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Abstract

It has been shown that the present interglacial has been climatically dynamic with both rapid and severe climate fluctuations. The spatial and temporal differences of these changes are however not fully resolved. The aim of this thesis is to present a detail high resolution record of past climate changes from the central South Atlantic.
Peat and lacustrine sediment sequences were retrieved from the Tristan da Cunha island group in the central South Atlantic. These sequences were analysed with a multiproxy approach including pollen analysis, measurements of total carbon, nitrogen and sulphur, mineral magnetic measurements and detailed radiocarbon dating. In addition tree-ring widths from two trees are presented.
The oldest sediment sequence extends back 10 700 years and the analyses show that the climate varied considerably during this time. Peat was accumulating from 10 700 cal. yrs BP to around 8600 cal. yrs BP when it was replaced by gyttja deposition. This change implies a substantial increase in effective humidity probably caused by increased precipitation. The cause of this change was probably a northward shift of the Southern Hemisphere westerlies and a large scale reorganisation of the circulation system, which was related to cooling of the Southern Ocean and the Atlantic sector of Antarctica.
Several periods with increased catchment erosion and further increased precipitation follow this transition. These periods were probably caused by increased air humidity as a response to higher sea surface temperatures. In the North Atlantic conditions were cool with increased deposition of ice rafted debris during these periods. Probably, these changes were caused by weaker meridional overturning circulation and less northward transport of warm shallow water in the Atlantic, which caused higher sea surface temperatures in the central South Atlantic and cooler conditions in the North Atlantic.
One period of increased precipitation and sea surface temperature is contemporaneous with the 8.2 ka event in the Greenland ice cores and is probably the South Atlantic response to the weaker circulation induced by freshwater forcing in the North Atlantic.
Tristan da Cunha was discovered in 1506 AD by Portuguese explorers, but not settled until the 19th century. The effect of the Portuguese explores on the vegetation is clearly seen in the pollen diagram as the first appearance of the introduced species *Plantago lanceolata*, which is dated to 1550 AD. Seal hunting during the 17th and 18th century and establishment of the permanent settlement in the 19th century caused increased land use and introduction of more alien species.

Key words: *Tristan da Cunha, South Atlantic, the Holocene, pollen analysis, peat, lake sediments, paleoclimate, bipolar seesaw, human disturbance*

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This thesis is based on four papers listed below as Appendices I-IV. Paper I is reprinted with the permission of Elsevier Science Ltd. Paper II is an unpublished manuscript. Paper III is accepted for publication in the journal indicated. Paper IV has been submitted to the journal indicated and is under consideration. Appendix V presents photographs of selected pollen types.

Appendix I:
Ljung, K., Björck, S., Hammarlund, D. & Barnekow, L. 2006. Late Holocene multi-proxy records of environmental change on the South Atlantic island Tristan da Cunha. *Palaeogeography, palaeoclimatology, palaeoecology*, 241, pp. 539-560.

Appendix II:
Ljung, K. Human vegetation disturbance during the last 450 years on the island Tristan da Cunha in the South Atlantic, *Unpublished manuscript.*

Appendix III:
Ljung, K., and Björck, S. Holocene climate and vegetation dynamics on Nightingale Island, South Atlantic – variations of the Southern Hemisphere westerlies and an apparent interglacial bipolar seesaw in action. *Manuscript accepted for publication in Quaternary Science Reviews.*

Appendix IV:
Ljung, K., Björck, S., Renssen, H., and Hammarlund, D. South Atlantic island record reveals a South Atlantic response to the 8.2 kyr event, *Manuscript submitted to Climate of the Past and published in Climate of the Past Discussions, 729-753, 2007.*

Appendix V:
Photographs of selected pollen and spore types from Tristan da Cunha.

Contents

1. Introduction

The present interglacial period, the Holocene, has not experienced climate changes that equal those during glacial times, but it has nonetheless been a climatically dynamic period with both rapid and marked climate changes, and in addition to natural changes humans have had a clear impact on the environment. The dynamics and timing of Holocene climate and environmental changes have been intensely studied using a wide range of methods on natural climate archives (e.g. Mayewski et al., 2004; Moberg et al., 2005). However, the extent, magnitude and regional differences of climate changes during the Holocene are not fully resolved, and the causes and feedbacks within the climate system are truly complex and not yet fully understood.

One of the reasons for our restricted knowledge of Holocene climate dynamics are the uneven distribution of paleoclimate records around the globe. The Northern Hemisphere is generally better studied with more available well dated, highly-resolved paleoclimate records. This is not only a result of fewer scientists having been active during a shorter period of time in the Southern Hemisphere, but it also has a physical/geographical explanation. A much larger proportion of the Southern Hemisphere is covered by ocean compared with the Northern Hemisphere. The deep ocean normally has too low sedimentation rates to allow detailed studies of the last 10 000 years (e.g. Wefer et al., 2003). This means that when it comes to studies of Holocene climate changes much of the Southern Hemisphere is a blank spot on the map.

One way of overcoming this problem is to study natural paleoclimate archives on islands. This allows for paleoclimate reconstructions with sufficiently high resolution to effectively discern shortlived changes during the last 10 000 years. Terrestrial climate archives are directly affected by atmospheric changes, and ^{14}C dating of terrestrial organic matter also avoids the problem with temporal and spatial variations of marine reservoir effects. Island records of past climate changes can also give information of atmospheric responses to marine changes, i.e. changes of ocean circulation and heat budgets.

Thus, terrestrial paleoclimate archives from islands are important for the studies of the climate and environmental dynamics of the present interglacial. Such records have the potential of improving the understanding of regional differences and causes of climate changes, and reveal linkages between the ocean and the atmosphere.

This thesis is based on proxy reconstruction of past environmental and climate changes from peat and sediment sequences from the Tristan da Cunha island group in the South Atlantic (Fig. 1). The thesis has a wide scope and covers many aspects of environmental dynamics and their causes. The variations in the proxy records reflect both local changes, such as infilling and overgrowing of basins, landslides and volcanic eruptions, as well as climatic changes of regional and hemispheric significance, such as changes caused by major atmospheric and ocean circulation changes. The climate of the South Atlantic is linked to other parts of the globe by the ocean circulation and paleoclimate studies from this region can thus reveal inter-hemispheric climate linkages.

Due to the remoteness of the Tristan da Cunha island group it was not discovered until 1506 and has been uninhabited until the beginning of the 19th century. Thus, any observed changes in the proxy record before 1500 must have natural causes. The late arrival of humans also allows for studies of their impact on the vegetation and environment. The aims of this thesis are therefore:

- To reconstruct the climate and environmental changes that have affected the Tristan da Cunha island group during the Holocene using proxy-based reconstructions on natural climate archives

- To explore the causes of the inferred environmental changes

- To reconstruct the history of human land use and their effect on the natural environment on Tristan da Cunha

1.2 Historical synopsis and previous paleoenvironmental studies

Tristan da Cunha was discovered in 1506 by Portuguese explorers, but they never inhabited the islands and it is not known how many landings they made in the 16th century (Wace, 1969). In the 17th and 18th century seal and whale hunters visited the islands to hunt the large populations of elephant seals, and replenish fresh water (Wace, 1969). The seal hunters only stayed for shorte time periods and it was not until 1790 that longer stays were made (Munch, 1971). The permanent settlement was founded in the beginning of the 19th century. The population grew throughout the 19th and 20th centuries and today the island has around 300 permanent inhabitants.

The first scientific investigation of the natural environment on Tristan da Cunha was by the French botanist Dupetit Toars in 1793 (Groves, 1981). He made notes on the vegetation, and collected and described plant species (Groves, 1981). In the early 19th century British scientific expeditions visited the islands and studied the vegetation and fauna of Tristan da Cunha (Carmichael, 1819; Groves, 1981).

Between 1937 and 1938 an ambitious Norwegian expedition studied many different aspects of the island (Christophersen, 1946-1968). Their studies included such diverse fields as sociology, medicine, climatology, botany, zoology and geology. During the expedition peat samples from several bogs on Tristan da Cunha and Nightingale Island were collected (Christophersen, 1946). These cores were later studied for their pollen content, which are the first works on the environmental history of the islands (Hafsten, 1951, 1960). The results show changes in the pollen composition which were mainly related to local dynamics of the sites (Hafsten, 1960). The arrival of humans on the islands is clearly seen in the pollen diagrams in the appearance of introduced plant species (Hafsten, 1960). These peat cores were however not dated.

Later paleoenvironmental studies have employed both pollen and diatom studies on peat and sediment sequences from Inaccessible and Gough Island (Bennett et al., 1989; Preece et al., 1986). Based on pollen and diatom analyses from Inaccessible Island it has been claimed that there have not been any large climatic changes affecting the islands during the last 9000 years (Preece et al., 1986).

There have also been studies of the Quaternary geomorphology of Tristan da Cunha and Gough Island (Gribnitz and Kent, 1989; Wace and Ollier, 1984). On Gough the dynamics of stream gullies have been used to infer precipitation changes (Gribnitz and Kent, 1989).

A study with the aim of reconstructing solar variations using ^{10}Be content in sediements has been preformed on the sediment sequence from Hillpiece Bog (Ljung et al., 2007).

The pioneering pollen studies of Ulf Hafsten from sites on Tristan da Cunha and Nightingale Island have been of particular importance for this thesis (Hafsten, 1951, 1958, 1960). His published photos and descriptions, and type slides were a great help in determination of pollen types. Some of the sites studied by U. Hafsten were revisited and sampled during the field work for this thesis and it has been possible to confirm some of the previous results and also add new information, particularly age chronological constraints.

2. Study area

2.1 Geologic and geographic setting

The Tristan da Cunha island group is situated at 37˚S in the central South Atlantic, about 2800 km from South Africa (Fig 1). The island group consists of the main island Tristan da Cunha and the two smaller islands Inaccessible Island and Nightingale Island. The islands are composite volcanoes formed on a hot-spot east of the Mid Atlantic Ridge (Smith, 1993). Tristan da Cunha is the largest island in the group rising to 2067 m a.sl. and measuring app. 12 km in diameter. It mainly consists of layers of basaltic lavaflows interbedded with pyroclastics, which are mostly derived from the main vent (Baker et al., 1964). Potassium-Argon dates from lava flows range from 0.01 ± 0.02 to 1.1 ± 0.15 Ma (Dunkley, 2002; Gass, 1967; Mc Dougall and Ollier, 1982). Lava flows from the summit crater are dated to 0.05 Ma with Ka-Ar, which probably represents the last eruption of the main volcano (Mc Dougall and Ollier, 1982). Several smaller eruptions have

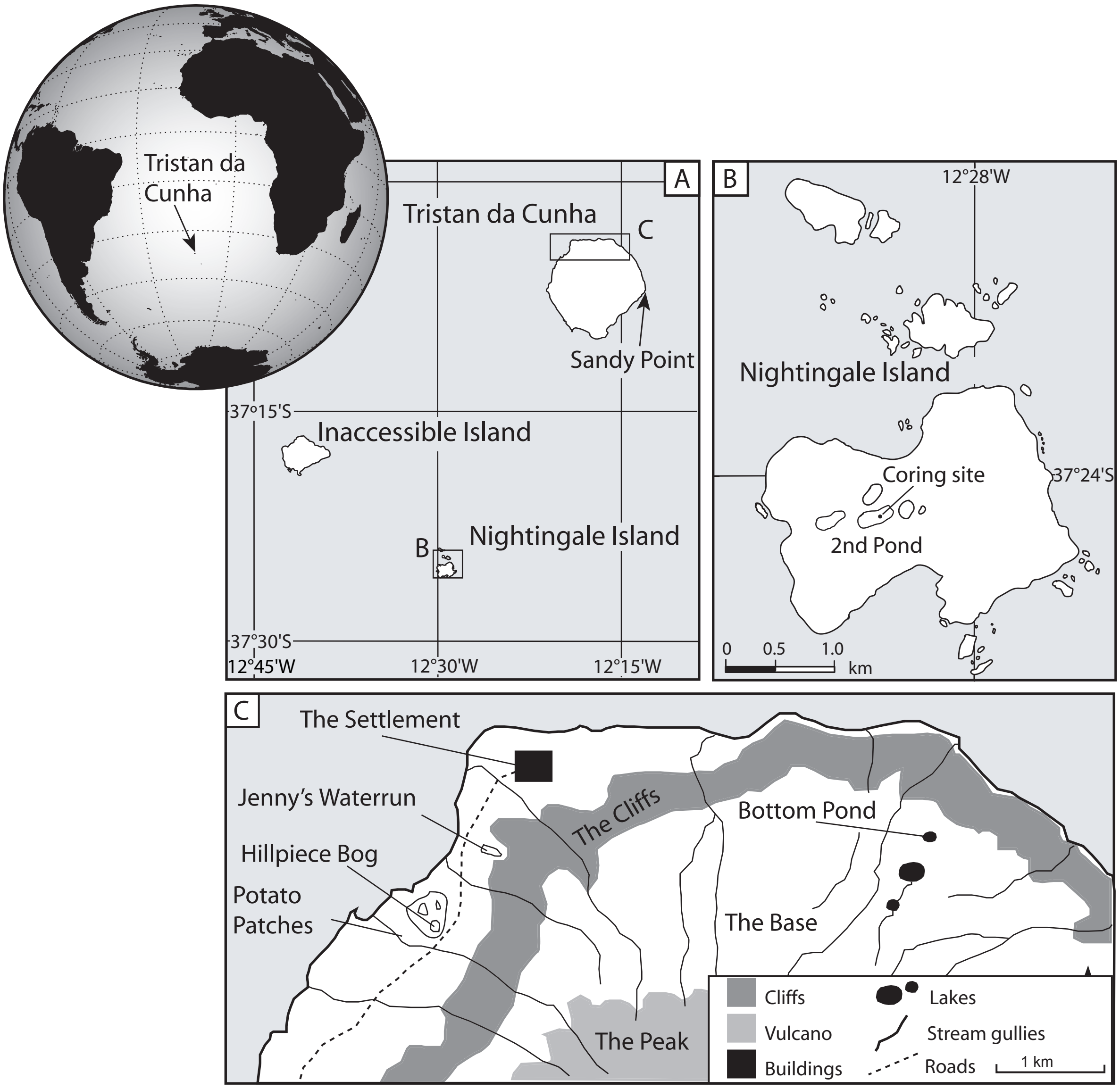

Figure 1: Map showing the location of the Tristan da Cunha island group. The island group and location of Sandy Point (A), the location of 2nd Pond on Nightingale Island (B) and location of investigated sites on Tristan da Cunha (C).

occurred since then, the latest in 1961, and many of the smaller volcanic cones that are scattered around the island are of Holocene age (Baker et al., 1964).

Nightingale Island is the oldest island in the group and it is today only the eroded remnant of a once much larger volcanic cone. It measures app. 2 by 1.5 km and reaches 300 m a.s.l. (Baker et al., 1964). A sill extending around the island indicates that it was probably as large as Tristan da Cunha (Baker et al., 1964). The island is mainly made up of volcanic ash, agglomerate and porphyritic trachyte (Baker et al., 1964). Potassium-Argon dates of lava flows have yielded ages of 18 ± 4 Ma (Baker et al., 1964). The youngest volcanic activity on the island is indirectly dated by a radiocarbon date of 40 000 ^{14}C BP on peat underlying a lava flow (Baker et al., 1964). There is no volcanic activity on the island today.

2.2 Climate

The Tristan da Cunha island group has a moist temperate climate, with small annual variation in temperature and rainfall (Höflich, 1984). The mean annual temperature at sea level on Tristan da Cunha is 14.5° C (Fig. 2). The extreme daily maximum is 23° C and the extreme daily minimum 3° C. The

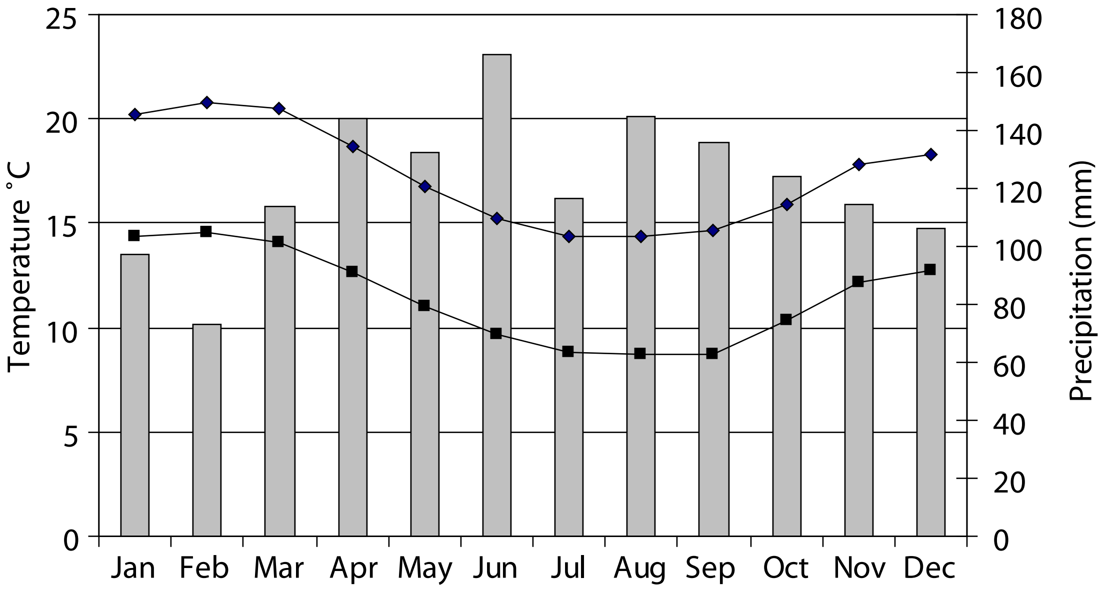

Figure 2: Mean monthly maximum (filled diamonds) and minimum temperatures (filled squares), and mean monthly precipitation (bars) from Tristan da Cunha. The measurements are from a climate station situated 23 m a.s.l. close to the settlement. The data is based on measurements from 1973-1983, the years 1984-1987 were excluded beacuse of missing data points (Data provided by The South African Weather Service, Pretoria, South Africa).

climate data are based on measurements running from 1942-1961 and 1972-1987 at a climate station close to the settlement at 23 m a.s.l. (Höflich, 1984).

Snow lies on the peak between May and October, but the temperature never falls below freezing at seal level (Dickson, 1965). The mean annual precipitation is 1670 mm with little interannual variation (Fig. 2). The amount of precipitation varies much on the island due to the orographic effect. The higher areas of the island probably receive between one and a half to three times as much precipitation as the Settlement at sea level (Christophersen and Schou, 1942).

On Nightingale there is no climate station. A climate station has been erected on Inaccessible Island approximately 20 km to the west of Nightingale Island, but it is only used for real-time forecasting. The data are not archived but show that the climate is similar to that of Tristan da Cunha (Ryan and Glass, 2001). There is no reason to believe that the climate of Nightingale would differ largely from Tristan da Cunha or Inaccessible Island.

The island group is positioned at the northern limit of the westerlies, which bring much of the precipitation. The seasonal latitudinal movement of the westerlies is the main explanation for the higher precipitation rates during the austral winter. North of the islands precipitation rates are much smaller, due to the South Atlantic high pressure area.

The sea surface temperature at Tristan da Cunha is around 18°C. The sea surface temperature decrease by 3-4 °C and the salinity decrease by 0.3‰ between 37 and 40°S, the Subtropical Front (Deacon, 1937; Smythe-Wright et al., 1998). The position of the front displays small seasonal variation, with somewhat lower temperatures during the austral winter months.

2.3 Vegetation of the islands

The Tristan da Cunha island group is among the worlds most remote islands, and the insularity has had a great impact on the vegetation. The flora is highly impoverished, with only 60-70 native vascular plants and a high number of endemic species (Groves, 1981; Wace and Dickson, 1965). Many of the species are capable of growing in various habitats and the number of available niches is large compared to the number of species (Wace and Holdgate, 1958). The vegetation has species affinities with both South African and South American floras, but generally the spreading of plant species follows the

Figure 3: Photograph of the Hillpiece Bog. The site is the green depression in the lower left corner. Photo: Dan Hammarlund

prevailing wind direction, which is from the west (Munoz et al., 2004).

The vegetation of Tristan da Cunha has a clear altitudinal zonation. The coastal plains are today covered by heavily grazed grasslands and are almost completely cleared of higher vegetation (Fig. 3 and 4). Before human settlement the lowland plains on Tristan da Cunha were possibly covered by *Phylica arborea*, the only native tree, and tussock grass (*Spartina arundinacea* and *Poa flabellata)* (Carmichael, 1819; Wace and Holdgate, 1958). Dense *Phylica arborea* forest covers large areas up to about 500 m a.sl. The trees form dense shrubs, between 3 and 5 meters in height. The ground vegetation is dense and dominated by *Drypoteris aquiline* and *Blechnum penna-marina*.

Above 500 m a.sl. extensive areas are completely covered by tree-ferns *(Blechnum palmiforme)*, which reach up to about 1 meter above the ground with a very dense canopy (Fig. 5). Light intensity at the ground surface is only about one percent of that above the canopy, which limits ground vegetation (Wace and Holdgate, 1958). The ground of the tree fern scrub is mostly peat covered with abundant dead *Blechnum palmiforme* trunks. *Phylica arborea* grows only in sheltered positions such as in gulches and depressions above 500 m a.s.l.

Peat bogs are abundant in the interior of the island, especially to the north-east. The bogs are covered by *Sphagnum* sp. and sedges, mostly *Scirpus* sp. Bogs also occur in depressions in the lowlands.

Above about 700-900 m a.s.l. heath vegetation dominates, with *Empetrum rubrum* and the introduced *Rumex acetosella* as the major constituents (Fig. 5). On the higher exposed areas of the volcanic cone vegetation is almost completely absent and the slopes are covered by loose scree.

The vegetation of Nightingale Island is completely dominated by tussock grass (*Spartinia arundinacea* and *Poa flabellata*) (Fig. 6). In the interior of the island *Phylica* trees form scattered stands, and on higher areas with open ground *Rumex frutescens*

Figure 4: View of Jenny's Waterrun. Photo: Karl Ljung.

and *Empetrum rubrum* grow. Several wetlands have formed in depressions in the interior of the island. These are called the Ponds, but all except one are completely infilled and overgrown. The surface vegetation of the overgrown ponds are dominated by *Sphagnum* sp. and *Scirpus* sp., with thick *Blechnum palmiforme* and scattered *Phylica arborea* trees on drier areas (Fig. 6). Only one of the ponds, the 4th pond, has open water, and in the littoral zone *Scirpus* sp. and the aquatic *Callitriche christensenii* forms a dense fringe.

There is no evidence of any species succession or arrival of new species during the Holocene (Preece et al., 1986). The speices present on the islands probably became established along time ago. Molecular studies on *Phylica arborea* indicate that the speices arrived on the islands around two million years ago (Richardson et al., 2003).

3. Site descriptions

3.1 *Hillpiece Bog*

Hillpiece Bog is a small overgrown lake approximately 10 by 20 meters situated in a volcanic crater at 62 m a.s.l. on the south side of the Hillpiece volcano about 2 km west-southwest of the Settlement (Fig. 1). The surface vegetation of the bog is dominated by *Sphagnum* sp. and *Scirpus* sp. The vegetation of the surrounding plain consists of heavily grazed grass land (Fig. 3).

3.2 Jenny's Waterrun

Jennys Waterrun is a small peat bog situated around 1 km west of The Settlement at 58 m a.s.l. (Fig. 1). The bog measures 250 by 100 meters with a slightly convex surface. The surface vegetation is dominated by *Scirpus* sp. (Fig. 4). On the seaward side a small stream emerges, and there are pools with open water on the sides of the bog. The bog is heavily influenced by human activity.

Figure 5: Coring at Bottom Pond. The thick Blechnum palmiforme *scrub is seen in the foreground. On the far slope* Phylica arborea *are seen as light green trees. Photo: Dan Hammarlund.*

3.3 Bottom Pond

Bottom Pond is the lowermost of three lakes situated at 550-600 m a.s.l. on the northeastern part of the island (Fig. 1). The lakes are formed in steep-walled explosion craters, with little lava flows or tephra deposition (Baker et al., 1964). Bottom Pond has no in- or out-flows. Temperature of the lake water in February was 20°C, pH 6.5 and conductivity 60 µS. The vegetation of the crater is dominated by thick *Blechnum palmiforme* scrub, with *Phylica arborea* growing in the sheltered sides down in the crater (Fig. 5). The lake is roughly circular and app. 150 m in diameter with a maximum depth of 11 meters.

3.4 2nd Pond

2nd Pond is one of four wetlands situated in the interior of Nightingale Island (Fig 1). The ponds are situated in depressions and separated by ridges. Only

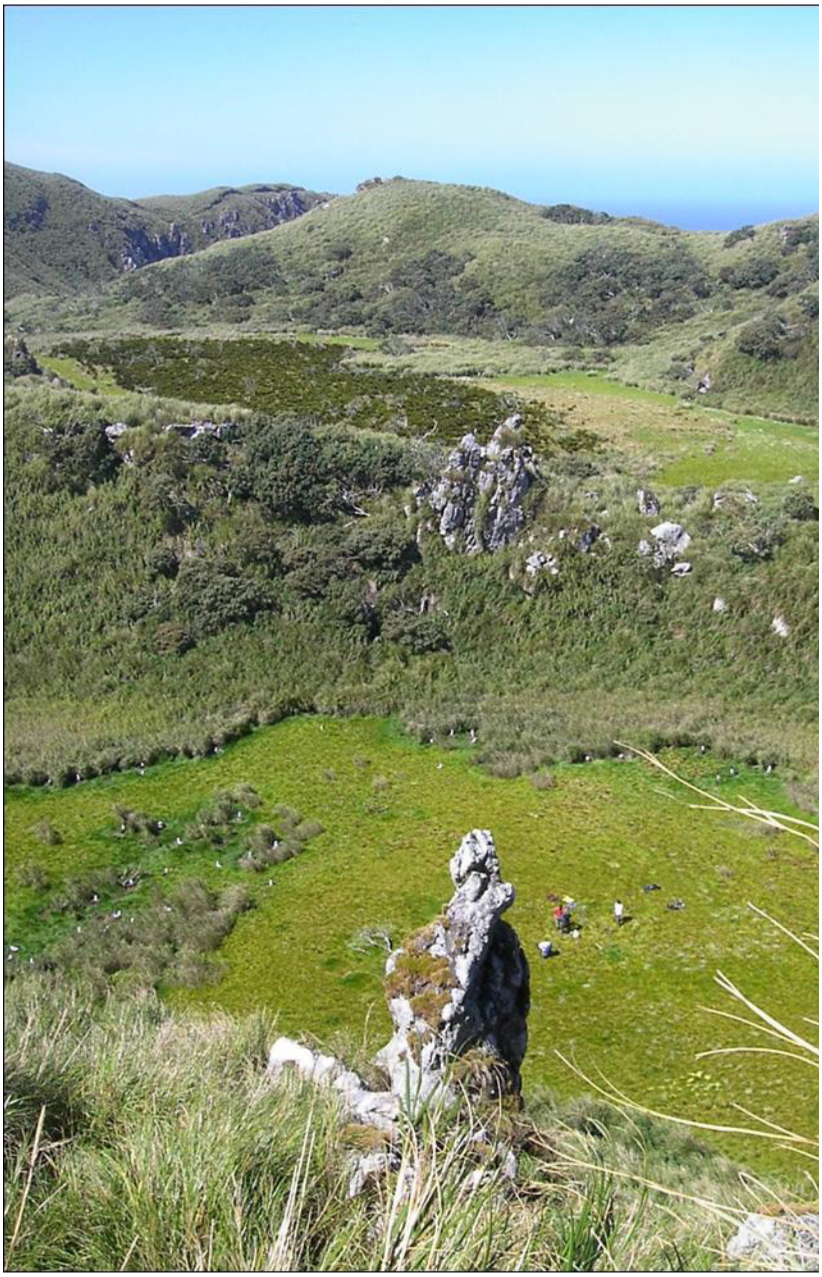

Figure 6: Coring at 2nd Pond on Nightingale Island. Note the abundance of Blechnum palmiforme *and* Phylica arborea *on the surface of 1st Pond in the background.* Phylica arborea *trees are seen on the slopes. Photo: Svante Björck.*

one of these, 4th Pond, has open water, the others are completely infilled and overgrown lakes (Fig 6). 2nd Pond is about 350 by 150 meters in diameter and situated 180 m a.sl. The surface vegetation is dominated by *Scirpus* sp. and *Sphagnum* sp. The vegetation surrounding the wetland is dominated by thick tussock grass, with scattered stands of *Phylica arborea* growing in the catchment.

4. Methods

4.1 Fieldwork, coring and subsampling

Fieldwork was carried out in February and March 2003. At Bottom Pond the coring was done from a platform on a rubber dinghy with a 5 cm Russian corer with a 1 m long chamber (Jowsey, 1966). Surface sediment samples were retrieved using a simple gravity corer.

Hillpiece Bog and Jenny's Waterrun were cored with a 7.5 cm Russian in the deepest parts of their respective basins.

On Nightingale Island the overgrown 2nd Pond was cored using a 5 cm Russian corer with a 1 m long chamber.

The cores were wrapped in plastic and stored in PVC tubes. At their arrival in Lund they were kept in the cold room at the department. The cores were correlated visually in the laboratory, and these preliminary correlations were refined with the aid of magnetic susceptibility measurements. Subsampling was carried out on the correlated cores and the different proxies were sampled from the same cores.

4.2 Radiocarbon dating and chronology

The chronology of the sediment sequences is based on accelerator mass spectrometry (AMS) radiocarbon dates on macroscopic plant remains and bulk sediment samples. Radiocarbon ages were calibrated using the program OxCal v.3.10 (Bronk Ramsey, 1995, 2001) and the SHCal04 calibration data set (McCormac et al., 2004). Radiocarbon ages yielding post 1950 ages were matched to the atmospheric ^{14}C excess record for age estimates (Hua et al., 2000; Hua et al., 2003).

The age-depth relationships were constructed by visually fitting lines to the calibrated ages. Lithological changes were considered crucial when constructing these age-depth models and any breaks in sedimentation rate were adjusted to fit lithological changes. Due to the possibility of reworking of terrestrial organic material around the lake basins, and with this highly dynamic environment, too old ^{14}C ages were considered more likely than the opposite.

4.3 Pollen analysis

Pollen samples of between 1 and 2 cm^3 were processed following standard method A as described by Berglund and Ralska-Jasiewiczowa (1986), and Lycopodium spores were added for determination of pollen concentration values (Stockmarr, 1971). The counting was made under a light microscope at magnifications of ×400 and ×1000. Pollen grains were identified by using published photos and descriptions (Hafsten, 1951, 1958, 1960), standard pollen keys (Moore et al., 1991), and a small collection of type slides from Tristan da Cunha prepared by Ulf Hafsten and borrowed from the Botanical Museum in Bergen, Norway. Pollen diagrams were plotted in C2 (Juggins, 2003) and divided into local pollen zones based on the variation of the major taxa.

4.4 Element analysis CNS

Total carbon, total nitrogen, and total sulphur content were measured on dried and homogenised samples at 2—3 cm intervals with a Costech Instruments ECS 4010 elemental analyser. The accuracy of the measurements is better than ± 5% of the reported values based on replicated standard samples. Total carbon is used as a proxy for the organic content. C/N atomic ratios were obtained by multiplying by 1.167 and are used as a measure of the changes of relative proportion of terrestrial and aquatic organic matter (Meyers and Teranes, 2001). Sulphur content in freshwater lake sediments is generally low (<2%). In marine sediments it is significantly higher (Berner and Raiswell, 1984), and at coastal sites without bedrock sources high values can indicate increased sulphur deposition by sea spray.

4.5 Magnetic susceptibility

Magnetic susceptibility was measured on 4 mm increments using a Bartington Instruments MS2EI magnetic susceptibility high-resolution surface scanning sensor coupled to a TAMISCAN automatic logging conveyor. Magnetic susceptibility reflects the minerogenic content of the sediment and is used as a proxy for in-wash of mineral matter and tephra deposition (Thompson and Oldfield, 1986).

4.6 Loss on ignition

Loss on ignition was used to estimate the content of organic matter (Heiri et al., 2001). Samples were dried over night at 105°C and combusted at 550°C.

4.7 Multivariate statistical analysis

Multivariate statistics are especially useful for summarising and reducing data sets without losing important information (Reyment and Savazzi, 1999). In this thesis principal components analysis (PCA) was employed to summarise pollen data, using the function "princomp" in MATLAB. The data were normalised and standardised prior to analysis.

4.8 Tree ring analysis

Cores were obtained with an increment corer at about 1.5 m above the ground. Cores were cut with a razor and the surface dusted with Talcum powder. Ring widths were measured, early wood and late wood separately, with an Aniol-measure instrument (accuracy 1/100 mm) (Aniol, 1987).

5. Summary of papers

5.1 Appendix I

Ljung, K., Björck, S., Hammarlund, D. & Barnekow, L. 2006: Late Holocene multi-proxy records of environmental change on the South Atlantic island Tristan da Cunha. Palaeogeography, palaeoclimatology, palaeoecology, 241, pp. 539-560, doi:10.1016/j.palaeo.2006.05.007.

In this study pollen analysis, measurements of total carbon, nitrogen and sulphur content, measurements of magnetic susceptibility, and radiocarbon dating were carried out on sediment cores from one open lake, one overgrown lake, and an open section in a stream gully. The aim of the study was to reconstruct the late Holocene environment on Tristan da Cunha.

The longest sequence was retrieved from the lake Bottom Pond at app. 550 m a.s.l. and extends back to 2300 cal. yrs BP. The core from Hillpiece Bog at the lowland plain covers the last 1600 cal. yrs BP. The section mostly consists of lacustrine sediments and deposition started around 1500 cal. yrs BP.

Fluctuations in the proxy records of the sites are interpreted as reflections of local hydrological changes and human vegetation disturbance. Hydrological changes are mainly inferred from changing proportions of pollen grains derived from telmatic and terrestrial taxa and corresponding changes in the deposition of mineral and terrestrial organic matter by fluvial erosion. High frequencies of Cyperaceae pollen in the Hillpiece Bog sediment sequence between 1450 and 1050 cal. yrs BP are interpreted as a result of lower lake levels and an expanded littoral zone with dense growth of sedges. Increased erosion and deposition of pollen from terrestrial taxa between c. 1050 and 300 cal. yr BP are interpreted as a period with higher lake levels and precipitation.

The inferred changes of effective humidity and precipitation partly correspond to palaeoclimatological changes in other regions and may have been caused by regional climate changes. The humid period 1050 to 300 cal. yr BP on Tristan da Cunha partly corresponds with the medieval warming in South Africa and warming in South Georgia.

Evidence for clearing of forest and introduction of new species occur around 300 cal. yr BP in the Hillpiece Bog in the lowland site, and about 100 years later at the upland site Bottom Pond. This implies that humans were present and started to affect the vegetation before the establishment of the settlement in the early 19th century. The establishment of the settlement caused more intense land use and increased forest clearing, and introduced species also spread to higher areas of the island.

5.2 Appendix II

Ljung, K.: Human vegetation disturbance during the last 450 years on the island Tristan da Cunha in the South Atlantic, Unpublished manuscript.

A pollen stratigraphic study covering the last c. 600 years from a small peat bog close to The Settlement on the lowland plain on the island Tristan da Cunha is presented. The main aim of the study is to detect and date the effect of human disturbance on the local vegetation.

Tristan da Cunha was discovered by Portuguese explorers in 1506, but was not permanently settled until the early 19th century. The results reveal that already the earliest discoverers must have landed on the island causing an impact on the natural vegetation. Around 1550 AD the introduced *Plantago lanceolata* first appears in the pollen diagram. This early anthropogenic indicator probably reflects the introduction of goats as food supply on future voyages, which was a common practice of Portuguese explorers in the 16th century. In the mid 17th century seal and whale hunters began to visit the island, and they introduced more alien species and started to clear the lowland plain. After the establishment of the permanent settlement in the early 19th century the land use became more extensive, and most of the lowland plain was cleared of its natural forest by the beginning of the 20th century.

The evidence of human presence on the island shows that landings took place already in the 16th century by the first discoverers, which was not known for certainty before. The results also show that utilisation of the natural resources of the island started in the mid 17th century and had an impact on the vegetation.

5.3 Appendix III

Ljung, K., and Björck, S: Holocene climate and vegetation dynamics on Nightingale Island, South Atlantic – variations of the Southern Hemisphere westerlies and an apparent interglacial bipolar seesaw in action. Manuscript accepted for publication in Quaternary Science Reviews.

In this paper a peat and sediment sequence from Nightingale Island, South Atlantic, covering the last 10 700 cal. yrs is presented. The sequence was retrieved from an infilled and overgrown closed basin, which measures approximately 350 by 150 m. The sequence has been studied using a multiproxy approach including pollen analysis, measurements of total carbon, nitrogen, and sulphur, measurements of magnetic susceptibility and a large set of radiocarbon dates.

The lowermost part of the sequence, 10 700-8600 cal. yrs BP, consists of peat. The peat is overlain by gyttja, which continues up to the final overgrowing of the basin around 500 years ago. The gyttja has high organic content and contains abundant sedge remains.

Recurring phases with higher content of

Table 1: Conributors to the research results presented in appendecies I-IV.

	Appendix I	**Appendix II**	**Appendix III**	**Appendix IV**
Fieldwork	Karl Ljung Svante Björck Dan Hammarlund Ole Bennike	Karl Ljung Svante Björck Dan Hammarlund Ole Bennike	Karl Ljung Svante Björck Dan Hammarlund Ole Bennike	Karl Ljung Svante Björck Dan Hammarlund Ole Bennike
Core correlation and subsampling	Karl Ljung	Karl Ljung	Karl Ljung	Karl Ljung
Core description	Karl Ljung	Karl Ljung	Karl Ljung	Karl Ljung
Magnetic susceptibility	Karl Ljung	Karl Ljung	Karl Ljung	Karl Ljung
Geochemistry	Karl Ljung	Karl Ljung	Karl Ljung	Karl Ljung
Pollen analysis	Karl Ljung	Karl Ljung	Karl Ljung	Karl Ljung
Radiocarbon dating	Poznan Radiocarbon lab, Lund Radiocarbon Lab	Lund, Radiocarbon lab	Karl Ljung (graphitization and pre-treatment of most samples) Poznan Radiocarbon lab, Lund Radiocarbon Lab	Karl Ljung (graphitization and pre-treatment of most samples) Poznan Radiocarbon lab, Lund Radiocarbon Lab
Age-model	Karl Ljung Svante Björck	Karl Ljung	Karl Ljung Svante Björck	Karl Ljung Svante Björck Dan Hammarlund
Climate model	-	-	-	Hans Renssen
Data interpretation	Karl Ljung Svante Björck Dan Hammarlund Lena Barnekow	Karl Ljung	Karl Ljung Svante Björck	Karl Ljung Svante Björck Dan Hammarlund Hans Renssen

minerogenic particles and terrestrial organic matter (high C/N ratios) occur throughout the sequence. These periods also have distinctly different pollen assemblages with higher frequencies and concentrations of pollen grains from plant taxa growing in more distal parts of the catchment. These changes indicate increased erosion, most likely caused by higher precipitation.

The hydrological changes inferred from the lithology and proxy records are explained by changes in the atmospheric circulation in the Southern Hemisphere and changes of the Atlantic Ocean circulation.

The change from peat to gyttja around 8600 cal. yrs BP implies a significant water table rise most likely caused by increased precipitation. This represents the establishment of the present day circulation regime with strong influence of the Southern Hemisphere Westerlies. The timing of this shift coincides with the end of the Antarctic thermal optimum (Epica community members, 2006) and northward movement and strengthening of the westerlies in South America. The cooling of Antarctica and expansion of sea ice in the Southern Ocean probably caused the northward movement of the Westerlies, and hence increased precipitation on Nightingale Island.

The periods of higher precipitation which occur throughout the sequence above 8600 cal. yrs BP are between 100 and 1000 years in duration. These periods are also characterised by decreased influence from marine aerosols, which indicates that there were no increase in storminess associated with the precipitaiton increas. In fact South American data indicate that the were dispalced southward during these periods. Precipitation on the Tristan da Cunha islands is also determined by the sea surface temperatures, with higher temperatures giving higher air humidity and precipitation. Therefore it is concluded that higher sea surface temperatures triggered these preciptiation increases. These periods are correlated with cool conditions, increased deposition of ice rafted debris and weaker deep water formation in the North Atlantic. During these periods the meridional overturning circulation (MOC) was probably weaker, triggered by the cool and fresh surface conditions in the North Atlantic. The weak MOC caused lower heat transport form the South to the North Atlantic, which caused warmer sea surface temperatures in the central South Atlantic and consequently increased precipitation. This pattern with contrasting temperatures in the North and South Atlantic caused by weaker MOC is similar to the bipolar seesaw during glacial times, and thus implies that it may have been operational also during interglacial conditions.

5.4 Appendix IV

Ljung, K., Björck, S., Renssen, H., and Hammarlund, D.: South Atlantic island record reveals a South Atlantic response to the 8.2 kyr event, Climate of the Past Discussions, 729-753, 2007.

The 8.2 kyr event is one of the most distinct climate fluctuations during the Holocene. It is generally considered to have been caused by catastrophic drainage and a freshwater outburst from Laurentide glacial lakes. The flux of freshwater to the North Atlantic caused the thermohaline circulation to weaken, which reduced the heat transported from the South- to the North Atlantic. In the North Atlantic region the effect was cooler temperatures which have been reported from many sites. Model results show that the weaker thermohaline circulation during the 8.2 kyr event also caused warming of the South Atlantic. However, no paleoclimate archives have shown an unambiguous response to the 8.2 kyr event in the Southern Hemisphere.

In this paper a detailed analysis of a sediment sequence from Nightingale Island, South Atlantic, covering the time period 10 700 to 7000 cal. yrs BP is presented. The sediments were analysed using a multiproxy approach including pollen analysis, determination of total carbon, total nitrogen, and total sulphur content, and measurements of magnetic susceptibility. A detailed set of radiocarbon dates allowed for good chronological control.

Based on increased deposition of minerogenic and terrestrial organic matter, and higher deposition of catchment derived pollen it is concluded that precipitation was significantly higher between 8275 and 8025 cal. yr BP. This is coeval with the 8.2 kyr event in the Greenland ice cores. The most likely cause of the increased precipitation is higher sea surface temperatures, triggering higher air humidity and precipitation.

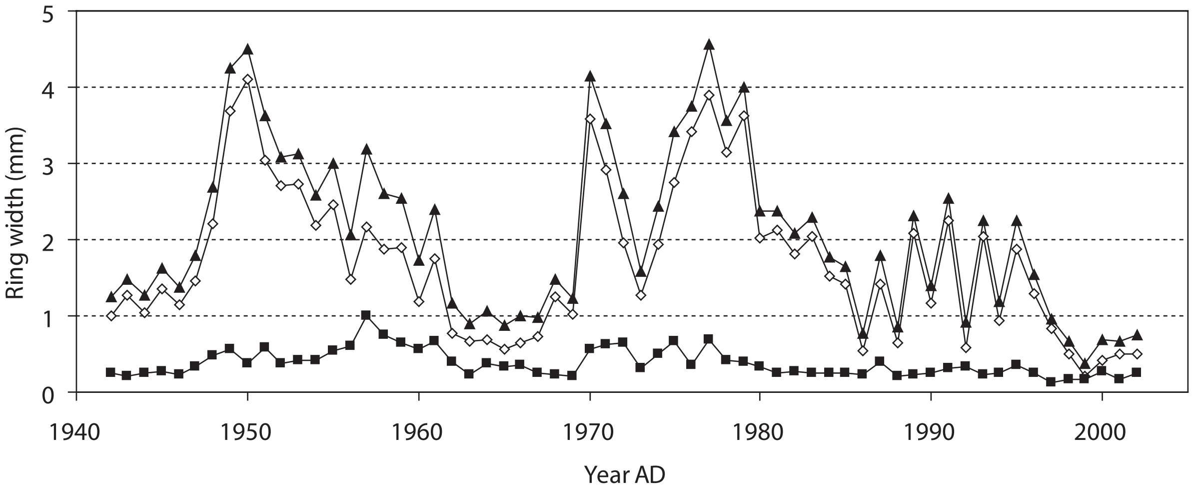

Figure 7: Mean total ring width (filled traingles), early wood (open diamonds) and late wood (filled squares) from two apple trees from Sandy Point on the east side of Tristan da Cunha

The results are in agreement with coupled ocean-atmosphere climate models of the 8.2 ka event, which shows that both SSTs and precipitation increased significantly as a consequence of the weaker thermohaline circulation.

In addition, the transition from peat in the bottom of the core to gyttja deposition reveals a significant hydrologic change at 8600 cal. yrs BP. This most likely represents a northward shift of the southern hemisphere westerlies following the end of the Antarctic thermal optimum and the establishment of the present day circulation regime.

6. Additional results

6.1 Tree-ring series

Cores from two apple trees *(Malus domestica)* growing at Sandy Beach on the east side of the island were obtained. The ring series have been added to one average curves of early wood, late wood and total ring widths, which are presented in figure 7. The tree ring series show two periods of thicker rings and increased growth in the 1950s and 1970s.

Due to the limited amount of climate data available from Tristan da Cunha it is not possible to make a strong correlation between the climate data and the tree ring widths. However, because of the high precipitation it is unlikely that the trees are limited by drought, and therefore it is suggested that thicker ring widths are the result of higher (summer) temperatures. Other non-climatic factors affecting tree growth, such as volcanic eruptions and changed forest dynamics caused by human disturbance cannot be excluded.

7. Discussion

7.1 The early Holocene 10 700-8600 cal. yrs BP

One of the most striking features of the sediment sequence from Nightingale Island is the change from peat to gyttja at 8.71 m, which corresponds to around 8600 cal. yrs BP (Appendix III, Fig. 8). This change implies a significant water table rise and higher effective humidity, which was probably caused by increased precipitation (Appendix III). The high precipitation rates on the Tristan da Cunha island group today are mainly caused by the Southern Hemisphere Westerlies (Christophersen and Schou, 1942; Höflich, 1984). The islands are situated close to the boundary between the westerlies and the dry south Atlantic high pressure region (Höflich, 1984). A southward displacement of the pressure and circulation systems over the South Atlantic would place the Tristan da Cunha island group within the low precipitation area of the South Atlantic high pressure. Shifts in the position of the circulation system would therefore cause changes of the

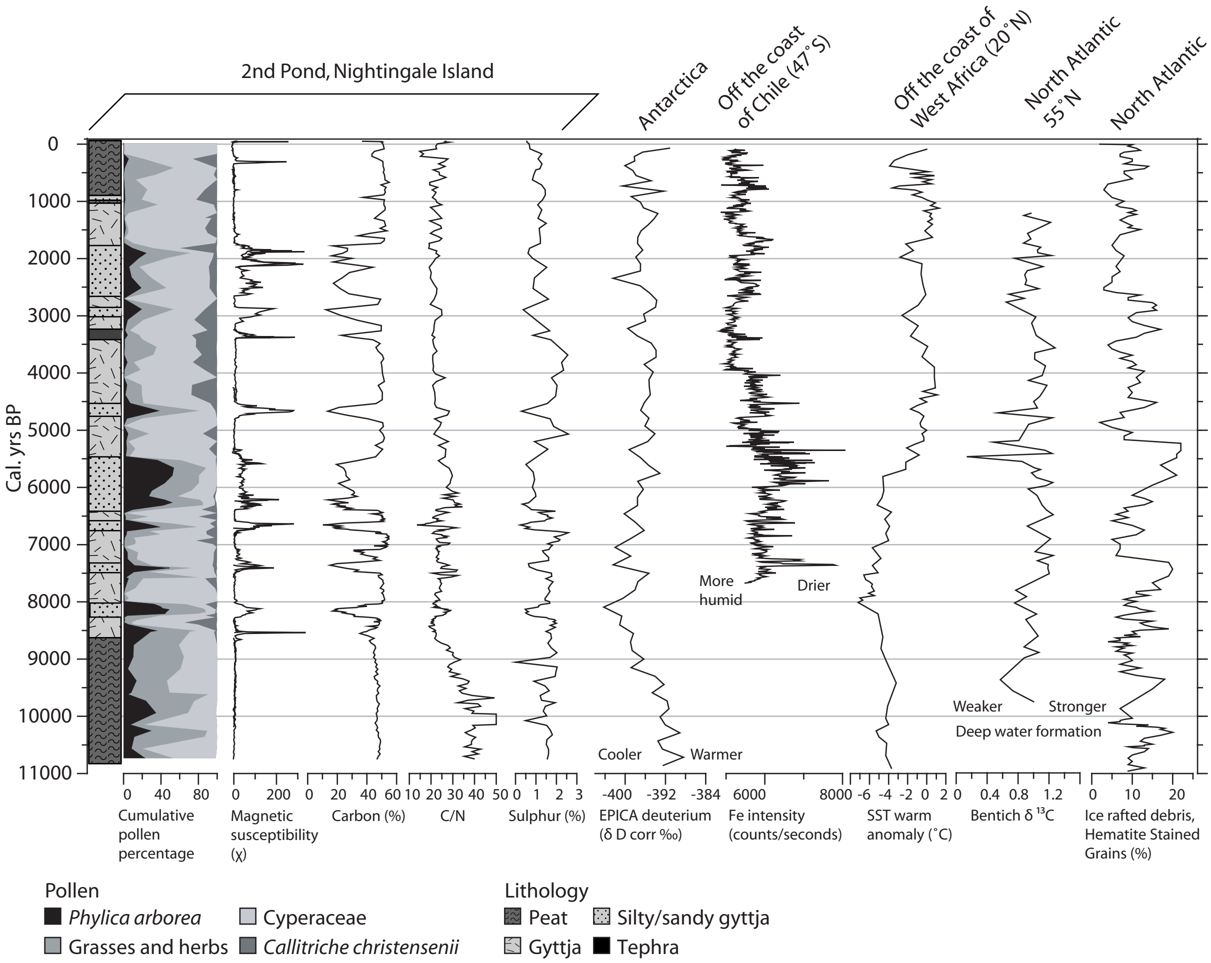

Figure 8: Proxy record from 2nd Pond, together with deuterium record from the Epica ice core in Antarctica (Epica community members, 2004), and Fe intensity from a marine core off the coast of Chile (Lamy et al., 2001), warm sea surface temperature anomalies off the coast of North Africa (deMenocal, 2000), bentich δ ^{13}C (Oppo et al. 2003), and ice rafted debris events in the North Atlantic expressed as percentage hematite stained grains (Bond et al., 2001).

climate regime on Tristan da Cunha. A northward movement of the Southern Hemisphere Westerlies around 8600 cal. yrs BP is thus a likely explanation for the increased precipitation manifested in the peat to gyttja transition.

In the Southern Hemisphere there is ample evidence for a change in the westerlies in the early Holocene. In Patagonia intensification and northward movement of the westerlies have been inferred between 10 500 to 8700 cal. yrs BP from both the Chilean coast (Heinz, 1995; Markgraf et al., 1992), and from Argentina in the east (Mayr et al., 2007; Pendall et al., 2000; Stine and Stine, 1990). Many South American westerlies records imply an earlier northward shift of the westerlies than on Nightingale Island. This difference between the change in westerlies in South America and on Nightingale could be explained by the latitudinal difference and that a gradual northward movement of the westerlies would first affect southerly sites (Markgraf et al., 1992).

A sediment and peat core from Dicks Bog on the neighbouring Inaccessible Island has a basal radiocarbon date of 8330 ± 65 BP (Preece et al., 1986). This is roughly simultaneous as the peat-gyttja transition at 2nd Pond on Nightingale Island, and it is possible that the onset of sedimentation at Dicks Bog was alos caused by the inferred change of the westerlies.

The position of the westerlies is mainly determined by the extent of sea ice, and the latitudinal temperature gradient in the Southern ocean (Hudson and Hewitson, 2001). Before 9000 cal. yrs BP marine cores from the Atlantic sector of the Southern Ocean indicate comparatively high sea-surface temperatures and little ice cover (Hodell et al., 2001; Nielsen et al., 2004), and in Antarctica temperatures were high during the early Holocene thermal optimum (Epica community members, 2004; Masson et al., 2000) (Fig. 8). The Antarctic thermal optimum ends around this time and conditions became cooler and the sea ice expanded. Sea ice has a large influence on the air circulation pattern, and this was probably the reason for the northward shift of the westerlies in the early Holocene, seen in a lake level rise on Nightingale Island.

7.2 Millennial to centennial climate variations

7.2.1. Evidence of precipitation variations

Periods of increased erosion rates and surface run-off occurs throughout the 2nd Pond sediment sequence from Nightingale Island (Appenix III and Fig. 8). These periods are characterised by higher content of minerogenic and terrestrial organic matter, changes of the composition and content of pollen and spores, and low sulphur deposition (Fig. 8).

During calm conditions and low erosion rates, the pollen spectra are dominated by the local fen taxa Cyperaceae and *Callitriche christensenii*. During periods with increased erosion pollen grains from more distal parts of the catchment dominate the pollen spectra. The frequencies and concentrations of *Phylica arborea* and Polypodiaceae, representing forest vegetation, and *Empetrum rubrum*, *Rumex frutescens* and Chenopodiaceae, which are typical open ground species, are high during the erosion phases. This simultaneous increase of pollen and spores from plant species with different habitat requirements indicate that the deposition of pollen from a heterogeneous catchment vegetation increased relative to the deposition of the local taxa, and that there was not necessarily a significant change of the general vegetation composition. For example, if the increased *Phylica arborea* pollen content represents an equally large increase in forest cover, the suitable habitats for open ground species would have decreased and these species should occur less frequently in the pollen diagram, which is contrary to what is observed.

The correlation between increased catchment erosion and higher deposition of *Phylica arborea* pollen is also evident from Hillpiece Bog and Bottom Pond on Tristan da Cunha (Fig 9 and 10). In Hillpiece Bog *Phylica arborea* pollen concentrations and erosion increase after 1650 AD when humans started to clear the lowland forest (Fig 10). This strongly implies that *Phylica arborea* pollen deposition increased as a consequence of erosion: when humans arrived on Tristan da Cunha they started to clear the lowland plain with *Phylica* forest. In the Bottom Pond record, periods with highest sedimentation and erosion rates also have the highest *Phylica arborea* pollen concentrations and frequencies (Fig 9).

The reason for the correlation between deposition of *Phylica* pollen grains and erosion is probably the fact that *Phylica arborea* is self pollinated and does not shed much pollen to the atmosphere (Hafsten, 1960; Wace and Dickson, 1965). Thus, to yield high concentrations of *Phylica arborea* pollen in sedimentary sequences *Phylica* trees have to grow at the site so that flowers are dropped directly into the lake or bog, or that pollen from the flowers are transported to the site by surface run-off or erosion. Even though increased growth of *Phylica* trees in the catchment at these sites cannot be excluded, it is highly unlikely that it is the sole or main explanation for the observed changes.

There are however, notable differences between the proxy records from 2nd Pond, Hillpiece Bog and Bottom Pond, which are caused by the very different settings and characteristics of the sites (Fig. 10). The most apparent difference is the high and variable magnetic susceptibility in Bottom Pond compared with the other two sites. This is explained by the steep walls of the crater, which are easily eroded (Fig. 5). Here magnetic susceptibility, C/N ratios and *Phylica arborea* pollen frequencies are very high between 600 and 800 cal. yrs BP and around 1200 cal, which indicate high erosion rates. Neither Hillpiece Bog nor 2nd Pond has any evidence of erosion during these periods. In contrast, the older period correlates with high Cyperaceae in both Hillpiece Bog and 2nd Pond which indicates drier conditions, while the later period correlates with periods which appear to be wetter. Thus, there is an apparent contradiction

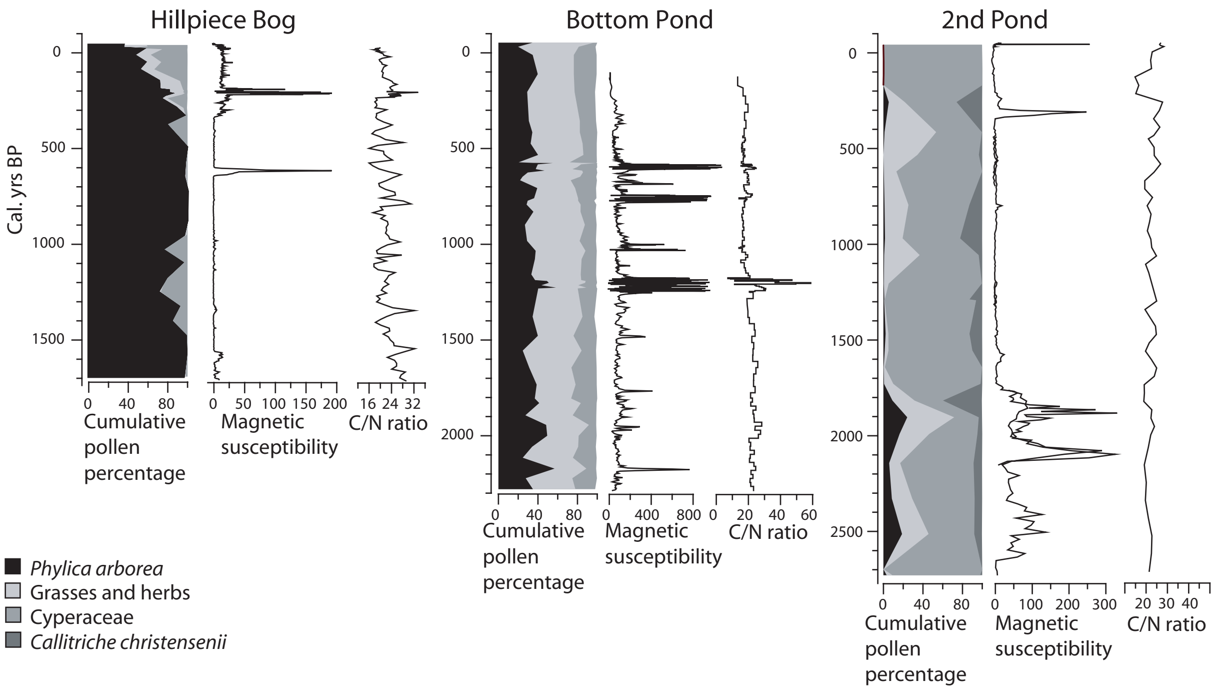

Figure 9: Cumulative pollen percentages, magnetic susceptibility and carbon/nitrogen ratio from Hillpiece Bog, Bottom Pond and 2nd Pond. The magnetic susceptibility and the C/N ratios are mainly proxies of increased erosion.

between the interpretations of the data set. The most likely explanation for this discrepancy is that the high susceptibility periods in Bottom Pond were not caused by climate-induced erosion, but by landslides in the steep walled crater. The extremely rapid sedimentation rate is a strong argument for this interpretation. In fact, the radiocarbon dates show that the sediments from these periods could have been deposited instantaneously (Appendix I).

Between Hillpiece Bog and 2nd Pond there is a better correlation. High Cyperaceae frequencies indicate drier conditions before 1050 cal. yrs BP in Hillpiece Bog and before 1100 cal yrs BP in 2nd Pond, and the following period is interpreted as being wetter.

The periods of increased erosion evident in the 2nd Pond sediment sequence, and to lesser extent in Hillpiece Bog, were most likely caused by increased precipitation rates (Appenidx III). Even though higher precipitation sufficiently explains the observed pattern of the proxy records, it cannot be excluded that lake level changes also occurred during these periods. Lower lake levels during drier periods could partly explain the high concentrations of Cyperaceae pollen as the lower lake levels would increase the shallow littoral zone which is dominated by sedges.

7.2.2 Causes of precipitation changes

Today precipitation on the Tristan da Cunha islands is mainly determined by the westerlies and sea surface temperatures. Both are explored as possible explanations of the observed pattern in the 2nd Pond proxy records (Appendix IV).

The periods are compared with a detailed high resolution marine record displaying latitudinal shifts of the Southern Hemisphere Westerlies off the coast of Chile at 41° S (Lamy et al., 2001) (Fig. 8). The correlation shows that when precipitation was high on Nightingale Island the westerlies were positioned further south. However, if the westerlies of the central Atlantic varied in concert with South America, precipitation would have been low on Tristan da Cunha during these periods. These periods of higher precipitation phases are also accompanied by lower sulphur deposition, which indicates that there were no significant increases in deposition of marine aerosols as a result of more frequent storms or higher wind speeds. Thus, it is unlikely that more intense westerlies caused these high precipitation periods. Therefore it is concluded that sea surface temperature was the main trigger for the increased precipitation.

One of the controlling mechanisms of sea-surface temperatures in the South Atlantic is the meridional overturning circulation (MOC), which brings warm water from the South to the North Atlantic (Broecker, 1998; Stocker, 1998). The strength of this circulation has been shown to vary on glacial time scales giving rise to a distinct seesaw behaviour between the temperatures of Greenland and Antarctica (Blunier et al., 1998; Blunier and Brook, 2001; Clark et al., 2002; Epica Community Members, 2006). The seesaw pattern also appears to have been pervesaive during previous glacial intervals (Martrat et al., 2007). The cause of these ocean circulation changes during glacial times is considered to have been freshwater forcing to the North Atlantic, limiting the deep water formation and weakening the thermohaline circulation (Crowley, 1992). It has been hypothesised that such bipolar seesaw mechanism may also have been active during the present interglacial period (Bond, 1997; Broecker, 2000).

Model results of freshwater forced ocean circulation changes show that Nightingale Island is situated in an area where weaker MOC causes warmer sea surface temperatures and increased precipitation (Appendix IV and Renssen et al., 2002; Renssen et al., 2001). Thus, the precipitation record from Nightingale Island may reflect the South Atlantic response to an interglacial bipolar seesaw in action. To test this hypothesis the Nightingale record is compared with North Atlantic records of ice rafting events, which are believed to have affected the deep water formation and the MOC (Bond et al., 2001).

There is a striking similarity between records of Ice Rafted Debris (IRD) in the North Atlantic and the inferred precipitation rich periods on Nightingale Island, which implies that during cold conditions and abundant sea ice in the North Atlantic the South Atlantic was warmer (Fig 8, and Appendix III). For example, one of the longest and most pronounced periods of increased precipitation on Nightingale Island is between 6500 to 5500 cal. yrs BP, which corresponds to one of the strongest IRD peaks (Bond et al., 2001).

Reconstructed deepwater formation from the North Atlantic also shows that the NADW formation rate was at its minimum around 6000 cal. yrs BP (Oppo et al., 2003), which matches both the Nightingale Island record and the IRD record (Fig. 8). A record from the upwelling area off the coast of northern West Africa (deMenocal, 2000) also shows changes which correspond with IRD events in the North Atlantic and high precipitation phases on Nightingale Island. A strong expansion of the polar vortex and cool atmospheric conditions have also been recorded from this time period (O'Brian, 1995).

The match between IRD events and hgih precipitation periods on Nightingale Island is, however, not perfect. The peak at 2600 cal. yrs BP in the Nightingale Island record has no corresponding peak in the IRD record, and the IRD peaks around 1500 and 500 cal. yrs BP have no corresponding peaks in Nightingale Island record (Fig. 8) (Bond et al., 2001). But other ocean circulation records show weaker NADW formation around this time (Hall et al., 2004; Oppo et al., 2003). Generally the correlation with IRD events in the North Atlantic is stronger before around 4000 cal. yrs BP. This may imply that the coupling between the hemispheres was stronger during the first half of the Holocene, when the melting continental ice sheets still could have a direct influence on the MOC. It could also be a consequence of using IRD records as a proxy for palaeocirculation regimes. It has been shown that the Bond cycles are not fully consistent throughout the North Atlantic (Andrews et. al., 2006), and some of the IRD events may not be coupled to ocean circulation changes. It should also be emphasised that the ^{14}C control of the Nightingale Island record provides a higher chronological resolution than any marine record.

The pattern of warmer sea surface temperatures and increased precipitation during periods of increased IRD deposition, cool air conditions and expanded polar vortex in the North Atlantic resembles the bipolar seesaw during glacial conditions (Blunier et al., 1998; Broecker, 1998; Stocker, 1998). This response would be expected if the cooling in the North Atlantic was caused by less energy transport from the South to the North Atlantic, and it is in agreement with climate models of freshwater-forced disturbances of the MOC (Renssen et al., 2002; Renssen et al., 2001) Appendix IV). Therefore it is proposed that this is the South Atlantic response to repeated disturbances of the MOC, and that this is the expression of an interglacial bipolar seesaw.

Such an interglacial bipolar seesaw is not very apparent in comparision of ice-core records from Antarctica and Greenland, or in marine records from the South and North Atlantic. This is probably because the MOC changes in the Holocene were much weaker than during glacial times and in the Southern Hemisphere this effect may have been restricted to the central South Atlantic. An island site, with its orographic effects on precipitation, is also a very sensitive recorder of rather small scale changes.

During glacial times fresh water release from the continental ice sheets to the North Atlantic is considered to be the main forcing causing slower MOC and the bipolar seesaw pattern (Blunier and Brook, 2001; Blunier et al., 1998). The Laurentide Ice Sheet had melted away by around 6000 years ago (Denton and Hughes, 1981), and an interglacial bipolar seesaw involving disturbances of the deepwater formation and thermohaline circulation, needs another forcing mechanism. Bond et al. (2001) suggest that ice rafting events in the North Atlantic were triggered by solar forcing. However, the direct effect of solar forcing is fairly small and implies that the MOC is sensitive to small perturbations during interglacial conditions. The weakening of the MOC probably also works as a feedback amplifying the effect of the solar variations.

7.3 The 8.2 ka event

On of the most pronounced climate fluctuations in the North Atlantic region during the Holocene is the rapid cooling centered around 8200 years ago, the 8.2 ka event (Alley et al., 1997). The event is most pronounced in the ice core delta O^{18} records from Greenland, which have become the template for the 8.2 ka event (Alley and Ágústsdóttir, 2005; Alley et al., 1997). The cooling event was widespread around the North Atlantic region and has been described from a wide range of proxy records (Morrill and Jacobsen, 2005; Rohling and Pälike, 2005; Wiersma and Renssen, 2006). In marine records it has been described from the North and Tropical Atlantic (Arz et al., 2001; Ellison et al., 2006; Hughen et al., 1996). The global extent of the event is still not fully resolved, but most sites with clear evidence of the 8.2 ka event seem to be under the influence of the Atlantic Ocean (Rohling and Pälike, 2005).

The cooling is normally attributed to a slowdown of the Meridional Overturning Circulation (MOC) triggered by a catastrophic drainage of lakes dammed by the Laurentide Ice Sheet (Barber et al., 1999; Teller et al., 2002). The weaker MOC brought less warm water from the South to the North Atlantic, which caused cooling of the North Atlantic. Climate models also show that the slower MOC result in a significant warming of the central South Atlantic (Renssen et al., 2002; Renssen et al., 2001).

In the 2^{nd} Pond sediment sequence from Nightingale Island one period of increased precipitation is dated to 8275 – 8050 cal. yrs BP, and is thus contemporaneous with the 8.2 ka event (Appendix IV). Results from a detailed coupled ocean- atmosphere climate model, which is presented in Appendix IV, show that a slowdown of the MOC caused by a rapid melt water discharge to the North Atlantic causes higher sea surface temperatures and increased precipitation in the South Atlantic. Thus, this event on Nightingale Island shows the response predicted by the model. Therefore it is postulated that this precipitation increase on Nightingale Island is the South Atlantic´s expression of the 8.2 ka event.

There is a striking difference between the Nightingale Island record and the Greenland Summit ice cores regarding the 8.2 ka event. In the ice cores the event stands out as the most severe cooling during the Holocene, and it is distinctly different from all other events (Alley et al., 1997), whereas in the Nightingale Island record it is only one of several events with higher precipitation, possibly forced by weaker MOC. The pattern of the 8.2 event as one singular Holocene event is also evident from records from Northern Europe (Rohling and Pälike, 2005), while reconstructions of Holocene ocean circulation changes show a distinctly different pattern. Changes of deepwater formation in the Holocene from the North Atlantic does not show such a distinct change around 8200 cal. yrs BP as could be expected from the ice cores (Oppo et al., 2003). For instance, one of the largest changes in deep water formation took place around 6000-5000 cal. yrs BP (Oppo et al., 2003). Similarly the IRD record of Bond and colleagues, which is probably also related to deepwater formation, shows a pattern of recurring phases of deepwater formation changes throughout the Holocene (Bond et al., 2001). Thus, the nature

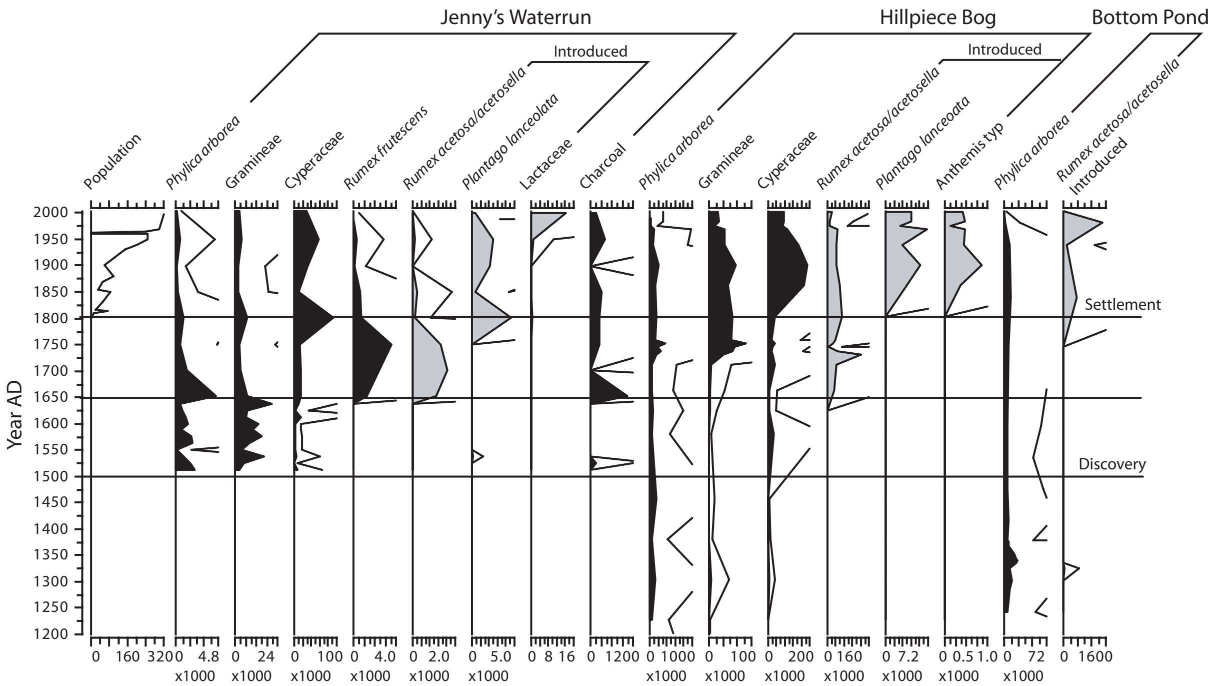

Figure 10: Concentration of pollen types indicative of human vegetation disturbance from Jenny's Waterrun, Hillpiece Bog and Bottom Pond on Tristan da Cunha, and number of permanent inhabitants on Tristan da Cunha.

of the 8.2 ka event is distinctly different when reconstructed from marine cores and from terrestrial records of atmospheric temperature changes. This is somewhat surprising and contradictory, since the 8.2 ka event in the Greenland ice cores is believed to be the atmospheric response to ocean circulation changes, and it would be expected that the strongest atmospheric response corresponds to the strongest marine forcing.

A possible solution to this problem is that the 8.2 ka event is only one of several MOC changes during the Holocene, but with a unique forcing. Probably, the large amount of freshwater added to the North Atlantic by the drainage of the Laurentide ice lakes had two effects on the North Atlantic climate, which made the 8.2 ka event stand out as a unique event in the Greenland ice cores. Firstly, the cold glacial meltwater itself cooled both sea surface temperatures and atmosphere, and secondly it triggered a slowdown of the MOC, which further cooled the ocean and the atmosphere. Such a behaviour of the surface and ocean circulation has been shown in the North Atlantic; there it is shown that the glacial meltwater cooled and reduced the salinity of the surface waters, and that this was followed by a reduction of the MOC (Ellison et al., 2006). This combination of glacial melt water influx and weaker MOC produced enhanced cooling in the North Atlantic region which has not been repeated since. Later periods with reduced MOC and cooling in the North Atlantic region, e.g. around 6000 cal. yrs BP, occur after the continental ice sheets had melted and the cooling associated with these period were not enhanced by large amounts of cold glacial waters (O'Brian, 1995; Oppo et al., 2003). This explains why the 8.2 ka event appear as the strongest Holocene cooling in the Greenland ice cores and other records of atmospheric cooling in the North Atlantic region, but appears as only one of many periods of weaker circulation in the Nightingale Island record. If this hypothesis is correct a near - uture "8.2 ka event" is very unlikely, since there are no continental ice sheets with large ice dammed lakes that can promote such a circulation change. The MOC and interhemispheric energy transport is variable during interglacial conditions, but to create the enhanced cooling of a 8.2 ka event large amounts of cool glacial waters are needed.

7.4 Discovery and settlement of the island – human vegetation disturbance

The Tristan da Cunha island group was discovered in 1506 by the Portuguese explorer Tristão dao Cunha, but remained uninhabited until the early 19th century (Munch, 1971; Wace, 1999-2000). It is not known if the discoverers, or any other Portuguese vessel after them, landed on the islands in the 16th century (Wace, 1969). However, the Portuguese are known to have landed on newly discovered islands and put ashore goats to use as supplies for future voyages, and it has been speculated that they may have done so also on Tristan da Cunha (Hafsten, 1960). There are also reports that goats were present on the island already in the late 18th century (Wace and Dickson, 1965). In the 17th century Tristan da Cunha started to receive regular visits by Dutch whale and seal hunters. The whaling and sealing industries were most intense during the later part of the 18th and beginning of the 19th century and the elephant seals breeding on Tristan da Cunha were hunted to extinction (Crawford, 1982).

From this study, the first evidence of human activity on the island is from 1550 AD when the introduced *Plantago lanceolata* appears in the pollen diagram from Jenny's Waterrun (Fig. 10, Appendix II). *P. lanceolata* was only found in one sample, but it is supported by an earlier pollen study from an undated core from the same site, which reports *P. lanceolata* and *Rumex acetosa/acetosella* in three samples (Hafsten, 1960). Although the core is undated the samples are from roughly the same depth and it is likely that they represent the same age. *P. lanceolata* was probably unintentionally introduced by the Portuguese who discovered the island in the early 16th century, and shows that they did make landfall on Tristan da Cunha. They probably also introduced goats, and the grazing favoured the introduced plants. However, even without the introduction of grazing animals the breeding grounds of elephant seals, sea lions and penguins would provide *P. lanceolata* with suitable natural habitat, and there was not necessarily any significant forest clearing.

Around 1650 AD humans seem to have started to visit the island more regularly. This caused clearing of the lowland *Phylica* forest and introduction of new plant species, which is evident in the pollen diagrams from Hillpiece Bog and Jenny's Waterrun. The introduced *Rumex acetosa/acetosella* appears in the pollen diagrams from Hillpiece Bog and Jenny's Waterrun simultaneous with the decline of *Phylica arborea* at Jenny's Waterrun and increased erosion at Hillpiece Bog. Charcoal concentrations also increase in the Jenny's Waterrun sequence, which indicate that fire was used to clear the lowland, today called The Settlement Plain.

When The Settlement was established around 1811-1815 AD landuse activities intensified. The remaining lowland forest was cleared as shown by further declining *Phylica arborea* pollen frequencies and *Plantago lanceolata* was favoured by increased grazing pressure. The forest clearing and grazing caused enhanced erosion, which is shown by increased minerogenic content and lower *Phylica arborea* pollen concentrations in the Jenny's Waterrun sequence. The effects of human vegetation disturbance are also evident at the upland site Bottom Pond where *R. acetosella/acetosa* appears around 1800 AD, which indicates that the land use became more extensive and that the higher areas of the island was used for grazing very early. The increased grazing and land use also changed the local vegetation on Jenny's Waterrun from a graminoid peat probably dominated by *Spartinia arundinacea*, to sedge-dominated peat.

The evidence of human presence on the island and significant vegetation disturbances around 1650 AD is >150 years before the establishment of the settlement and shows that human activities were more extensive in the 17th and 18th century than previously thought. Dutch ships are reported to have called on Tristan da Cunha and explored the possibilities of seal hunting in the mid 17th century, which evidently had an effect on the vegetation (Wace, 1969). The extent of landuse of these early visitors was probably small and restricted to the lowland plain. The first written accounts of longer stays on the island by whale hunters are from the end of the 18th century by Dutch whalers (Wace, 1969). The pollen diagrams show that the whale and seal hunting in the 17th century significantly affected the environment on Tristan da Cunha.

Both the appearance of *P. lanceolata* in 1550 AD and increased erosion, forest clearing and spread of introduced species after 1650 AD show that the

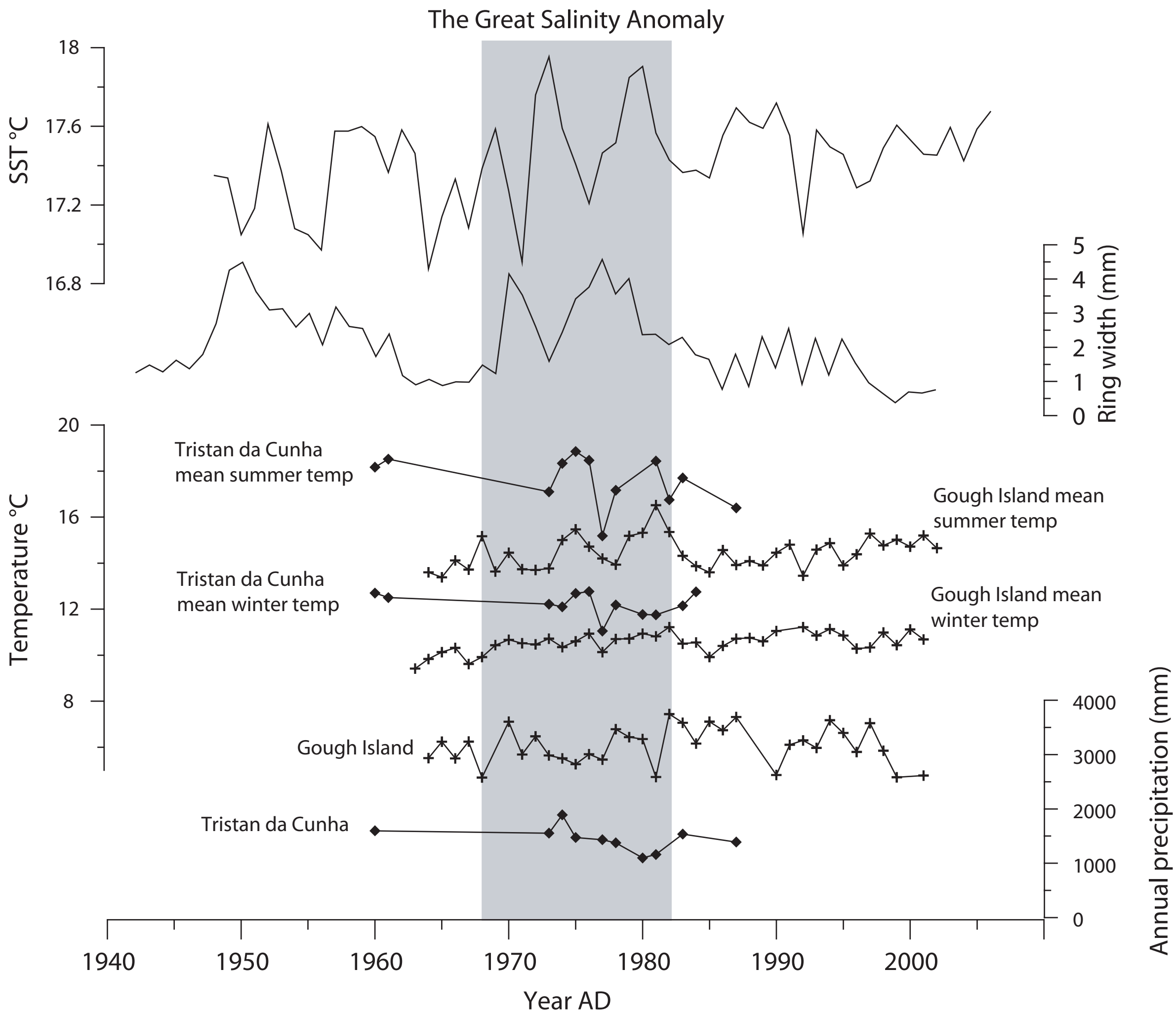

Figure 11: Figure showing NCEP sea surface temperature for the central South Atlantic (20-45S, 20W-10E) (Kalnay et al. 1996), tree ring widths from Tristan da Cunha, mean summer and winter temperatures from Tristan da Cunha (filled diamonds) and Gough Island (crosses). The grey box shows the timing of the Great Salinity Anomaly (GSA) in the North Atlantic (Belkin et al. 1998).

environment on Tristan da Cunha is very sensitive to human disturbance. There are no natural land mammals on the island and the vegetation is not adapted to grazing (Wace and Dickson, 1965). This is probably the reason why the small number of humans visiting the island could have an effect that is visible in pollen diagrams. This is also makes preservation of the natural vegetation, with its high number of endemic plant and animal species - on the Tristan da Cunha islands and other isolated islands - very challenging. Only small disturbances, which may not be all that dramatic for larger land masses, can have a disastrous effect on the local flora and fauna on islands.

7. 5 Climate change in the last 50 years – a South Atlantic response to the Great Salinity Anomaly?

During the Great Salinity Anomaly (GSA) of the 1970s surface salinities in the North Atlantic decreased by about 0.5 salinity units, which is in the same range as during Holocene IRD events (Belkin et al., 1998; Bond et al., 2001; Dickson et al., 1988). The freshening was basin wide and propagated through the North Atlantic between 1968 and 1982 (Belkin et al., 1998). This anomaly has been proposed to be a modern analogue to the IRD events of the Holocene inferred from marine cores (Bond et al., 2001). The freshening associated with the IRD events probably also affected the deep water formation and caused weaker MOC. If this was indeed a modern analogue for such events and if, following the arguments in Appendices III and IV, that these events correspond to a warming and increased precipitation in the South Atlantic, the GSA of the 1970s should also have a South Atlantic response.

In the following discussion NCEP/NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research) reanalysis data of sea-surface temperatures for the central South Atlantic, a small tree ring data set spanning the last 40 years from Tristan da Cunha, and air temperature data from Tristan da Cunha and Gough Island are used to investigate climate changes in the South Atlantic during the GSA.

NCEP sea surface data for the central South Atlantic (20-45°S, 20°W-10°E) are shown in figure 11 (Kalnay et al., 1996). The extracted section is the same as for the coupled ocean-climate model results shown in Appendix IV. The data extends back until 1948 and the years with highest sea-surface temperatures are around 1973 and 1980. This is coeval with the GSA in the North Atlantic and is in agreement with the concept of warmer sea surface temperatures in the South Atlantic as a consequence of weaker MOC induced by surface freshening and less deep water formation in the North Atlantic.

The small amount of climate data available from Tristan da Cunha precludes any inferences of the 1970s being warmer or wetter than any other decade (Fig. 11). However, the temperature anomalies are similar to those from the Gough Island record where continuous climate data are available from 1960. The warmest period in the Gough Island temperature data was during the 1974-1982, which corresponds to the GSA. The anomalies are most pronounced in the summer temperatures in both the Tristan da Cunha and Gough Island data sets. The annual precipitation does not show any clear response to the warmer sea surface temperatures during the 1970s, or any clear correlation with temperature. Probably increased air humidity caused by the warmer sea surface temperature was small compared with the seasonal variations and any changes may therefore be overshadowed by the natural variability. The climate stations are also situated close to sea level and it is possible that precipitation may have increased at higher areas due to the orographic effect.

The small tree-ring series obtained from Tristan da Cunha show thickest ring widths, indicating highest growth rates, in the 1950s and in the 1970s. The high precipitation on Tristan da Cunha makes it unlikely that trees are limited by drought. If the increase in growth rate during the 1970s was caused by climate it was most likely a response to higher temperatures. The tree-ring series are, however, not in perfect agreement with the available temperature series.

The chronological constraints of the sediment and peat sequences are too weak to precisely relate any changes during the last 50 years in the other proxy records from Tristan da Cunha and Nightingale Island to climatic recods of the 1970s. However, increasing magnetic susceptibility and minerogenic matter in the peat in the topmost part of the 2nd Pond sequence from Nightingale Island may be a response to increased precipitation triggered by higher SST (Appendix IV).

From the available climate and proxy data it can be concluded that during the last 50 years the 1970s was the warmest, and possibly the wettest decade on Tristan da Cunha, and that sea surface temperatures at this time were at their highest. It is intriguing that these changes coincide with the GSA in the North Atlantic. However, this could be merely coincidental and there may not be a causal link. On the other hand the assumption that the observed temperature changes in the South Atlantic are indeed related to weaker MOC caused by freshening of the North Atlantic during the GSA, raises questions about the mechanisms involving deep water formation and the MOC. It implies that there is virtually no time lag, or at a maximum only a few years, between the forcing and the effects on circulation. Such a rapid effect of freshwater forcing on the circulation is confirmed by the modelled response of the 8.2 ka event, which shows an almost immediate increase of SST in the South Atlantic (Appendix IV). It also shows that large freshwater forcings, such as drainage of glacial lakes is not necessary to trigger circulation changes. Small freshwater forcings on short time scales (decadal) in the North Atlantic is enough to limit the northward energy transport from the South Atlantic.

8. Conclusions

This thesis presents proxy based records of climate and environmental dynamics of the last 10 700 years on the Tristan da Cunha island group in the central South Atlantic. These are the first well-dated high resolution paleoclimate records from Tristan da Cunha and Nightingale Island and they are also the longest continuous high resolution record of Holocene climate and environmental changes from the central South Atlantic. The following conclusions can be made from this thesis:

- The proxy records show large changes which imply that the Tristan da Cunha islands have been affected by significant climate changes during the last 10 700 years. The results reveal a much more dynamic Holocene climate than indicated by previous paleoclimate studies on the islands.

- Around 8600 cal. yrs BP the effective humidity, mainly driven by higher precipitation, increased considerably, which caused a change from peat accumulation to gyttja deposition at 2nd Pond on Nightingale Island. The increased precipitation was probably caused by a northward shift of the Southern Hemisphere Westerlies and coincides with the end of the thermal optimum in Antarctica and inferred changes of the westerlies in South America. The cause of this shift was probably falling temperatures in Antarctica and expanding sea ice cover in the Southern Ocean, which pushed the circulation system and associated fronts northward.

- Evidence for short periods, between 100 and 1000 years long, with increased precipitation occur throughout the peat and sediment sequence from Nightingale Island. These periods of higher precipitation in the South Atlantic are correlated with ice rafting events and cool conditions in the North Atlantic, and it is hypothesised that the increased precipitation was caused by higher sea surface temperatures in the South Atlantic caused by weaker Meridional Overturning Circulation. This pattern is similar to the "bipolar seesaw" mechanism during glacial times, and indicates that this process was active also during interglacial periods.

- A period of increased precipitation is dated to 8275-8025 cal. yrs BP and is thus coeval with the 8.2 ka event. The increased precipitation at this time was probably caused by higher sea-surface temperatures caused by weakening of the Meridional Overturning Circulation triggered by freshwater forcing in the North Atlantic during the 8.2 ka event.

- The discovery of Tristan da Cunha in 1506 and the following utilisation of its natural resources and establishment of the permanent settlement had profound effects on the natural vegetation. The first palynological evidence of human presence on Tristan da Cunha is the appearance of *Plantago lanceolata* around 1550 AD, which was introduced by the Portuguese who discovered the islands. The land use intensified and new plant species were introduced by seal hunters around 1650 AD, and in the 19th century most of lowland forest was cleared.

- During the Great Salinity Anomaly of the 1970s in the North Atlantic, sea surface temperatures and atmospheric temperatures were higher in the central South Atlantic. On Tristan da Cunha thicker tree rings show that growing conditions were more favourable in the 1970s. It is hypothesised that the cool and fresh conditions in the North Atlantic caused a short weakening of the Meridional Overturning Circulation, which caused warmer conditions in the central South Atlantic.

9. Potential for future studies

The Tristan da Cunha island group is strategically situated in the central South Atlantic and, as has been shown in this thesis, climate changes of regional and interhemispheric significance have affected the islands. Thus, the potential for future paleoclimate studies on these islands are great and can reveal new and important insights into the Quaternary climate.

Nightingale Island is around 18 Ma years old, with no evidence of volcanic activity during the last 40 000 years, and it may be possible to retrieve continuous sediment sequence extending well into the last glacial. Such a record would cover the climatically dynamic period of the Pleistocene-Holocene boundary and could improve our understanding of the role of the Atlantic during deglaciation.

The hypotheses and conclusions in this thesis could be corroborated, or perhaps refuted, with future studies employing other methods. The inferred precipitation changes could be further studied using diatom analysis. This could reveal any lake level changes associated with higher precipitation periods. Variations of the strength of the westerlies could be studied with proxies for wind and sea-spray, such as deposition of far-travelled minerogenic particles and marine Na and Cl.

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Svensk sammanfattning

Jordens klimat varierar naturligt på tidsskalor från årtionden till årmiljoner. Orsakerna till dessa variationer är komplexa och involverar många olika processer och återkopplingsmekanismer i atmosfären, haven och biosfären. Variationerna drivs både av förändringar i systemet och av extern påverkan som tillexempel variationer i jordens bana runt solen, jordaxelns lutning, och vulkanutbrott. Under de senaste hundra åren har mänsklig påverkan också lagts till de naturliga variationerna.

En förutsättning för att kunna förstå hur detta komplexa system fungerar är att man har en god bild av hur klimatet har varierat bakåt i tiden. Från 1700 talet och framåt finns det tillgång till systematiska instrument mätningar av klimatet, men före detta är man tvungen att använda sig av naturliga klimatarkiv. Torvmossar och sediment från sjöar fungerar som arkiv där spår av tidigare klimatförändringar finns lagrade. Dessa kan vara biologiska, kemiska eller fysiska parametrar som påverkas av klimatet. Till exempel kan ett ändrat klimat ge förändringar i vegetationssammansättningen, vilket kan rekonstrueras med hjälp av pollen som ligger lagrade i sjösediment.

I den här avhandlingen har sjösediment och torv från ögruppen Tristan da Cunha i centrala Sydatlanten använts för att rekonstruera hur klimatet och miljön har varierat och förändrats under de senaste 10 700 åren. Tristan da Cunha är mycket strategiskt belägen i mitten av Sydatlanten och klimatet på öarna påverkas både av förändringar i havsströmmarnas- och atmosfärens cirkulation.

Borrkärnor från en öppen sjö, två igenväxta sjöar och en torvmosse har studerats och analyserats med avseende på innehåll och ursprung av det organiska materialet, innehåll av pollen från vegetationen på ön, mineralmagnetiska analyser och daterats i detalj med hjälp av kol-14 metoden. Sammantaget ger dessa analyser en god bild av hur klimat- och miljöförändringar har påverkat öarna och resultaten visar på stora klimatvariationer under de senaste 10 700 åren, vilka har orsakats både av förändringar i atmosfärens och havsströmmarnas cirkulation.

Från 10 700 till omkring 8600 före nutid var förhållandena betydligt torrare än idag med torv tillväxt i en av de undersökta lokalerna som idag är en övervuxen sjö. Övergången från ett torrare klimat med torv till mera nederbördsrikt klimat och avsättning av sjösediment markerar en dramatisk förändring i atmosfärens cirkulation på södra halvklotet. Troligen orsakades denna förändring av en förskjutning av västvindsbältet norrut. Från slutet av istiden och fram till för omkring 9000-8600 år sedan var klimatet i den Atlantiska delen av Antarktisk och Sydatlanten varmare än idag vilket också gjorde att västvindsbältet var förskjutet söderut.

Flera kortare perioder, mellan 100 och 1000 år långa, med ökad nederbörd och erosion förekommer i lagerföljderna. Dessa perioder beror troligen på högre havsytetemperatur i Sydatlanten. Under dessa perioder var Nordatlanten kallare med mer isberg längre söderut. Att Sydatlanten värmdes upp samtidigt som det blev kallare i Nordatlanten berodde troligen på att transporten av varmt vatten från Syd till Nordatlanten var svagare. Detta visar att den storskaliga cirkulationen har varierat och att detta har påverkat energibalansen i Atlanten.

En av dessa perioder med ökad nederbörd på Tristan da Cunha sammanfaller med de så kallade ”8.2 eventet” när Nordatlanten kyldes ner av stora mängder kallt sötvatten som dränerades från isjöar i Nordamerika. Detta fick till följd att transport en av varmt vatten från Syd- till Nordatlanten minskade, vilket höjde havsytetemperaturen och ökade nederbörden i Sydatlanten. Datorsimuleringar av denna störning visar att havsytan värms upp och nederbörden ökar i området runt Tristan da Cunha, vilket resultaten från den här avhandlingen också stödjer.

Tristan da Cunha upptäcktes 1506 av portugisiska upptäcktsresande, men blev inte permanent bosatt förrän på 1800-talet. Redan de första Portugisiska upptäckarna påverkade miljön på Tristan da Cunha. Det visar fynd av pollen från den introducerade *Plantago lanceolata* som har daterats till omkring 1550 AD. Troligen satte de första portugisiska besökarna iland getter på ön och förde samtidigt ovetande med sig *P. lanceolata* frön. Under 1600 och 1700 talen besöktes ön av säl och valfångare från Storbritannien och Holland. Deras aktivitet ledde till att skogen på låglandet minskade, samt att spridningen av introducerade växtarter och markerosionen ökade. Under 1900 talet ökade befolkningen på ön vilket ledde till intensivare markanvändning och att nya arter introducerades.

Resultaten från denna avhandling visar att klimatet och miljön på Tristan da Cunha har varierat och förändrats under de senaste 10 700 åren till följd av förändringar i atmosfärens- och havsströmmarnas cikrulation, och av antropogena effekter efter det att människan kom till ön.

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