook stormen met een oostelijk windrichting voor. Deze situatie ontstaat als er een hogedrukgebied boven noordelijk Scandinavië ligt. Omdat stormintensiteit en -frequentie gekoppeld zijn aan de luchtdrukverdeling en de grootschalige luchtcirculatie, kan een reconstructie van de stormactiviteit in dit gebied een belangrijke bijdrage leveren aan de kennis over atmosferische circulatie in het verleden. Naast stormactiviteit zijn ook veranderingen in neerslag en verdamping van belang voor het regionale klimaat. Om de landschappelijke ontwikkeling in zuidwest Zweden te verklaren is er, naast een klimatologische reconstructie, ook informatie nodig over de veranderingen in landgebruik. Met name in de kustvlakte van Halland hebben mensen gedurende de laatste 6000 jaar in wisselende mate invloed uitgeoefend op het landschap. Dit gebied is dus uitermate geschikt voor een onderzoek naar klimaatverandering, ontwikkeling van de vegetatie en landbouw, en de mogelijke invloed van het klimaat op de aard en en de variatie van landbouw.

In dit onderzoek zijn twee veengebieden in de kustvlakte van Halland onderzocht, de Undarsmosse en Store Mosse venen. Beide veenkernen zijn gedateerd met de ^{14}C methode. De hoeveelheid ingewaaid zand per jaar (zandinflux) is gebruikt als indicatie voor stormactiviteit, aangezien eolisch transport de meest aannemelijke verklaring vormt voor de aanwezigheid van zandkorrels in het centrale deel van deze veengebieden. Zandinflux wordt echter ook beïnvloed door de beschikbaarheid van zand in de omgeving van de venen. Daarom is het belangrijk om te kijken naar de eventuele invloed van intensieve veeteelt en akkerbouw, omdat deze kunnen leiden tot een toename van het voor transport beschikbare sediment. Veranderingen in de vegetatiesamenstelling zijn gereconstrueerd met behulp van pollenanalyse. Naast de 'klassieke' pollenpercentages is de vegetatiesamenstelling rondom een van de onderzoeksgebieden ook kwantitatief benaderd. Hiervoor is gebruik gemaakt van het REVEALS model, dat corrigeert voor soort-specifieke verschillen in pollenproductie en -verspreiding. De hydrologische condities in de venen zijn gereconstrueerd met behulp van microfossielen (testate amoebae) en het gehalte organische koolstof in verhouding tot het watergehalte van het veen.

De resultaten voor de zandinfluxwaarden zijn voor beide venen vrijwel identiek, met hoge influxwaarden ca. 4700, 2800-2000, 1500, 1100 en van 400-50 jaar geleden. Deze resultaten kunnen vergeleken worden met bijvoorbeeld duinontwikkelingsfases in west Denemarken, waar een vergelijkbaar patroon van eolische activiteit gereconstrueerd is. Een directe vergelijking tussen zandinfluxpieken en pollenwaarden van gewassen die specifiek zijn voor akkerbouw laat zien, dat zandinflux hoog is wanneer akkerbouw beperkt is. Dit geeft aan dat de hoeveelheid beschikbaar sediment geen beperkende factor is en dat de intensiteit van landbouw niet bepalend is voor de zandinflux. Deze resultaten duiden er op, dat de zandinflux-waarden gebruikt kunnen worden als indicator voor stormactiviteit op een regionale schaal.

De hydrologische condities in beide venen laten eveneens vergelijkbare veranderingen zien en deze komen grotendeels overeen met resultaten van andere studies in zuid Zweden. Stijgingen van de lokale waterspiegels zijn gedateerd in periodes rond 4400 en 2000 jaar geleden. Droge condities waren dominant rond 4700 jaar geleden en van 400 tot 50 jaar geleden. Een voorlopige interpretatie van deze resultaten luidt, dat langdurig droge condities duiden op een dominantie van hoge luchtdruk boven het onderzoeksgebied, mogelijk in combinatie met een breed meanderende luchtstroom (meridional flow) van de hogere luchtlagen. Tijdens de meest recente droge periode is het mogelijk dat een algehele zuidwaartse verschuiving van het polaire front is opgetreden. Perioden met vochtigere condities kunnen mogelijk verklaard worden door een dominantie van een sterke, westelijke luchtstroom (zonal flow) van de hogere luchtlagen. De toename van stormactiviteit in bepaalde periodes is moeilijk te verklaren, maar duidt op een toename van luchtdruk- en temperatuurcontrasten in de atmosfeer. Enkele periodes waarin regionale klimaatveranderingen optreden, lijken te vallen tijdens periodes met verminderde zonneactiviteit. Dit suggereert, dat zonneactiviteit een belangrijke factor is voor het klimaat in deze regio. Echter, niet alle klimaatveranderingen die in deze studie gereconstrueerd zijn kunnen aan een afname van zonneactiviteit gekoppeld worden, wat aangeeft dat dit niet de enige verklaring kan zijn voor grootschalige en regionale klimaatverandering.

Svensk sammanfattning

Händelserika och varierande data från två torvprofiler i Halland, sydvästra Sverige – resultat av regionala klimatvariationer och vegetationsförändringar under de senaste 6500 åren.

Klimatet i den Nordatlantiska regionen har varierat betydligt under holocen (de senaste 11600 åren), och därmed har också klimatet i sydvästra Sverige påverkats. En viktig faktor för det globala och regionala klimatet är hur den atmosfäriska cirkulationen fungerar. Jordens klimat styrs till stora delar av denna cirkulation, men för att kunna rekonstruera cirkulationen behövs data om såväl temperatur, nederbörd och vindstyrka. Ett av huvudsyftena med denna avhandling har varit att rekonstruera stormaktivitet och humiditetsvariationer i sydvästra Sverige under de senaste 6500 åren. Stormaktivitet anses vara en speciellt viktig klimatfaktor eftersom den är direkt kopplad till den atmosfäriska cirkulationen.

Landskapsutvecklingen med dess vegetationsförändringar, har också undersökts eftersom vegetationen, med dess utveckling och förändringar, delvis är kopplad till klimatförändringar. Mänsklig aktivitet har påverkat landskap och vegetation alltmer under holocen. Å andra sidan har klimatet möjligtvis påverkat människors användning och utnyttjandegrad av landskapet: ett samband mellan minskat lantbruk och klimatförsämringar - sjunkande temperatur och ökad humiditet - har påvisats i ett antal studier. Klimat-människa-landskap är alltså en komplex triangel av orsak-verkan förhållanden.

Den halländska kustzonen i sydvästra Sverige är belägen i en region av Nordvästeuropa vilken är starkt påverkad av intensitet och frekvens av västliga stormar. Närheten till havet och det öppna landskapet bidrar till att kraftiga stormar, som till exempel stormen Gudrun den 8-9 januari 2005, kan orsaka omfattande skador inom ett stort område. Den årliga nederbörden är hög och den dominerande vindriktningen är från väster. Östliga vindar med stormstyrka förekommer också men är mindre vanliga: de uppstår när norra Skandinavien präglas av en högtryckssituation.

Människor har påverkat landskapet kraftigt i södra Sverige, och arkeologiska och palynologiska undersökningar visar att i vissa områden inleddes denna antropogena påverkan redan för ca. 6000 år sedan. Därmed är sydvästra Sverige lämpligt för studier av sambandet mellan antropogen aktivitet och klimatförändringar, särskilt variationen i cyklonaktivitet. Dessutom är kunskapen om den holocena vegetationsutvecklingen på den halländska kustslätten begränsad, varför nya dylika undersökningar är av vikt.

I denna studie har två högmossar (Store Mosse och Undarsmosse) på den halländska kustslätten undersökts med olika metoder. Borrkärnor från dessa mossar har provtagits och daterats med kol-14 metoden. Förekomst av sandkorn har analyserats i torvlagerföljderna och mängden av transporterade sandkorn till högmossarna per tidsenhet och deras kornstorleksvariationer har tolkats som förändringar i sandflykt. Denna har i sin tur kopplats till variationer i stormaktivitet. Torvens organiska densitet och analys av dess innehåll av testata amöbor har använts som indikatorer för högmossarnas fuktighetsvariationer, dvs grundvattenytans fluktuationer. Pollenanalys har utförts för att kunna rekonstruera vegetations- och landskapsutvecklingen och använts för vegetationsmodellering med den s k REVEALS-modellen. Denna modell har utfört en kvantitativ rekonstruktion av den regionala vegetationssammansättningen under olika tidsperioder.

Resultaten av sandflyktsvariationerna från de båda lokalerna är samstämmiga: perioder med ökad sandflykt har inträffat ca 4700, 2800-2000, 1500, 1100 och 400-50 år före nutid (1950 AD). Likheter med t ex dynutvecklingen i sydvästra Danmark tyder på att dessa perioder med ökad sandflykt återspeglar regionala klimatscenarier. Dessa perioder kännetecknas av ökade kontraster i den atmosfäriska cirkulationen, men den faktiska atmosfäriska situationen är svår att rekonstruera. Detaljerade jämförelser mellan sandflyktsmaxima och humiditetsförändringar, baserade på testata amöbor i Undarsmosse under de senaste 1700 åren, indikerar ökad stormaktivitet under perioder med humiditetsförändringar. Rekonstruktioner av högmossarnas grundvattenyta visar kortvariga stigningar av grundvattenytan under perioder med toppar i stormaktivitet. Detta tyder på att "stormperioder" har kännetecknats av ökad nederbörd och lägre temperatur.

Markanvändningen har varierat mycket under den studerade perioden, vilket visas av hur arealerna av betes- och odlingsområden har växlat. Perioder med ökande odlingsarealer kan påvisas ca 4100, 2900, 1550, 1300, 850 samt efter 350 år före nutid. Denna utveckling sammanfaller väl med det antropogena utvecklingsmönstret i nordvästra Europa. En detaljerad jämförelse mellan sandflykt och markanvändningsindikatorer visar att lägre grad av markanvändning sammanfaller med sandflyktstoppar. Detta visar att den styrande processen bakom sandflykten inte är direkt kopplad till markanvändning. Detta är en stark indikation på att klimatet styr förekomsten av sandflyktstopparna, och att sandflyktsvariationerna kan användas för regionala klimatrekonstruktioner.

Rekonstruktion av fuktighetsvariationerna från de båda lokalerna tyder på relativt torra förhållanden mellan 6500 och ca 2000 år före nutid, med en kort, mycket torr period kring 4800-4500 år före nutid. Efter 2000 år före nutid har fuktigheten varierat, men båda lokalerna visar torra förhållanden efter 400 år före nutid. Vid en jämförelse med stratigrafiskt och isotopkemiskt baserade paleohydrologiska studier av sjöar i södra Sveriga visar det sig att utvecklingen stämmer väl överens med resultaten från denna studie. Resultaten från dessa studier har använts för en hypotetisk rekonstruktion av de viktigaste förändringarna av den atmosfäriska cirkulationen i södra Sverige. Efter 4400 och 2000 år före nutid indikerar den ökade fuktigheten och minskade temperaturen att cirkulationen dominerades av zonalt flöde, medan perioderna innan 4400 och 400-50 år före nutid tycks ha dominerats av meridionalt flöde med ett klimat präglat av blockerande högtryck över Skandinavien. De regionala klimatförändringarna omkring 4600, 2800-2000 och 400-50 år före nutid indikerar att förändringar i solaktivitet/kosmisk strålning kan ha spelat en viktig roll: dessa tidsperioder sammanfaller väl med distinkta maxima i kosmisk strålning/minima i solaktivitetet. Många av de andra rekonstruerade regionala klimatförändringarna i denna avhandling sammanfaller dock inte med dylika variationer, varför kosmisk strålning/solaktivitet bara kan ha varit en av flera olika klimatstyrande faktorer inom denna region.

References

Ackerman SA, Knox JA, 2003. Meteorology – understanding the atmosphere-. Brooks/Cole – Thomson learning, Pacific Grove, 486 p

Ahrens CD, 1991. Meteorology Today -an introduction to weather, climate and the environment (4th edition). West Publishing Company, St. Paul, 575 p

Alexandersson H, Schmith T, Iden K, Tuomenvirta H, 1998. Long-term variations of the storm climate over NW Europe. Global Atmosphere and Ocean Systems 6, 97-120

Alexandersson H, Tuomenvirta H, Iden K, 2000. Trends of storms in NW Europe derived from an updated pressure data set. Climate Research 14, 71-73

Barber KE, Chambers FM, Maddy D, 2003. Holocene palaeoclimates from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland. Quaternary Science Reviews 22, 521-539

Barry RG, Chorley RJ, 1998. Atmosphere, Weather and Climate (7th edition). Routledge London, 409 p

Berglund BE, 1969. Vegetation and human influence in South Scandinavia during Prehistoric time. Oikos supplement 12, 9-28

Berglund BE. 2003. Human impact and climate changes - synchronous events and a causal link? Quaternary International 105, 7-12

Berglund M. 1995. The late Weichselian deglaciation, vegetational development and shore displacement in Halland, southwestern Sweden. Lundqua thesis 35, Lund University, Lund.

Berglund BE, Ralska-Jasiewiczowa M, 1986. Pollen analysis and pollen diagrams. In Handbook of Holocene palaeoecology and palaeohydrology. BE Berglund, Ed., p. 455-484. Wiley& Sons, Chichester.

Björck S, 1987. The answer to the Ancylus enigma?- presentation of a working thesis. GFF 109, 171-176

Björck S, Clemmensen LB, 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record for winter storminess variation in southern Scandinavia? The Holocene 14, 677-688

Björkman L, Bradshaw R, 1996. The immigration of Fagus sylvatica L. and Picea abies (L.) Karst. into a natural forest stand in southern Sweden during the last 2000 years. Journal of Biogeography 23, 235-244

Bond G, Showers W, Cheseby M, Lotti R, Almasi P, deMenocal P, Priore P, Cullen H, Hajdas I, Bonani G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Science 278, 1257-1266.

Bond G, Kromer B, Beer J, Muscheler R, Evans MN, Showers W, Hoffmann S, Lotti-Bond R, Hajdas I, Bonani G. 2001. Persistent solar influence on north Atlantic climate during the Holocene. Science 294, 2130-2136.

Borgmark A, Schoning K, 2006. A comparative study of peat proxies from two eastern central Swedish bogs and their relation to meteorological data. Journal of Quaternary Science 21, 109-114

Bronk Ramsey C, 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37, 425-430

Bronk Ramsey C, 2001. Development of the radiocarbon calibration program. Radiocarbon 43, 355-363

Chambers FM, Mauquoy D, Brain SA, Blaauw M, Daniell JRG, 2007. Globally synchronous climate change 2800 years ago: Proxy data from peat in South America. Earth and Planetary Science Letters 253, 439-444

Charman DJ, Blundell A, Chiverell RC, Hendon D, Langdon PG, 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. Quaternary Science Reviews 25, 336-350

Charman, D.J., Blundell, A., Accrotelm members, 2007. A new European testate amoebae transfer function for palaeohydrological reconstruction on ombrotrophic peatlands. Journal of Quaternary Science 22, 209-221

Clarke M, Rendell H, Tastet JP, Clave B, Masse L. 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine coast, southwest France. The Holocene 12, 231-238.

Clarke ML, Rendell HM, 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. The Holocene 16, 341-355

Clemmensen LB, Andreasen F, Heinemeier J, Murray A, 2001. A Holocene coastal aeolian system, Vejers, Denmark: landscape evolution and sequence stratigraphy. Terra Nova 13, 129-134.

Clemmensen LB, Pedersen K, Murray A, Heinemeier J, 2006. A 7000-year record of coastal evolution, Vejers, SW Jutland. Bulletin of the Geological Society of Denmark 53, 1-22.

Clemmensen LB, Murray A, 2006. The termination of the last major phase of aeolian sand movement, coastal dunefields, Denmark. Earth surface Processes and Landforms 31, 795-808

Dahl-Jensen D, Mosegaard K, Gundestrup N, Clow GD, Johnsen SJ, Hansen AW, Balling N, 1998. Past temperatures directly from the Greenland ice sheet. Science 282, 268-271

Dawson AG, Hickey K, Holt T, Elliott L, Dawson S, Foster IDL, Wadhams P, Jonsdottir I, Wilkinson J, McKenna J, Davis NR, Smith DE, 2002. Complex North Atlantic Oscillation (NAO) Index signal of historic North Atlantic storm-track changes.

Holocene 12, 363-369.

Denton GH, Karlén W, 1973. Holocene climatic variations –their pattern and possible cause. Quaternary Research 3, 155-205

Digerfeldt, G., 1982. The Holocene development of Lake Sambosjön – the regional vegetation history. Lundqua report 23, Lunds Universitet.

Grimm, E.C. 1992. Tilia and Tilia graph: Pollen spreadsheets and graphics programs. Programs and Abstracts, 8th International Palynological Congress, Aix-en-Provence, September 6-12, 1992

Grimm, E.C. 1987. CONISS: a fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13, 13-35

Grove JM, 2001. The initiation of the "Little Ice Age" in regions round the North Atlantic. Climatic Change 48, 53-82.

Hammarlund D, Björck S, Buchardt B, Israelson C, Thomsen CT, 2003. Rapid hydrological changes during the Holocene revealed by stable isotope records of lacustrine carbonates from Lake Igelsjön, southern Sweden. Quaternary Science Reviews 22, 353-370

Hass HC, 1996. Northern Europe climate variations during late Holocene: Evidence from marine Skagerrak. Palaeogeography, Palaeoclimatology, Palaeoecology 123, 121-145

Henderson-Sellers A, Robinson PJ, 1996. Contemporary Climatology. Prentice Hall, 456 p

Hughes PDM, Mauquoy D, Barber KE, Langdon PG, 2000. Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. The Holocene 10, 467-479

Hurrell JW, 1995. Decadal Trends in the North-Atlantic Oscillation - Regional Temperatures and Precipitation. Science 269, 676-679

Iversen J, 1941. Landnam i Danmarks Stenalder - en pollenanalytisk Undersøgelse øver det første Landbrugs Indvirkning paa Vegetationsudviklingen. C.A. ReitzelsForlag, København, 68p

Jessen CA, Rundgren M, Björck S, Hammarlund D, 2005. Abrupt climatic changes and an unstable transition into a late Holocene thermal decline: a multiproxy lacustrine record from southern Sweden. Journal of Quaternary Science 20, 349-362.

Jessen C, 2006. The ups and downs of the Holocene: exploring relationships between global CO2 and climate variability in the North Atlantic region. LUNDQUA thesis 55, Lund University, 34p

Johnson RA, Wichern DW, 1998. Applied multivariate statistical analysis. Prentice-Hall Inc, Upper Saddle River, NJ

Jönsson P, Bärring L, 1994. Zonal index variations, 1899-1992: links to air temperature in southern Scandinavia. Geografiska Annaler Serie A-Physical Geographie 76, 207-219

Lagerås P, 2007. The ecology of expansion and abandonment – Medieval and post-medieval agriculture and settlement in a landscape perspective. Grahns Tryckery AB, Lund

Lamb HH, 1985. Climate, history and the modern world. Routledge, London.

Li XY, Liu LY, Wang JH, 2004. Wind tunnel simulation of aeolian sandy soil erodibility under human disturbance. Geomorphology 59, 3-11

Lundqvist J, Wohlfarth B, 2001. Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. Quaternary Science Reviews 20, 1127-1148

Mann ME, Bradley R, Hughes MK, 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392, 779-787

Mauquoy D, van Geel B, Blaauw M, van der Plicht J, 2002. Evidence from northwest European bogs shows 'Little Ice Age' climatic changes driven by variations in solar activity. The Holocene 12, 1-6

Mayewski PA, Rohling EE, Stager CJ, Karlen W, Maasch KA, Meeker LD, Meyerson EA, Gasse F, van Krefeld S, Holmgren K, Lee-Thorp J, Rosqvist G, Rack F, Staubwasser M, Schneider RR, Steig EJ, 2004. Holocene climate variability. Quaternary Research 62, 243-255

Messerli B, Grosjean M, Hofer T, Nunez L, Pfister C, 2000. From nature-dominated to human-dominated environmental changes. Quaternary Science Reviews 19, 459-479

Middleton R, Bunting MJ, 2004. Mosaic v1.1: landscape scenario creation software for simulation of pollen dispersal and deposition. Review of Palaeobotany and Palynology 132, 61-66.

Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlen W, 2005. Highly variable Northern Hemisphere temperatures reconstructed from low-and high-resolution proxy data. Nature 433, 613-617

Moore PD, Webb, J.A., Collinson, M.E. 1991. Pollen Analysis. Blackwell Scientific Publications, Oxford.

Mörner NA. 1969. The Late Quaternary history of the Kattegat Sea and the Swedish west coast. Trydells Boktryckeri AB, Stockholm.

Nilsson C, Stjernquist I, Bärring L, Schlyter P, Jönsson,AM, Samuelsson H, 2004. Recorded storm damage in Swedish forests 1901-2000. Forest Ecology and Management 199, 165-173

O'Brien, S.R., P.A.Mayewski, L.D.Meeker, D.A. Meese, M.S.Twickler, & S.I. Whitlow, 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. Science 279, 1962-1964

Påsse T. 1987a. Jordartsgeologiska kartblad Varberg SO/ Ullared SV. Sveriges Geologiska Undersökning serie Ae 86, 1:50.000. OffsetCenter AB, Uppsala.

Påsse T, 1987b. Shore displacement during the Late Weichselian and Holocene in the Sandsjöbacken area, SW Sweden. GFF 109, 197-210.

Påsse T, 1988. Beskrivning till jordartskartan Varberg SO/Ullared SV. Sveriges Geologiska Undersökning, serie Ae 86

Påsse, T. 1989. Jordartsgeologiska kartblad Varberg NO, Sveriges Geologiska Undersökning serie Ae 102, Uppsala

Påsse, T. 1990. Beskrivning till jordartskartan Varberg NO. Sveriges Geologiska Undersökning, serie Ae 102. OffsetCenter AB, Uppsala

Raab B, Vedin H. 1995. Sveriges Nationalatlas. Bokförlaget Bra Böcker, Höganäs.

Reimer P, Baillie M, Bard E, Bayliss A, Beck J, Bertrand C, Blackwell P, Buck C, Burr G, Cutler K, Damon P, Edwards R, Fairbanks R, Friedrich M, Guilderson T, Hogg A, Hughen K, Kromer B, McCormac G, Manning S, Ramsey CB, Reimer R, Remmele S, Southon J, Stuiver M, Talamo S, Taylor F, Van der Plicht J, Weyhenmeyer C, 2004. IntCal04 Terrestrial Radiocarbon Age Calibration, 0-26 cal Kyr BP. Radiocarbon 46, 1029-1058.

Seppä H, Hammarlund D, Antonsson K, 2005. Low-frequency and high-frequency changes in temperature and effective humidity during the Holocene in south-central Sweden: implications for atmospheric and oceanic forcings of climate. Climate Dynamics 25, 285-297

Sjörs H, 1965. Forest regions. Acta Phytogeographica Suecica 50, 48-63

Stockmarr J 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 615-621.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac FG, van der Plicht J, Spurk M, 1998. INTCAL 98 radiocarbon age calibration 24.000-0 cal. yrs BP. Radiocarbon 40, 1041-1083

Sugita S, 2007. Theory and quantitative reconstruction of vegetation.I. Pollen from larger sites REVEALS regional vegetation composition. The Holocene 17, 229-241

Tsoar H, Pye K, 1987. Dust Transport and the Question of Desert Loess Formation. Sedimentology 34, 139-153

Van Geel B, Buurman J, Waterbolk HT, 1996. Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatic teleconnections around 2650 BP. Journal of Quaternary Science 11, 451-460

Van Geel B, Raspopov OM, Renssen H, van der Plicht J, Dergachev VA, Meijer HAJ, 1999. The role of solar forcing upon climate change. Quaternary Science Reviews 18, 331-338

von Post L, 1947. Hallands marina fornstränder-och vid nordens senkvartära nivåförändringar-. Meddelanden från Stockholms Högskolas Geologiska Institut 80, 293-320

Wanner H, Brönniman S, Casty C, Gyalistras D, Luterbacher J, Schmutz C, Stephenson DB, Xoplaki E, 2001. North Atlantic Oscillation –concepts and studies. Survey in Geophysics 22, 321-382

Wiggs GFS, Baird AJ, Atherton RJ, 2004. The dynamic effects of moisture on the entrainment and transport of sand by wind. Geomorphology 59, 13-30.

Wilson P, McGourty J, Bateman MD, 2004. Mid- to late-Holocene coastal dune event stratigraphy for the north coast of Northern Ireland. The Holocene 14, 406-416

Wilson P, Orford JD, Knight J, Braley SM, Wintle AG, 2001. Late-Holocene (post-4000 years BP) coastal dune development in Northumberland, northeast England. The Holocene 11, 215-229