Tree rings and climate in Scandinavia and Patagonia

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Tree-growth and climate in high-latitude environments in Fennoscandia and Patagonia

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Abstract

The present knowledge of temperature variability during the past millennium has been greatly improved due to an increasing availability of reconstructions made based on paleoclimate proxies, such as tree-rings. These improvements however, do not suffice to provide a coherent representation of the past climate at local to regional scale at higher latitudes. The reasons, are mainly due to the poor spatial density of the networks and the little understanding of how microsite variability affects the signal stored in the varied tree-ring proxies. Fennoscandia and Patagonia are strategic locations for studies on past climates, and were chosen to extend and improve the existing dendrochronology networks. This work also aimed to provide high quality improved chronologies with skills to reconstruct primarily temperature, with attention to the effects of microsite conditions and large scale atmospheric and oceanic patterns. Using *Pinus sylvestris* L., two temperature reconstructions were made: a local from the west central Scandinavian mountains extending 970 years using the blue light intensity absorption from tree-rings, and a regional built on ten chronologies extending through the Scandinavian mountains using density and blue intensity information from the tree rings. Additionally, a gridded reconstruction was made on the latter. In Patagonia six *Nothofagus betuloides* and one *Pilgerodendron uviferum* chronologies were developed and analyzed. These contained limited and non-statinary information on temperature and precipitation, probably on account of microsite conditions. Chronologies at both study sites were proven to contain information of large-scale atmospheric and oceanic patterns. In Fennoscandia, Atlantic Multidecadal Oscillation and Summer North Atlantic Oscillation in addition to volcanic forcing modulate significantly local to regional climate and therefore tree-growth. In Southern Patagonia in turn, tropical and subtropical sea surface temperatures seem to affect tree-growth. While relationships between tree-growth with the Southern Annular Mode were found on years of extreme growth, they were marginal and non-stationary when tested with index at interannual scale. Patterns of spatial correlations with sea level pressure further suggest these links. Moreover, the Pacific sector of the Southern Ocean, specifically the areas of the Amundsen and Bellingshausen Seas are indicated to have an unprecedented importance to the growth dynamics of the southernmost forest in the world. The new chronologies developed in the study areas possess potential to be used on studies of climate evolution at higher latitudes taking into account that microsite conditions affect the climate signal recorded in the tree-growth.

Key words: Tree-rings, *Pinus sylvestris* Fennoscandia, Atlantic Multidecadal Oscillation, Scandinavian Pattern, *Nothofagus betuloides*, *Pilgerodendron uviferum*, temperature precipitation, Southern Annular Mode, Southern Oscillation Index, Amundsen Lows, Sea Level Pressure, Sea Surface Temperature, Southern Pacific Patagonia

Tree Rings and Climate in Scandinavia and Patagonia

To Olivia, Enzo, Leandro and Sofia and Juan and Bessie.

List of publications included in the thesis

Paper I

Fuentes, M., Salo, R., Björklund, J., Seftigen, K., Zhang, P., Gunnarson, B.E., Aravena, J-C. and Linderholm, H.W. 2017: A 970 year-long summer temperature reconstruction from Rogen, west central Sweden, based on Blue Intensity from tree rings. *The Holocene* DOI: 10.1177/0959683617721322. (Online first)

MF planned the article, collected and prepared the data, analyzed the data and led the writing of the article.

Paper II

Linderholm H.W., Björklund J.A., Seftigen K, Gunnarson B.E. and **Fuentes, M.** 2015: Fennoscandia revisited: A spatially improved tree-ring reconstruction of summer temperatures for the last 900 years. *Climate Dynamics* 45: 933-947. DOI: 10.1007/s00382-014-2328-9

MF helped to plan the study, collected and analyzed the data and contributed to the text.

Paper III

Linderholm, H.W., Zhang, P., Gunnarson, B.E., Björklund, J., Farahat, E., **Fuentes, M.**, Rocha, E., Salo, R., Seftigen, K., Stridbeck, P. and Liu, Y. 2014: Growth dynamics of tree-line and lake-shore Scots pine (Pinus sylvestris L.) in the central Scandinavian Mountains during the Medieval Climate Anomaly and the early Little Ice Age. *Frontiers in Ecology and Evolution* 2: 20. DOI: 10.3389/fevo.2014.00020

MF helped to plan the study, collected and analyzed parts of the data, collaborated in writing the bulk of the text.

Paper IV

Fuentes M., Seim. A., Aravena J.C., Linderholm H.W. Assessing the dendroclimatic potential of Magellan's beech (Nothofagus betuloides) in the southernmost Patagonian Archipelago. *Trees* (in review)

MF planned the article, collected and analyzed the data and had a leading role in writing the article.

Paper V

Fuentes, M., Seim, A., Christie D., Gutierrez, A., Aravena J., Seftigen K., Björklund J. and Linderholm, H.W. Climate sensitivity of *Nothofagus betuloides* (Mirb) Oerst and

Pilgerodendron uviferum (D.Don) Florin; growing in the southernmost forest in the world: the signal of the Southern Annular Mode, the Southern Osculation Index and large scale spatial patterns from the southern pacific.

MF planned the article, collected and analyzed the data and had a leading role in writing the article.

Publications not included in this thesis

Fuentes M, Björklund J., Seftigen K., Salo R., Gunnarson B.E., Linderholm H.W. and J.C. Aravena A (2016) Comparison between Tree-Ring Width and Blue Intensity high and low frequency signals from *Pinus sylvestris* L. from the Central and Northern Scandinavian Mountains (2016): *TRACE - Tree Rings in Archaeology, Climatology and Ecology*, Volume 14. Scientific Technical Report 16/04, GFZ German Research Centre for Geosciences, p. 38-43. doi: 10.2312/GFZ.b103-16042

Seftigen, K., Cook, E.R., Linderholm, H.W., **Fuentes, M.** and Björklund, J. 2015: The potential of deriving tree-ring based field reconstructions of droughts and pluvials over Fennoscandia. *Journal of Climate* 28: 3453–3471. DOI: 10.1175/JCLI-D-13-00734.1

Wilson, R., David Wilson, D., Rydval, M., Crone, A., Büntgen, U., Clark, S., Ehmer, J., Forbes, E., **Fuentes, M.**, Gunnarson, B.E., Linderholm, H.W., Nicolussi, K., Wood, C., Mills, C. 2017: Facilitating tree-ring dating of historic conifer timbers using Blue Intensity. *Journal of Archaeological Science* 78: 99-111. DOI: 10.1016/j.jas.2016.11.011.

Farahat, E., Peng Zhang, P., Gunnarson, B.E., **Fuentes, M.**, Stridbeck, P. and Linderholm, H.W. 2017: Are standing dead trees (snags) suitable as climate proxies? A case study from the central Scandinavian Mountains. *Scandinavian Journal of Forest Research* DOI: 10.1080/02827581.2017.1341547 (Online first)

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1. Introduction

The knowledge of temperature variations during the past millennium has improved greatly since the first hemispheric reconstruction by Mann *et al.* (1999), which opened the door for successive attempts to reach more a accurate understanding of climate variability back in time. This knowledge allows us to identify and connect historical and natural events affecting humanity through time, those very issues that modulate human history in connection with the natural world. As described by Wilson *et al.* (2016) in their reconstruction of the Northern Hemisphere temperatures, the beginning of the last millennium is characterized by warm anomalies through the tenth century, followed by steady declining in temperatures for the following 500 years with a period dominated by cool temperatures called the Little Ice Age (LIA) from 1450 to 1850. From 1850 to 1950, steady increases of temperature are identified followed by an abrupt increase: the so called 20th century warming. For this reconstruction, Wilson *et al.* (2016) used 54 tree-ring chronologies assembled across the Northern Hemisphere to portray the climate history of the last millennium. For the Southern Hemisphere, a reconstruction by Neukom *et al.* (2014), showed a steady increase in temperatures until ca 1350, after which temperatures decreased to a minimum in ca. 1650. The LIA ended around 1900, and was followed by a strong increase in temperatures mirroring the Northern Hemispheres record. These reconstructions have been the fruits of arduous work, but the information they provide is for large scales due to the limited geographical distribution of paleoclimate records. There are still several areas in the world where little is known about past temperature variability, partly due to the lack of long instrumental records from meteorological stations and limited proxy data availability. Data scarcity, including observations and proxy data, is most pronounced in undeveloped countries and/or inaccessible areas such as southern Patagonia, but also in Scandinavia there are regions from which detailed knowledge of past natural climate variability is still lacking (Linderholm *et al.,* 2010, 2015).

Knowledge of past climate variability with high spatiotemporal resolution can help to set the changes observed today in a long-term context, and thus determine anthropogenic effects on the climate system (Bradley, 1985; IPCC, 2013). This is of extreme importance, since it may justify political engagement and actions for mitigation measures and improvements of legislation for economic activities (IPCC, 2013).

1.1. High-resolution paleoclimate studies in high-latitude environments

While a majority of dendroclimatological studies have focused on the midlatitudes (St George, 2014; Boninsegna *et al.,* 2009), remote high-latitude regions have received less attention. In this context, the relevance of studies of past climate based on tree-rings in Scandinavia and Southern Patagonia can be motivated in relation to the importance of high-latitude influences on low-latitude climates (Hurrel and Van Loon, 1997; Quintana and Aceituno, 2012; Garreaud *et al.,* 2009, Semenov *et al.,* 2009). In addition, the climate sensitivity of tree-rings in Scandinavia is generally greater than in most other areas in the Northern Hemisphere (St George, 2014), providing excellent tools for past climate assessment. Moreover, Patagonian tree-ring data represent an important terrestrial paleoclimate proxy for the southernmost forested continental land masses in the Southern Hemisphere. They have the potential to describe past climate changes, glacier variability, or past changes of atmospheric circulation (Villalba *et al.,* 1997; Masiokas *et al.,* 2009; Boninsegna *et al.,* 2009). Thus, tree-ring data from these two high-latitude regions are important tools for assessing present and past climate and its links to dominant large-scale patterns (Boninsegna *et al.,* 2009; Linderholm *et al.,* 2010).

Scandinavia and Southern South America display similarities such as strong maritime influences, dominance of westerly winds in connection to the landscape and the orographic precipitation, (Busuioc *et al.,* 2001; Garreaud *et al.,* 2009; 2013). On the other hand, differences are also evident, indicated by temperature and precipitation regimes, with cooler and wetter summers in southern western Patagonia (Figure 1) and lower amplitude in the yearly cycle compared to Scandinavia. The strong influence of the Gulf Stream in the Atlantic is responsible for the warm climate in northern Europe, and has no counterpart in the southeastern Pacific. The sea-surface temperatures (SST) in the subtropical and south Pacific have nevertheless been connected to sea ice extent in the Amundsen and Bellingshausen Seas, and temperature trends in west and central Antarctica (Renwick, 2002; Steig *et al*., 2012; Schneider *et al*., 2012).

Although Scandinavian climate is influenced by the proximity to the North Atlantic, the additional influences from the Eurasian continent results in higher amplitude in the annual temperature cycle compared to southern South America, the latter is surrounded by oceans which together with the permanent westerly wind flow moderates the variability of the year cycle (Garreaud *et al*., 2009; 2013). Moreover, In the Southern Hemisphere, the presence of the cold Antarctic continent and the surrounding oceans leads to a rather symmetrical structure, for which the pressure differences are strong between high and subtropical latitudes enhancing the westerly wind flow. This causes a stronger pressure gradient in Southern compared to the Northern Hemisphere. Moreover, few major obstacles in the latitudes between 56°S to 65°S means that the westerlies can flow uninterrupted, with reduced eccentricity and high stability (Garreaud *et al.,* 2009; 2013). The westerly flow drives the Antarctic Circumpolar Current (ACC) that is one of the strongest currents in the world. Part of the ACC is diverted northwards forming the Humboldt Current. When this meets the southern portion of the Americas, upwelling of cold, deep waters provoke a cooling effect of the surface air (Falvey and Garreaud, 2009).

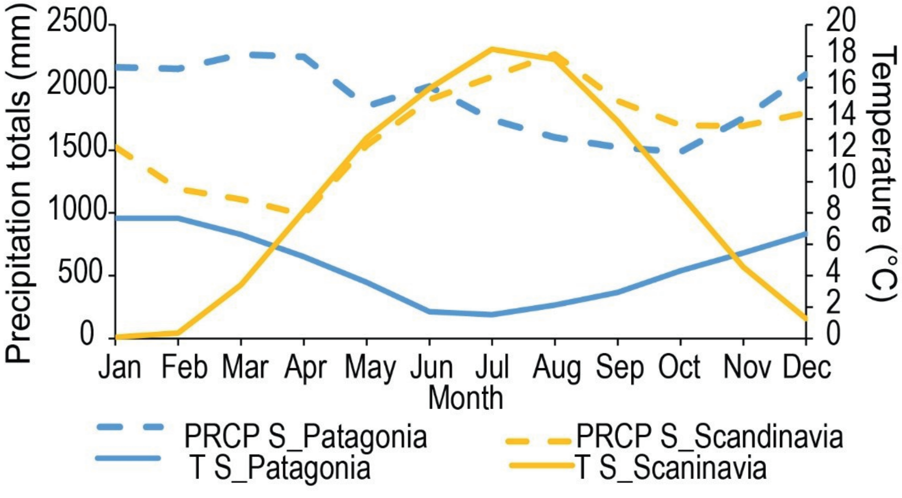

Figure 1. Year cycle of precipitation in broken lines (data from CRU TS 4.0, Harris and Jones 2017), and temperature in continuous lines (data from CRU TS3.24.01, Harris et al., 2014) for the grid points 71W, 55S representing Southern Patagonia (blue lines) and 13E, 55N representing Southern Scandinavia (yellow lines)

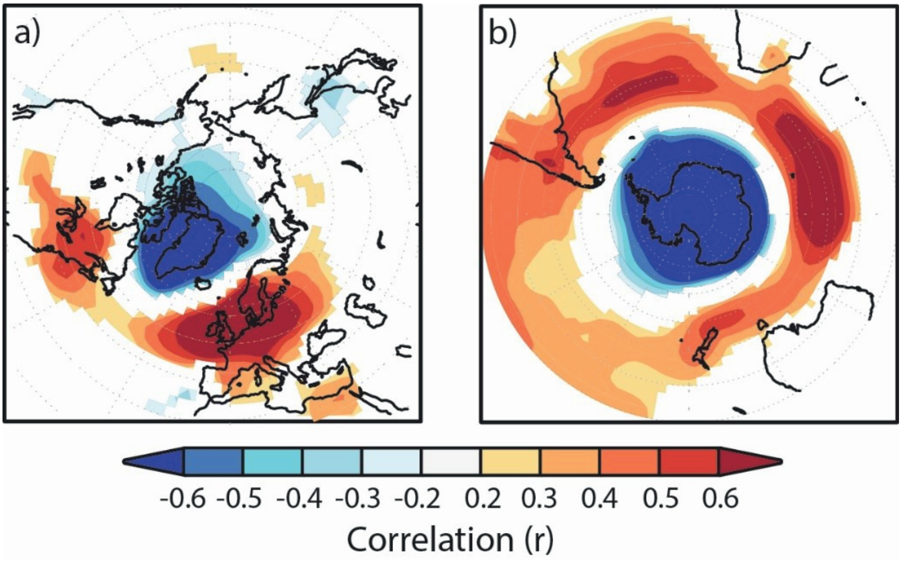

Figure 2. Spatial correlations of respective summer average Sea level pressure (NCAR/NCEP Kalnay, et al., 1996) with a) Summer North Atlantic Oscillation "SNAO" (NCAR/NCEP Kalnay et al., 1996. Averaged over 40-70N, 90W-30E JJA 1950-2010) and b) December through February Southern annular mode station based (Marshall 2003; 1958:2016).

1.2 Knowledge gaps

The knowledge of the high-frequency variability of past temperatures in Scandinavia has mainly been restricted to the northern parts of the region. This problem led to the statement by Esper *et al.* (2012), that despite the numerous tree-ring records and reconstructions existing in the area, past temperature variability in the whole of Fennoscandia is still not well understood. The lack of sufficient high-quality proxy records throughout the entire region results in a bias when only the northern data represents Fennoscandia in large-scale temperature reconstructions. In recent years several new reconstructions covering significant parts of the last millennium have been introduced (e.g. Björklund *et al.,* 2015; Linderholm *et al.,* 2015), but there is still a lack of records representing southern Scandinavia. Such records would also serve as links between northernmost and central Europe, and hence facilitate studies of spatiotemporal temperature variability across the continent.

In southern Patagonia, there is a need for updating and expanding the existing network of *N. betuloides* and *P. uviferum*. Very few datasets are available, and just a few records extend from 1990 to the present (Boninsegna *et al.,* 1989; 2009). Further, only a few studies have examined the influence of SST and SLP on *Nothofagus spp*. tree growth in southernmost Patagonia

(Villalba, 2007; Villalba *et al.,* 1997; 2004; 2012), and there are no publications which aim specifically on local SLP patterns, focusing for on the area of Amundsen and Bellingshausen Seas. Moreover, only in one study the dendroclimatological potential of *P. uviferum* south of 50° S was examined (Aravena, 2007).

2 - Aims and objectives

Dendroclimatological studies provide information on climate dynamics back in time. In order to understand the natural variability of climate, knowledge of the evolution of parameters, such as temperature or precipitation or large-scale modes such as the SAM, SOI or SNAO, is vital. As noted above, there are some clear knowledge gaps when it comes to understanding high-latitude climate evolution in both hemispheres. Moreover, given the increased interest in spatial variation in climate through time (e.g. Silvestri and Vera, 2009; Folland *et al.,* 2009) a sufficient geographical representation of paleoclimate data is needed.

The objectives of this thesis were:

i) To extend and update the existing dendrochronological networks in Sweden and southernmost Patagonia and to apply new proxy developments such as blue intensity when possible. (Papers I II and IV and V)

ii) To improve the current status of knowledge of the temperature evolution during the last millennia in Scandinavia and Patagonia. (Papers I and II and IV and V)

iii) To provide methodological guidelines for improving the detection of climate signals in the newly developed chronologies. (Papers I to V)

iv) To assess the link between the new chronologies and the large-scale climate patterns known to affect high-latitude environments. (Papers I, II and IV and V)

The work presented here is the result of a collaboration between researchers from the Gothenburg University Laboratory for Dendrochronology (GULD) and Chilean dendrochronology groups of the University of Magallanes and Universidad Austral de Chile and Universidad de Chile.

3. Background

3.1. Climate settings

3.1.1. Scandinavia

The meridional gradient shapes the temperature variability in Scandinavia, with decreasing temperatures to the north and at higher elevations. The influence of the Atlantic Ocean is strongest in the west, but also influences climate well into the central Scandinavian mountains. The orographic nature of the precipitation reaches about 2400 mm on the western slopes of the Scandinavian Mountains, decreasing eastwards were the climate becomes increasingly continental, although there is a slight increase in precipitation close to the Baltic Sea. These patterns underline the importance of the westerly winds bringing moisture from the Atlantic as they move inland (Busuioc *et al.,* 2001; Linderson 2003). This implies the direct relationship between wind intensity and precipitation totals (Busuioc *et al.,* 2001), but also temperature variability (Chen and Hellström, 1999). High temperature anomalies with extremes around 30° C can occur in connection to persistent high pressure cells during the warm season (Johansen, 1970). These situations are called blockings, and can persist for several days. The North Atlantic Oscillation (NAO) (Walker and Bliss, 1932) influences the strength of the westerly winds and the path of the storm tracks (Gagen *et al.,* 2016) and is closely linked to regional temperature and precipitation patterns (Hurrell 1995; Slonoski *et al.,* 2001). The influence of the NAO, which can be defined as the pressure difference between Iceland and the Azores, is strongest during winter due to the stronger temperature gradient (Hurrell, 1995). However, the variability of the summer NAO (SNAO), where the pressure nodes are found above UK-Scandinavia and Greenland, is also closely associated with climate in northwestern Europe (Folland *et al.,* 2009).

In addition to the influence of intra- and interannual variations in North Atlantic SST on Fennoscandian climate, influences on longer timescales are also evident. On decadal to multidecadal scales, North Atlantic SST variability has been linked to the thermohaline circulation (Sutton and Hodson, 2005) and it is characterized by warm and cold phases alternating on about 60-80 year timescales, affecting climate in North America and Western Europe. This pattern, termed the Atlantic Multidecadal Oscillation (AMO), is clearly distinguished in both observations and paleoclimate reconstructions (Schlesinger and Ramankutty, 1994; Kerr, 2005; Parker, 2007; Knudsen *et al.,* 2014).

3.1.2. Patagonia

In Patagonia, a thorough description of the climate characteristics is difficult due to the sparse distribution meteorological stations, for which non-continuous datasets pose difficulties in connection to the shortness of the records (Miller, 1976; Villalba *et al.,* 2003). Local climate regimes are consistent with geographic patterns. In this area one of the strongest precipitation gradients in the world is found, were the super humid windward coast receives above 10 000 mm/year at the southern Patagonian Ice Field, decreasing to ca. 430 mm/year in Punta Arenas, less than 200 km east (Carrasco *et al.,* 2002), changing to highly evaporative conditions in the Patagonian plains. The precipitation totals are evenly distributed through the year (Carrasco *et al.,* 2002). The most important feature in the area is the westerly wind flow, which is stronger in summer but exhibits little seasonality. The westerlies modulate precipitation and temperature patterns, the latter by controlling the amplitude of the annual cycle surface temperatures through seasonal advection, provoking little seasonal variation with greater spatial homogeneity than precipitation. Long-term temperature changes have been reported (Rosenblüth *et al.,*1995;1997), indicating warming in the last century (Miller, 1976; Carrasco *et al.,* 2002, Villalba *et al*., 2003; Garreaud *et al.,* 2009).

The Southern Oscillation Index (SOI) (Walker and Bliss, 1932; Ropelewsky and Halpert, 1987; Halpert and Ropelewsky, 1992) is the atmospheric component of the El Niño Southern Oscillation (ENSO). The SOI is defined as the normalized pressure difference between Tahiti and Darwin, and is related to a distinct pattern of alternating SST anomalies and a spatial structure of bands from the tropical to the southern Pacific and Atlantic. The SOI is normally related to anomalous precipitation north of 40 °S, but Pittock (1980) indicated precipitation anomalies also at latitudes south of 50°S. Later it has been suggested that the influence of the SOI reaches as far as the Southern Ocean and the Antarctic Peninsula (Renwick, 1998; Renwick and Revell, 1998; Kwok and Comiso, 2002; Schneider and Gies, 2004; Fogt and Bromwich, 2006), where the SOI is related to atmospheric pressure anomalies (Figure 3).

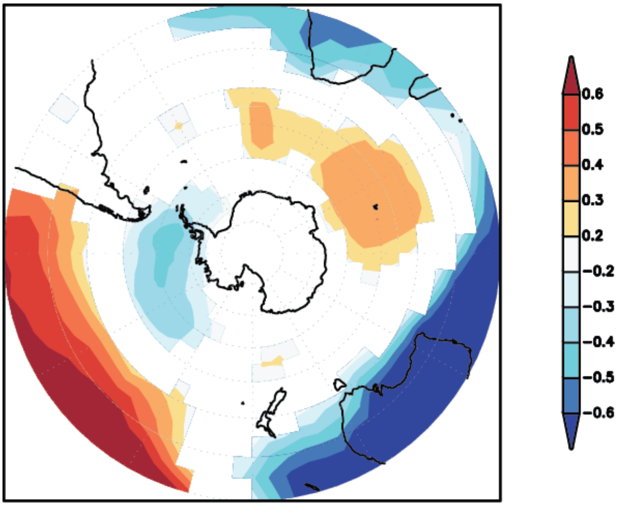

Figure 3. Point by point correlation between DJF mean SOI (CRU, Ropelewsky and Jones, 1987; Könen et al., 1998) with DJF mean HadSLP2r SLP (Allan and Ansell, 2006) detrended data, p<10%.

The Southern Annular Mode (SAM) (Marshall, 2003) (Figure 2b), has received attention from the scientific community due to its influence on precipitation and temperature regimes (e.g. Marshall, 2003; Gillet *et al.,* 2006; Garreaud *et al.,* 2009; 2013) as well as tree-growth patterns (Villalba *et al.,* 2012) in the Southern Hemisphere. The SAM can be described as a large-scale latitudinal dipole structure in the atmosphere between 40°S and 65°S, and describes the strength and latitudinal variability of the westerly flow. In northern Patagonia (around 40°S), positive SAM years are related to dry conditions in the southern Andes (Mundo *et al.,* 2012; Villaba *et al.,* 2012) but it may also be valid for southern Patagonia at ca. 45°-55°S (Lara *et al.,* 2015; González-Reyes *et al.,* 2017). The SAM, provides information on wind patterns on a hemispheric level, which may not always be suitable for local climate conditions. To deal with this issue, some authors have developed "local" SAM indices (Meneghini *et al.,* 2007; Quintana and Aceituno, 2012).

Another useful atmospheric mode in the Southern Ocean is the Amundsen Sea Low (ASL, Hosking *et al.,* 2013; 2016). The ASL is a climatological low-pressure system located in the Pacific sector of the Southern Ocean (an analogue to the Aleutian Low in the North Pacific). Here the SLP variability is greatest in the Southern Hemisphere, and the position and strength of the ASL are key drivers of regional change over West Antarctica (Hosking *et al.,* 2013; 2016; Turner *et al.,* 2013). The ASL is defined as the point of lowest central pressure within the ASL sector region (170–290° E, 80–60° S) (Hosking *et al.,* 2013; 2016; Turner *et al.,* 2013). An index based on the latitudinal variations in the ASL provides information of the meridional flow from the Pacific into West Antarctica and the Antarctic Peninsula, the Drake Passage and southern Patagonia. It was originally designed for assessments of West Antarctic climate and sea-ice variability, but the local character of the index makes it attractive to engage in dendroclimatological studies concerning species in southern Patagonia.

3.2. Tree-rings as climate indicators - dendroclimatology

Trees are excellent sources of climate information, since the physiological mechanisms involved in tree growth are affected by environmental factors (Frits, 1965; 1976), and through their life span they store information in their yearly increments and wood properties (Frits, 1976; Cook and Kairiukstis, 1989). An excellent example of this is the thermal control of tree growth in Scandinavia (Eide, 1926; Erlandsson, 1936). The most commonly used climate proxy from trees is the yearly increment, more generally referred to as ring width (RW), utilized since the beginning of dendrochronology as a scientific discipline (Douglas, 1909; 1914). Other variables such as isotopic composition (McCarroll and Loader, 2004), Radio-densitometry (Schweingruber, 1978), and more recently blue light intensity (absorption or reflection) (McCarroll *et al.,* 2002) have been introduced climate proxies for dendroclimatological applications. The discipline of dendroclimatology relies on several principles, which will be shortly introduced here.

Cross-dating: this principle is the base of the discipline, consisting of assigning the correct year-date to every ring in every sample. The patterns of the tree rings are compared between samples so the dates will be consistently assigned.

The aggregated tree growth is a conceptual model of the components of the growth often exemplified by an equation, $R_t = f(G_t, C_t, D1_t, D2_t, E_t)$, where R_t is the ring growth in the year t, but can actually represent parameters other than tree-growth, for example mean blue intensity. Subsequently, G, C, D and E represent age (size), climate, endogenous and exogenous disturbances, and E is the error or noise not accounted in the previous terms.

Limiting factors indicates that tree growth is governed by certain environmental variables, but only those that are scarce will limit tree-growth. It is implicit in the definition that stressed trees (e.g. those growing in extremely cold or dry environments) provide stronger climate signals than those growing under more suitable conditions.

Site Selection refers to a certain population of tree-rings containing the climate signal related to the variable being examined. Thus, populations growing in sites that maximize the environmental signal in a study should be visited for sampling. For example, if the aim of the study is reconstructions of temperatures, sites where temperature is limiting tree growth should be visited for sampling.

Ecological amplitude is a concept associated to the spatial ecological distribution of the species. A species may grow better at the centre of the ideal distribution range, but will present greater signs of stress at the edges of the distribution (see above).

The principle of *uniformitarianism* has lately been questioned. This principle implies stability in relationship between tree-growth and a particular environmental variable through time. In practical terms it assumes that trees responded to e.g. temperature in the past in a similar manner as in the present. It has been suggested that this principle should be dropped in favour to the "principle of trees as dynamic entities", adding the possibility of trees to adapt to the environment.

Tree-ring data can be observed and measured from various sources: living trees, preserved remains of dead trees standing or lying on the surface and trees buried in various sediments (called subfossil trees). Living trees are sampled using an increment corer in order to minimise the impact on the trees. From dead trees, discs are taken using a chainsaw. After sampling and preparation of the samples, assessments of common ring patterns from the individual samples from a site are made in a process called cross-dating. In this process, tree-ring patterns are scrutinized first by eye, with graphical methods or by listing the years with interesting features such as very narrow or wide rings. The result of this process is the assignment of an absolute calendar year to each tree-ring. After the measuring or estimation of the chosen tree-ring parameter, cross-dating is repeated using computer software (Fritts, 1967; Holmes, 1983) allowing correction of dating and measuring errors and further sample selection. Subsequently, noise unrelated to climate (i.e. systematic tendencies, such as the age trend) must be removed from the time series derived from tree-ring measurements. For this purpose several methods are available, and it is usually done by fitting a function to the tree-ring series from which residuals or ratios are obtained as dimensionless indices (Cook, 1985). Then, the individual time series can be averaged into a chronology and subsequently compared to climate data. Tree-ring data have been intensely used for reconstructions of temperature and hydroclimate from local to hemispheric scales, and have been useful to portrait the temperature history for the last millennia (Jones *et al.,* 2001; Moberg *et al.,* 2005, 2008; Schneider *et al.,* 2015; Wilson *et al.,* 2016; Anchikaitis *et al.,* 2017) and even on multi-millennial time scales, (Grudd *et al.,* 2002; Helama *et al.,* 2002; Linderholm and Gunnarson, 2005; Pages 2k Consortium, 2013). Furthermore, tree-rings have also been used to assess or reconstruct atmospheric circulation patterns, such as the Southern Annular Mode (Villalba *et al.,* 2012; Abrams, 2014) and the North Atlantic Oscillation (Linderholm *et al.,* 2009; Trouet *et al.,* 2012).

3.2.1. Dendroclimatology in Scandinavia

Pinus sylvestris L. is a coniferous species present in Europe and Eurasia. It is widely used in dendroclimatological studies, and it is a typical component of the Boreal forest belt. In Scandinavia, the species can surpass 700 years (Andersson and Niklasson, 2004), and can, in general, provide information on temperature at higher latitudes/altitudes and precipitation at lower latitudes (See Linderholm *et al.,* 2010 and Seftigen *et al.,* 2015).

The short and cool summers in central and northern Scandinavia is the main reason why temperature during summer is the main limiting factor for tree growth in this area (Eide, 1926; Erlandsson, 1936). This is also one of the reasons for the strength of the climatic signal in tree-ring data, argued to be among the strongest in the world (St George, 2014; Wilson *et al.,* 2016). Moreover, the climate provides optimal conditions for the preservation of woody material, by limiting the microbial and fungal activity on land and within lakes (under water and buried in sediments), making it possible to find and analyse trees having grown several millennia ago (Gunnarson, 2008). Given the quality of the data and the lengths of the tree-ring records, many temperature reconstructions at hemispheric level have included data from Scandinavia (see Linderholm *et al.,* 2010, Willson *et al*., 2016; Anchukaitis *et al*., 2017). Moreover, some of the world's longest temperature reconstructions belong to central and northern Scandinavia, extending several millennia back in time (Grudd *et al.,* 2002; Helama *et al.,* 2002; Linderholm and Gunnarsson, 2005). The strength of the temperature signal declines southwards, coinciding with a gradual increase of the precipitation signal (Seftigen *et al.,* 2015). This, together with a preferred sampling at the latitudinal ends of the distribution of the species, have caused an over-representation of temperature reconstructions from northernmost in Fennoscandia (Grudd, 2002; Esper *et al.,* 2012; 2014). Until recently, the summer temperature reconstruction from the central Scandinavian mountains was the southernmost one in Scandinavia, which was firstly developed from RW, ultimately reaching ca 7000 years back in time (Gunnarson and Linderholm, 2002; Linderholm and Gunnarson, 2005; Gunnarson, 2008). Later significant improvements were made using the maximum latewood density (MXD) parameter, where warm season (April-September) temperatures during the last millennium were targeted (Gunnarson *et al.,* 2011; Zhang *et al.,* 2016).

3.2.2. Dendroclimatology in Patagonia

Most dendroclimatological studies in southern South America have targeted hydroclimate variability in the Mediterranean climatic zone (e.g. Le'Quesne, 2006; Lara *et al.,* 2001; Boninsegna *et al.,* 2009), but the area south of 40°S has received limited attention. Studies from southernmost Patagonia (south of 50°S) have focused mainly on temperature (Boninsegna *et al.,* 1989; Aravena *et al.,* 2002; Villalba *et al.,* 2003; Lara *et al.,* 2005). The species used in these studies belong to the *Nothofagus spp*, *Nothofagaceae* family, where *N. antarctica*, *N. betuloides*, and *N. pumilio* have been used. Generally, *Nothofagus spp.* RW data from southern South America contain a mixed signal of temperature and precipitation, evident by very modest correlations in the summer season. Also associations with SLP patterns have been found in this species (Villalba *et al.,* 1997; 2012). The connection between tree growth and SLP is related to the link between pressure and temperature and precipitation (Villalba *et al.,* 1997). Recent studies have suggested that the observed decreasing trends in tree growth in the last decades is an effect of the persistent positive phase of the SAM during the last 50 years (Llancabure, 2011; Villaba *et al.,* 2012). However, not all tree-ring data indicate negative growth trends (Soto-Rogel and Aravena, 2017), and trends can vary dramatically depending on the detrending method used (Villaba *et al.,* 2012). Up to today, little has been published on inter-site comparisons of climate signals in RW data.

3.3. Sampling of tree-ring material

In Sweden, the selection of the sites where trees were to be sampled was based on background information from land administration and environmental offices (e.g. Länsstyrelsen, Naturvårdsverket and Skogsstyrelsen). In Sweden, getting permission for sampling is mainly straight forward, and access to a sampling site is usually quite easy and uneventful. In Patagonia, however, the logistics make sampling a complex task. Landowners need to be contacted individually for permissions. Moreover, there are limited roads to get access to sites in remote areas like Tierra del Fuego. In the Magellan Strait archipelago, travel by boat is the only way to reach potential sampling areas, and usually very little is known about the site conditions. Thus, getting to some areas within 400 kilometers of Punta Arenas may take several days, just on account of sailing conditions. If landing close to a sampling area is possible, long marches are needed, crossing rivers, mires, dense forests patches, cliffs or the like, to come to adequate sampling points if there are any. The sampling must be done efficiently, to return to the landing point in time, since the tide and the wind restrict navigation of the small crafts.

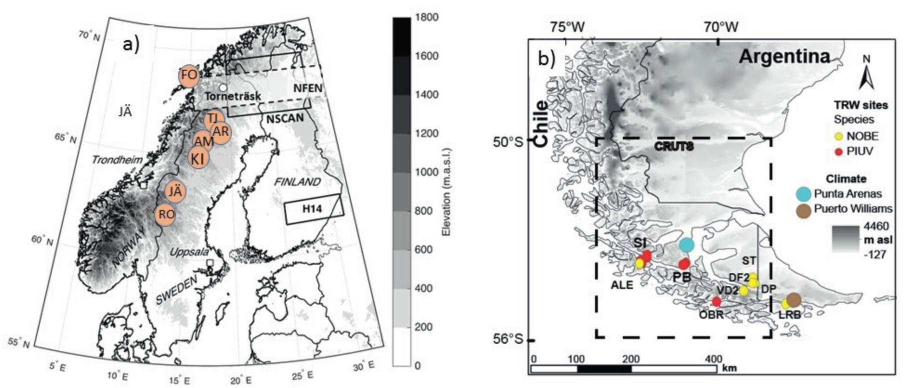

Figure 4. Study areas, a) Study area from Paper I, II, and III. Datasets H14 (Helama et al., 2014); NSCAN, (Esper et al., 2012), NFEN (McCarroll et al., 2013) grey field with dotted borderlines; White circle Torneträsk (Melvin et al., 2013) Orange circles FO= Forfjordalen, TJ= Tjeggelvas, AR= Arjeplog, AM = Ammarnäs, KI= Kittefjäll, JÄ= Jämtland (CSCAN, Zhang et al., 2016) and RO = Rogen.; H14, NSCAN used in paper I, Sites ***a*** *to* ***g*** *used in paper II, data from site f was used in paper III. Figure 4b, Nothofagus betuloides sites red dots (paper IV) and Pilgerodendron uviferum yellow dots (paper V), light blue and light brown dots indicate Punta Arenas and Puerto Williams Climate Stations.*

For paper I, sampling was conducted in the Rogen nature reserve (62° 22'N, 12° 24'E), located close to the border between Sweden and Norway (Figure 4a). The topography of Rogen is characterized by a succession of moraine ridges and lakes, with gentle slopes resulting from glaciofluvial processes. The mountain ridges and tops rise up to 1500 m a.s.l. The forest is dominated by Scots pine (*Pinus sylvestris* L) accompanied with birch (*Betula pubescens* Ehrh.) and Willow species (*Salix spp*.). The sampling site was characterised by an open forest with limited human disturbance. The ground was covered occasionally by a sparse field layer (*Calluna vulgaris* (L) Hull, *Empetrum nigrum* L.). Due to its location, the site is affected by the inflow of maritime

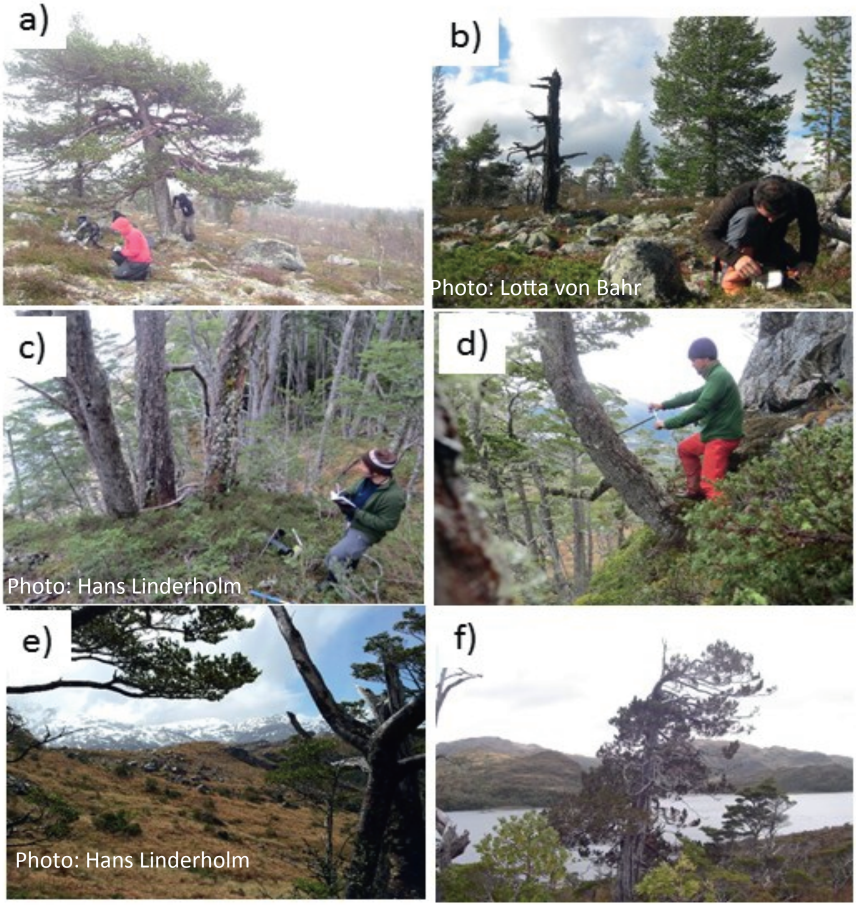

Figure 5. Fieldwork, a, b) Rogen, Pinus sylvestris forest c) M. Fuentes during fieldwork at site NZ southern Patagonia d) HW Linderholm at fieldwork in VD2 Southern Patagonia e) N. betuloides site Alejandro Valley (ALE) and f) P. uviferum site Southern Patagonia.

winds, due to the east west orientation of the valleys. Trees between 800 and 600 m a.s.l., where the tree line is located at ca. 800 m a.s.l., were sampled with Haglöf increment borers at ca. 130 cm above the root collar. Samples from dead trees were collected with the help of a chainsaw at similar height when possible. For paper II, data from previously published studies was used (see Table 1 for more information on this data).

For paper III, the objective was to assess the stability and consistency of the signals in tree-ring width chronologies sampled from trees growing in moist and dry environments in the central Scandinavian mountains. Mount Håckervalen (63°10' N, 13°30' E) has a typical tree line environment, with a forest dominated by *Pinus sylvestris* L, with accompanying species *Betula pendula* Roth, *B pubescens* Ehrh., *B nana* L., *Salix spp*. and *Picea abies* L (H. Karst). The soils were rather thin and covered by a field layer composed of ericaceous shrubs: *Vaccinium myrtillus* L. and *V.vitis-idaea* L. which left some exposed patches of bedrock. The moist sites, the shores of Trolltjärnen (530 m a.s.l.), Lill-Rötjärnen (560 m a.s.l.) and Östra Helgtjärnen (646 m a.s.l.), were typical mountain lake environments, displaying similar vegetation as the dry sites, but with greater occurrence of *Gramineae* and Norway Spruce (*Picea Abies*). Subfossil wood collected from the lakes represented trees growing on the lake shores in the past and dead wood from the mountain slopes represented past dry tree-line environments.

For papers IV and V, 15 sites in southern Patagonia were sampled in 2011, 2012 and 2013. This resulted in six chronologies of *Nothofagus betuloides* and one of *Pilgerodendron uviferum (Figure 4b)*. Alejandro Valley, ALE (53° 44' S, 72° 29' W) was the westernmost site at Santa Inés Island, in the Pacific outlet of the Strait of Magellan. The site had a SE aspect, an altitude of 125 m a.s.l. and a slope of ca. 45%. Three sites were collected on Tierra del Fuego island: two mountainous sites: DF2 (54°24' S, 68°42'W) between 300 and 400 m a.s.l., with aspects approximately NW and W, and DP (54°25'S, 68°49'W) with NNE, and NW aspects with altitudes of about 400 m a.s.l. Slightly to the north, in a somewhat less hilly environment, ST (54° 10' S, 68° 47'W) had a N aspect and an altitude of about 250 to 300 m a.s.l. DF2 and DP were steeper sites with slopes >30%, while at ST it was <30%. Two southern sites were collected in the Cordillera Darwin in southern Tierra del Fuego: Valle de los Divorcios, VD2 (54°36' S, 69°03° W), which had a SW aspect with varying slopes and an average altitude of 270 m a.s.l. and Glaciar Nueva Zelanda NZ (54º42' S, 69º20' W) which also varied in slope, with altitudes from 10 to 80 m a.s.l. At Bahía Mussel (BM, Carlos III Island) (53° 37' S, 72° 18' W) *P. uviferum* was collected at an altitude of ca. 100 m a. s. l. This species is restricted to environments corresponding largely to raised bogs, characterized by thick layers of *Sphagnum* spp. interspersed with bedrock. Moreover, tree-ring data from an additional seven *P. uviferum* sites and one *N. betuloides* (LRB) (Table 1) were provided by South American colleagues and included in the analysis. In addition, previously collected *P. uviferum* sites were used for paper V (Table 1).

Table 1 Chronologies used in these studies (Δ parameter developed for these studies with material provided by original authors (indicated in the table) following (Björklund et al., 2014) ΔBIadj is adjusted contrast for blue intensity deltas. (EPS si empirical population signal >0.85 quality standard). SP is the abbreviation for species: PISI Pinus Sylvestris; NOBE Nothofagus betuloides; and PIUV Pilgerodendron uviferum. Zelanda, NZ (54°42' S, 69°20' W) which also varied

Paper	Location	SP	Proxy	latitude	Longitude	Span (EPS)	Source
I, II	Rogen	PISI	ΔBI -ΔBIadj	62°2'N	12°1 E	1038–2010	Paper I
II	NSCAN	PISI	ΔDensity	66°5'-69°3' N	19°5' – 29°E	1100-2006	Esper *et al.,* 2012
II	Forfjorddalen	PISI	ΔDensity	68°5' N	15°4' E	1100–2007	McCarroll *et al.,* 2013
II	Tjeggelvas	PISI	ΔDensity	66°3' N	17°4' E	1550–2010	Björklund *et al.,* 2013
II	Arjeplog	PISI	ΔDensity- ΔBI	66°2' N	18°1' E	1200–2010	Björklund *et al.,* 2014
II	Ammarnäs	PISI	ΔDensity	65°1' N	16°6' E	1550–2010	Björklund *et al.,* 2013
II	Kittelfjäll	PISI	ΔDensity	65°1' N	15°3' E	1550–2007	Björklund *et al.,* 2013
II-III	Jämtland	PISI	ΔDensity- ΔBI–RW	63°1' N	13°3' E	1100–2008	Björklund *et al.,* 2014
IV	Alejandro Valley ALE	NOBE	RW	53° 4' S	72°3'W	1825-2010	This report
IV	Deseado Fagnano DF2	NOBE	RW	54° 2' S,	68° 4' W	1731-2011	This report
IV	Despreciado DP	NOBE	RW	54° 2' S	68°5' W	1739-2011	This report
IV	Glaciar Nueva Zelenda NZ	NOBE	RW	54°4' S	69°2' W	1880-1960	This report
IV	Lote 10 (ST)	NOBE	RW	54°1' S	68°5' W	1747-2011	This report
IV	Valle de los divorcios VD2	NOBE	RW	54°4' S	69°1' W	1807-2012	This report
V	Lago robalo (NAV)	NOBE	RW	54° 58' S,	67°41' W	1588-2008	Llancabure 2011
V	Monte Tarn (PBA)	PIUV	RW	53º 45'S	71º 00'W	1600-2000	Aravena pers. com
V	Bouchage (PBB)	PIUV	RW	53º 49'S	71º 7'W	1632-1686	Aravena pers. com
V	San Nicolás (PBC)	PIUV	RW	53º 49'S	71º 07'W	1654-2002	Aravena pers. com
V	Santa Inés (SIA)	PIUV	RW	53º 45'S	72º 29'W	*1677-2002*	Aravena pers. com
V	Seno ballena (SID)	PIUV	RW	53º 40'S	72º 33W	1732-2003	Aravena pers. com
V	Bachelor (SIF)	PIUV	RW	72º 18'S	72º 18'W	1733-2003	Aravena pers. com
V	Obrien (OBR)	PIUV	RW	54º 54'S	70º 00'W	1787-2003	Guriérrez pers. com
V	BM	PIUV	RW	53° 37' S,	72° 18' W	1657-2010	This report

3.4. Sample preparation and obtaining the tree-ring parameters

The procedures to prepare the samples differ depending on the type of proxy to be used. Samples from living trees and dry wood were surfaced by sanding with successively finer grit until the cell walls are evident under magnification and no scratches are visible as described by Stokes and Smiley (1968). Samples obtained in lakes were surfaced with a razor blade and chalk was added to increase contrast and improve visualization of the cell structures. Samples used for densitometric analysis were prepared following the protocols delineated by Schweingruber (1978) and Gunnarson *et al.* (2011), and subsequently scanned in an ITRAX multiscanner from Cox Analytical Systems (www.coxsys.se) at the department of Physical Geography at the University of Stockholm, Sweden. Finally, samples used for blue intensity were cut to 4 mm thick sections and washed in a refluxed ethanol solution at 95% for periods between 32 to 72 hours to remove extractive compounds. Later the samples were air dried and sanded to a grit up to 1200 to be scanned in a scanner (Epson Perfection V600) with a resolution of 1600 dpi using the software Silverfast with a calibration target of IT8.7/2, following the procedures of Campbell *et al.* (2011), adapted in Björklund *et al.* (2014).

For all the chronologies, the dating process was started by assigning a calendar year to the fully formed ring under the bark of the living trees, which correspond to the last growing season increment before sampling. While doing this, the samples were also cross-dated, to ensure correct dating of each annual ring. Cross-dating is the process of visually controlling the dated segments between different samples (Yamaguchi, 1991), and it is done by comparing the tree ring patterns between samples. Later this process is repeated with the use of statistical programs such as TSAP (Rinntech, Heidelberg, Germany) or COFECHA (Holmes, 1983; Grissino-Mayer, 2001). Subfossil samples were dated through statistical comparison using student t and sign tests available in the TSAP software (paper III).

RW data were measured with the LINTAB system with interface of the TSAP software (paper I, II and III) and the Velmex TA measuring system (www.velmex.com) (paper IV). Finally, the maximum density (MXD) and blue intensity (BI) data were extracted from the density and optical images with the use of commercial software WinDendro™. The density measurements in paper II, were later transformed to the delta parameter (ΔMXD). The delta (Δ) parameter indicates a subtraction between early and latewood information, and was designed by Björklund *et al.* (2014) to eliminate possible bias from latewood densitometric measurements due to, for example, extractives remaining in the latewood portion of the tree rings. This new parameter represents an improvement of reconstructive skills of ca. 20% for June through August temperatures compared to ordinary MXD (Björklund *et al.,* 2014). It is derived by subtracting the earlywood density from the respective maximum density, and for the case of blue intensity, the process is executed in the same manner, but with an additional step to adjust the low frequency trend of ΔBI to the analogue Δdensity (Björklund *et al.,* 2015). This process is done following the guidelines in Björklund *et al.* (2015), where a set of slopes and intercepts of the regressed (earlywood blue intensity (EWBI) and earlywood density (EWD) from Swedish chronologies were developed and applied in three equations used to adjust the EWBI parameters for each sample with no need for local density data for Rogen. These guidelines allow adjustments of EWBI in the absence of density data for other stands as well (paper I). This process was done under the assumption that BI and the density parameters behave similarly through the Scandinavian landscape for Scots pine. The application of BI data for assessments of lower frequencies using *Pinus sylvestris* in Scandinavia would be impractical without these adjustments. The definition and development of ΔBI and ΔDensity proxies are not a technical achievement developed in this thesis, instead in paper I and II of this work, these proxy-types were applied following the guidelines of the developers (Björklund *et al.,* 2014; 2015).

3.5. Detrending tree-ring data and chronology development

After measuring the tree ring samples, the time series contain an amount of information that is deemed unrelated to climate, for example the growth trend which is a product of the yearly increment of the stem volume (Cook, 1985). These trends were removed from the density and BI data using the RSFi method (Björklund *et al.,* 2013) (paper I and III) by applying a regional constrained individual signal free standardization based on the signal free method of Melvin and Briffa (2008). This was done by a combination of individual signal free and regional curve standardization (RCS). Later, signal-free and RCS functions for each sample were averaged. In paper I, two regional curves were created, one for each group of fast and slow growing trees respectively. In paper II, only one RCS curve was produced to represent the growth of each of the local populations. A more traditional method was used in paper III, by fitting a negative exponential curve and a straight line through the mean of the tree ring measurements (Cook, 1985). Similarly, in paper IV and V, a cubic smooth spline with 67 year filter length (Cook and Peters, 1981) was fitted to the power transformed RW data. The latter is used to stabilize the variance of the time series (Cook and Peters, 1997) (paper IV). The tree ring data was processed in this step with the programs Signal Free (Melvin and Briffa, 2008) (papers I, II VI and V) and ARSTAN (Cook and Krusic, 2005) (Paper III). The detrending process produces dimensionless indices (standardized) that can be used in climate analyses (Cook, 1985).

3.6. Climate data

In this work, data from global gridded datasets of various climate parameters were used, including temperature and precipitation (CRU TS, Harris *et al.* (2014)), CRUTEM 4.2.0.0 (Jones *et al.,* 2012)), sea-level pressure (HADSLP, Allan and Ansell (2006)), sea-surface temperature (HADlSST, Rayner *et al.* (2003)) and SLP from NCEP/NCAR (Kalnay *et al.,* 1996), as well as data from meteorological stations Punta Arenas (Dirección Meteorological de Chile (DMC), Puerto Williams (DMC).

The indices representing atmospheric modes used in papers IV and V, were obtained from https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based (SAM, Marshall (2003)) and http://www.cpc.noaa.gov/data/indices/ (SOI). Furthermore, local versions of the SAM for the regions indicated in Figure 6 were created using SLP data from the NCEP/NCAR reanalysis project (Kalnay *et al.,* 1996) based on the areas of highest correlation values between the *P. uviferum* chronologies and the gridded SLP data. The ASL index (version 2 used in this study) (Hosking *et al.,* 2013), was downloaded from https://climatedataguide.ucar.edu/climate-data/amundsen-sea-low-indices.

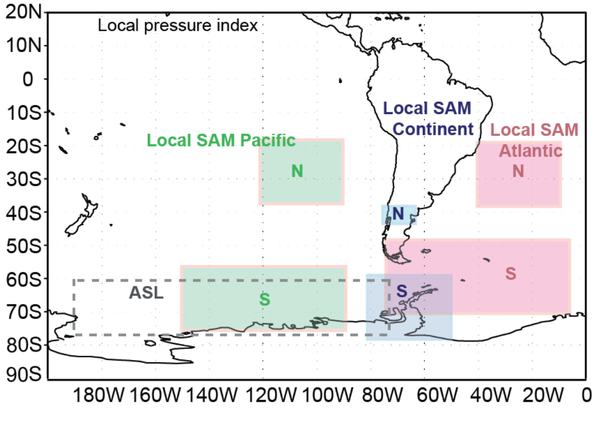

Figure 6. Local pressure indices data-area cutoff from NCEP/NCAR gridded data 1948-2016. Squares in green correspond to the Pacific, blue on the continents and light red in the Atlantic. N and S areas were used to develop local pressure indices based on extensions of correlation fields with chronologies. The dashed line approximately indicates area where Amundsen Sea Low (ASL) index is derived (Hosking et al., 2013).

3.7 Statistical analyses

3.7.1. Principal component analysis

In paper V, principal component analysis (PCA, Jolliffe, 2002) was used to extract the main modes of variability in the tree-ring and climate data. In the case of tree-rings it is run with the assumption that the common variability in a set of samples (sites) is caused by climate. Linear PCA generates *n* new variables which are linear combinations of the *n* original variables. This allows for the creation of subsets of samples or chronologies, increasing the potential of detection of climate signal and decreasing background noise (Peters *et al*., 1981).

3.7.2. Spectral analysis

Spectral analysis provides information of the main oscillatory modes contributing to the temporal structure of a time series. Thus, this method can detect cyclic patterns common among datasets. In paper I, the common spectral characteristics for RW and ΔBI_{adj} chronologies were assessed using a coherency test from the software Anclim (Stepanek, 2008) This analysis can be interpreted as the frequency dependent square correlation coefficient (Von Storch and Zwiers, 2004).

3.7.3. Spatial correlation analysis

Spatial correlation tests were applied to assess the geographical relationships between tree-ring data with SLP and SST. The spatial features shown in the correlation maps provide information of spatial patterns that can be associated to atmospheric or oceanic circulation. The tests were assessed by Pearson correlations between the chronologies and gridded data to assess the spatial agreement between the datasets. The level of the correlation together with the extension of the correlated fields with determined sign (positive or negative) can be interpreted in terms of structural patterns of the process which is investigated. These tests were run in MATLAB™ for paper I and II, and using the web based application Climate Explorer (climexp.knmi.nl, Trouet and Van Oldenborgh, (2013)) in paper IV. For these exercises, all data was detrended and first differenced.

3.7.4. Superposed Epoch Analysis

In tree ring sciences, anomalous tree growth can be a result of environmental effects or disturbances, such as forest fires, cuttings, drainage, or floods, or climatic events such as volcanic eruptions. The latter can be related to warmer and colder anomalies during winter and summer respectively. For papers I and II, the reaction of the tree-ring indices was tested with Superimpose Epoch Analysis (Panofsky and Brier, 1958; Lough and Fritts, 1987) using the R software (R Core Team, 2013) and package dplR (Bunn *et al.,* 2017), and the mean response to volcanic eruptions was assessed for significance. The test was run over a period of 1 to 5 years before and after the eruption date and the significance envelopes were calculated with bootstrap resampling.

The datasets from GAO *et al.* (2009) in paper I and II, and Crowley and Unterman (2013) and Sigl *et al.* (2015) were used in paper I.

3.8. Temperature reconstruction for a single site

In paper I, simple linear regression (Fritts, 1976) was used to target mean June to August temperature from the CRU TS 3.23 grid point closest to the study area (62°N,12°E) for the period 1901-2010, using the split sample method (Snee, 1977). In this method, the datasets are divided into two parts, where the early part is first used for calibration, and then the reconstruction is verified against the withheld data. The process is then re-done with calibration on the late part and verification of the early. The aim is to test the temporal stability in the relationship between the tree-ring data and the climate parameter. In paper II, nested linear regression (Meko, 1997; McCarroll *et al.,* 2013) was used, in which a nest of chronologies are created. This is done by Z-scoring all chronologies to the period of the shortest chronology for the first nest, and the next shortest chronology for the following nest, and so on. For each nest, the chronologies are averaged and used as predictor to temperature by means of linear regression (by calibrating with CRUTEM 4.2.0.0 (Jones *et al.,* 2012)). After the first and second nests are averaged, the process is repeated for all the chronologies. Seven nests were used, and the amount of chronologies included in each nest diminished back in time.

3.9. Spatial reconstruction

In paper II, a point-by-point regression approach (PPR) (Cook *et al.,* 1999) was used to generate fields of JJA temperature anomalies from the tree-ring network. The PPR reconstruction was performed by K. Seftigen in the MATLAB (Release 2013a) environment. The method employed a 1500 km search radius (Cook *et al.,* 2012). The chronologies within the search radius were screened by means of Pearson correlation between corresponding gridded data and the current year growth. For every grid, only significantly correlated chronologies were retained and transformed into orthogonal eigenvectors (>1.0), and used as predictors in a stepwise regression. For every grid each nest was later scaled to the corresponding calibration period of the instrumental data and averaged to obtain full-length reconstruction for each grid point (for details see Cook *et al.,* 1999).

4. Results

This section summarises the papers included in the thesis. The full papers are presented in the appendix.

4.1. Paper I

Fuentes, M., Salo, R., Björklund, J., Seftigen, K., Zhang, P., Gunnarson, B.E., Aravena, J-C. and Linderholm, H.W. 2017: A 970 year-long summer temperature reconstruction from Rogen, west central Sweden, based on Blue Intensity from tree rings. *The Holocene* DOI: 10.1177/0959683617721322. (Online first)

The aim of this paper was to increase the knowledge of local temperature variability in west-central Fennoscandia as well as increasing the tree-ring data coverage further to the south. A new temperature reconstruction was presented using the ΔBI_{adj} parameter, targeting June through August temperatures, from 985 to 2010 CE with a temperature signal of 64% explained variance.

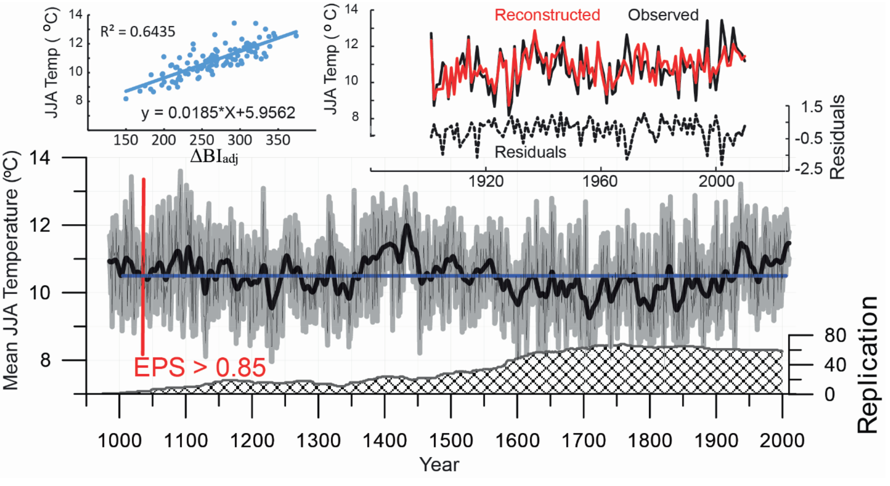

Figure 7. JJA ΔBI_{adj} temperature reconstruction from the west central Scandinavian mountains. Upper left plate shows regression model. To the right, reconstructed vs observed mean JJA temperature 1901-2010. Bottom, JJA temperature reconstruction- Black thick line 20 year Gaussian filter, thin line JJA temperature reconstruction. Grey lines (RMSE). Cross-lined field indicates sample depth. Blue horizontal line is mean average (10.5°C).

The record indicated three warm periods; one in the beginning of the chronology coinciding with the end of the medieval warm period, a conspicuous warm pulse between 1350 and 1456 and the 20th century warming. A period of prolonged below average temperatures coincided with the Little Ice Age between 1456 and the beginning of 1900, with the coldest years around 1710. Good agreement was found when compared to previously published Fennoscandian temperature reconstructions (Esper *et al.,* 2012; Helama *et al.,* 2014; Zhang *et al.,* 2016)

Much of the methodological aspects of the blue intensity have already been discussed elsewhere (Campbell *et al.,* 2007; Campbell *et al.,* 2011; Björklund *et al.,* 2014; Rydval *et al.,* 2014), but the trend differences between RW and ΔBI_{adj} were remarkable. The validity of the representation of the low frequency variability of ΔBI_{adj} was demonstrated by correlations with long-term instrumental temperature records from Oslo and Uppsala, and supported by trends found in MXD data in paper II and results from Esper *et al.* (2012; 2014) and Helama *et al.* (2014).

The association of Rogen with large scale atmospheric circulation indicated a dipole SLP pattern, with one node located over Scandinavia and another over Iceland, resembling the so called Scandinavian pattern (Barnston and Lizevey, 1987).This study demonstrated the usefulness of ΔBI_{adj} for proxy to temperature reconstruction contributing to a better representation of the southern Swedish and Scandinavian temperature evolution during the last millennium.

4.2. Paper II

Linderholm H.W., Björklund J.A., Seftigen K, Gunnarson B.E. and Fuentes, M. 2015: Fennoscandia revisited: A spatially improved tree-ring reconstruction of summer temperatures for the last 900 years. *Climate Dynamics* 45: 933-947. DOI: 10.1007/s00382-014-2328-9.

The aim of this paper was to improve the understanding of Fennoscandian summer temperature variability during the last millennium using a new tree-ring network. The regional mean JJA reconstruction was built on seven ΔDensity and three ΔBI chronologies, incorporated in 4 nests. The reconstruction captured over 50% of the variance in observed temperatures and showed sufficient skill to represent past temperature variations across the region. The temporal evolution of the temperature generally agrees with previous records (Melvin *et al.,* 2013; McCarroll *et al.,* 2013; Esper *et al.,* 2012), but some discrepancies were noted, for example in the 13^{th} century, with best agreement corresponding with the 20^{th} century. The new reconstructions displayed a much improved spatial representation of the temperature fields due to the incorporation of similar high-quality proxies as well as sites with more southern provenance. The gridded JJA temperature reconstruction provided a new and improved representation of the Scandinavian temperature evolution for the last 900 years. The correlations between nests and instrumental data were maintained with decreasing number of predictants, which was in contrast to previous works. In comparison with previous field (European level) reconstructions, the best agreement was found with Lutherbacher, *et al.* (2004), but only back to ca 1700 CE, a period which includes instrumental data. After that the correlation decreased significantly. Limited agreement was also found when compared to Guiot *et al.* (2010), probably due to the seasonal window chosen for the reconstruction, the type of proxy used and the influence of central European data contained in them, biasing the results and not making them representative for Fennoscandia. A brief exploration of the climatic forcings over Scandinavian temperatures was also made, in which northern hemispheric volcanic forcing and SST from the Atlantic were compared to the local reconstruction. The new regional temperature reconstruction provides highly valuable information of the temperature history for Scandinavia over the last 900 years, evidencing the importance of the development of local southern reconstructions allowing for a more realistic representation of the temperature of the area back in time.

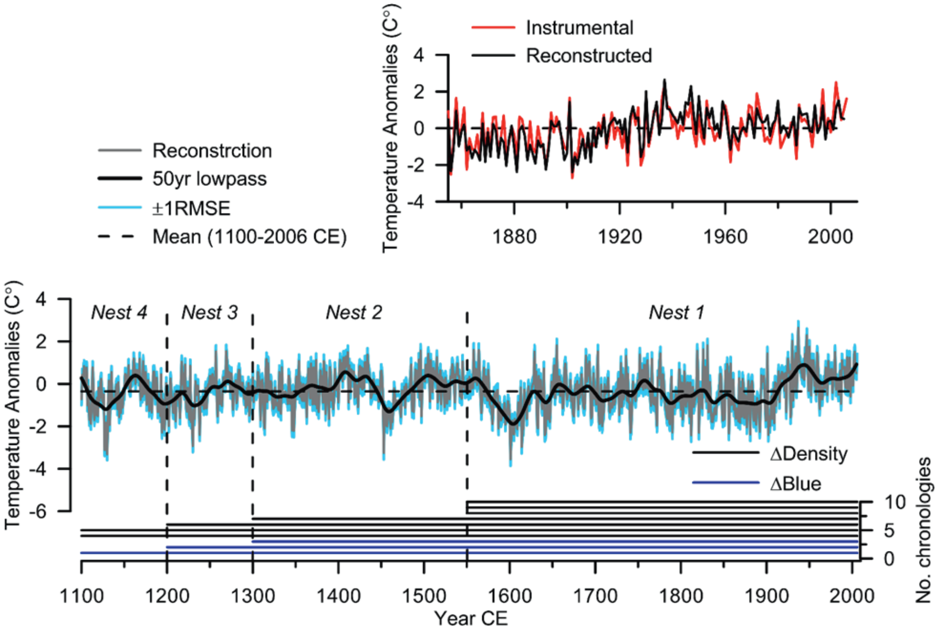

Figure 8. Mean JJA temperature reconstruction from Scandinavia. Upper plate, reconstructed vs observed temperature, lower plate, the black line represents JJA temperature reconstruction with a 50 cubic smooth spline of 50 year frequency response cutoff. Long term mean in dashed horizontal line. The uncertainty in form of root mean square error (RMSE) symbolized by light blue lines.

4.3. Paper III

Linderholm, H.W., Zhang, P., Gunnarson, B.E., Björklund, J., Farahat, E., Fuentes, M., Rocha, E., Salo, R., Seftigen, K., Stridbeck, P. and Liu, Y. 2014: Growth dynamics of tree-line and lake-shore Scots pine (*Pinus sylvestris* L.) in the central Scandinavian Mountains during the Medieval Climate Anomaly and the early Little Ice Age. *Frontiers in Ecology and Evolution* 2: 20. DOI: 10.3389/fevo.2014.00020.

In order to assess differences in climate signals captured by RWs in two types of Scots pine material from the central Scandinavian mountains, two datasets were collected and chronologies were developed from living trees and subfossil wood in riparian (lakeshore) mountain environments (908-2012 CE) and from samples collected from living and dead (drywood) trees around the local tree line (709-2011 CE). Both chronologies correlated well with each other, although a higher variability in the ring-width indices was found for the drywood chronology. The analysis focused on two main periods, from 950 to 1150 coinciding with the Medieval Climate Anomaly (MCA) (Lamb, 1969), where there was a good agreement between the records, and between 1300 and 1500 CE, corresponding to the early part of the Little Ice Age (LIA), when the records agree less. The LIA divergence between the records was likely caused by cold temperatures and raised lake levels (Young *et al.,* 2012; Rosqvist *et al.,* 2013).

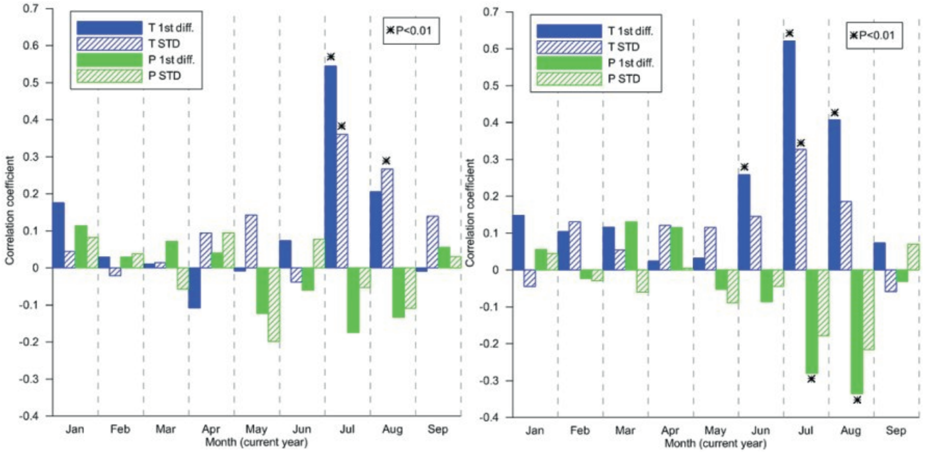

Figure 9. *Pearson correlation coefficients between 1st differenced (solid bar)/standardized (shaded bar) ring width indices from (left) tree-line living tree chronology (Håkervalen 20 trees), (right) lakeshore living tree chronology (Trolltjärnen 19 trees) and temperature (T, blue /dark) and precipitation (p, green/light) from the closest grid-point in the CRU TS 3.10 dataset (Harris et al., 2014) 1901-2008.*

The diverging signals could be interpreted as consequence of moisture changes affecting the temperature sensitivity of the riparian trees. Such a discordance in temperature signals from the two growth environments could lead to less accurate reconstructions of late Holocene temperatures provided that both sources of tree-ring data are included. The quantification of the bias between the datasets is a matter for further studies. In addition, the assumption that trees grew at higher altitudes during the MCA (Kullman and Öberg, 2009) is challenged by the results obtained in the studied area, since a similar amount of wood material was found for the study area for both MCA and LIA periods. Moreover, the current tree line has not reached MCA levels (which is ca. 140 m higher than its current position) in the study area.

4.4. Paper IV

Fuentes M., Seim. A., Aravena J.C., Linderholm H.W. Assessing the dendroclimatic potential of Magellan's beech (*Nothofagus betuloides*) in the southernmost Patagonian Archipelago. *Trees* (in review)

The aim of this study was to investigate the climatic signal in six newly developed *N. betuloides* (Coigüe de Magallanes, southern beech) RW chronologies from the southernmost forests in the world, in Patagonia. Besides the analysis of the relationships between tree-growth and local precipitation and temperature, the large-scale influences from SST, SLP, SOI and SAM were analysed, and the potential of these trees as paleoclimate indicators discussed. The network of six *N. betuloides* chronologies showed marked differences in climatic signals among the chronologies, probably due to differences in microclimate at the sites. The precipitation signal was weak at all sites, not suitable for reconstructions. The temperature signal, on the other hand, reached slightly higher correlation values, suggesting some potential of *N. betuloides* as a temperature proxy. The SAM correlated significantly ($p<0.05$) with RW chronologies at three sites. Influences on tree growth from the tropical and subtropical Pacific were demonstrated at five sites through significant ($p<0.05$) correlations with the SOI in November (which here corresponds to late spring and early summer). Moreover, an influence of the SAM was noted, where positive SAM index years were related to an intensification of the westerly wind together with a contraction southwards of the flow of the circumpolar wind causing drier conditions, and hence decreased tree-growth in southern Patagonia.

When the RW records were compared to gridded SLP data (HadSLP2r, Allan and Ansell, 2006) and SST (HadISST 1, Rainer *et al.,* 2003), it was revealed that tree growth is favoured by high pressure patterns over southern Patagonia, western Antarctica and the adjacent southern

Pacific Ocean, the Antarctic Peninsula, Weddell Sea and Drake Passage. Two chronologies were positively influenced by tropical Pacific SST, and five chronologies were positively correlated with western Southern Pacific SST. The latter suggests a mechanism of heat transport from the

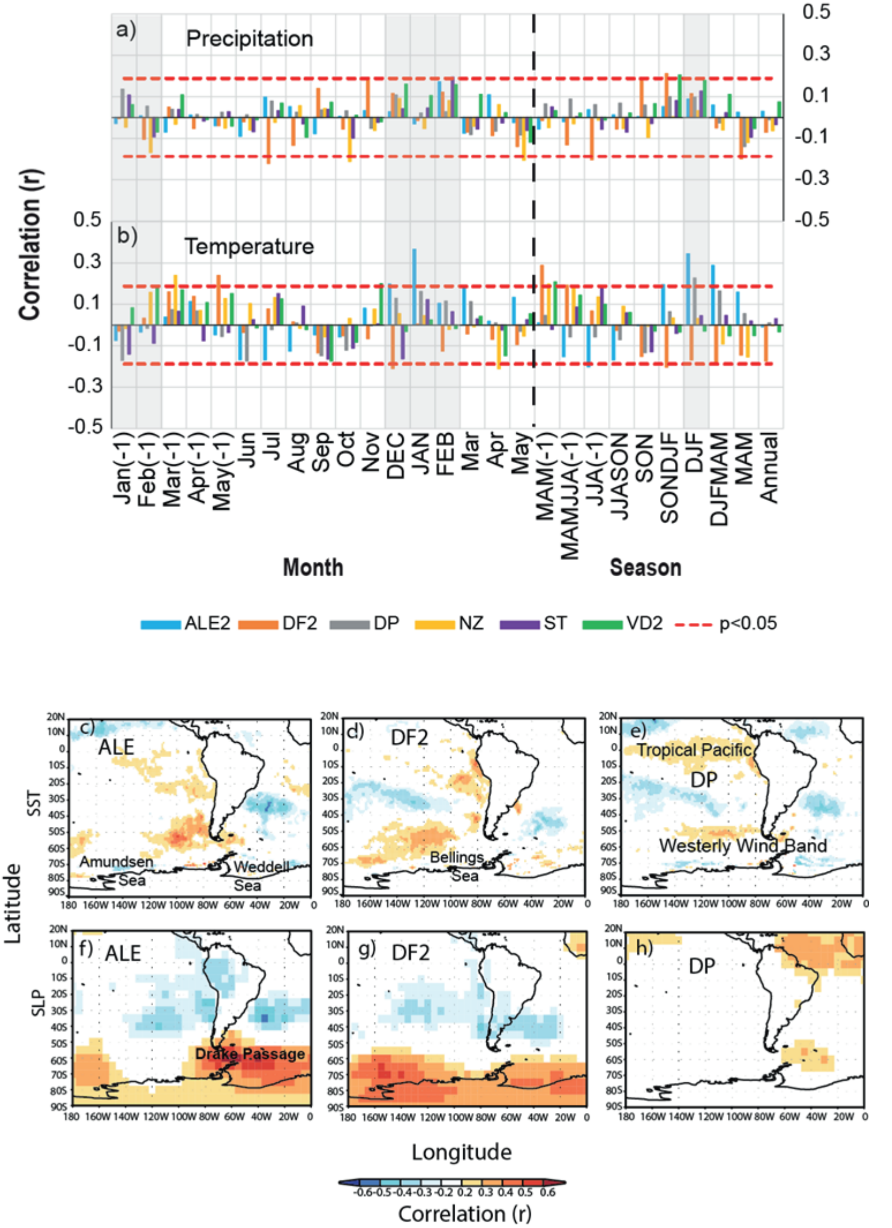

Figure 10. a) Correlations between precipitation data at Punta Arenas climate station (1900-2010) and N. betuloides tree ring chronologies. b) As in a, with temperature data. c) Point by point correlations with tree

-ring data in c, d and e, selected chronologies with HadlSST1 Sea surface temperature (Rayner et al., 2003); f, g and h with HadSLP2r Sea level pressure (Allan and Ansell, 2006).

Southern Ocean downstream into southern Patagonia by means of the westerlies. Regarding the dendroclimatological potential of *N. betuloides*, the results point to the feasibility of using data from ALE, DF2, DP and even NZ and VD2 in further climate studies, with potentials to assess past variability of variables such as temperature, SLP, and Pacific SST patterns. However, the lack of meteorological data of reasonable quality at suitable distances from the sampling sites should be stressed. Presently, reanalysis or satellite based data can be used to calibrate reconstructions, but there is no possibility to test for stationarity of the relationships unless compared with other independent reconstructions. The use of this species to paleoclimate reconstructions may be limited by site specific conditions that modulate the climate signal.

4.5. Paper V

Fuentes, M., Seim, A., Christie D., Gutierrez, A., Aravena J., Seftigen K., Björklund J., Linderholm, H.W. Climate signal of tree-rings from *Pilgerodendron. uviferum* Cupresaceae from the southernmost forest in the world (manuscript)

The aim of the study was to re-examine the dendroclimatological potential of *P. uviferum (Ciprés de las Guatecas)*, where an average was compared to precipitation and temperature data from CRUTS 3.23 (74°-68° W, 50°-56° S) (Harris *et al.,* 2015) and observations from the meteorological stations at Punta Arenas (DMC, 70°55' W, 53°9' S) and Puerto Williams. (DMC, 67°36' W, 54°55' S). The chronology was further compared to hemispheric atmospheric index SAM (Marshal, 2003) and local versions of SAM developed with NCAR/NCAP SLP data (Kalnay *et al.,* 1996) and SOI (Allan *et al.,* 1991; Können *et al.,* 1998; Ropelewski and Jones 1987) together with the Amundsen Sea Low index (Hosking *et al.,* 2013; Turner *et al.,* 2013). The relationships between *P. uviferum* and precipitation indicated an influence in summer (January), while significant negative correlations were found for temperature in the previous growing season (January and February) as well as early spring (September) of the growth year. The relationships with the atmospheric indices were to a large extent non-significant, (figure 11 a -f), indicating a limited influence of the westerly winds. It was clear that the association between SOI and tree growth changed through time (Figure 11g), and correlation with SAM became significant (negative) in January and March after 1979. The strongest correlation was found between tree growth and the ASL index in September, a relationship consistent with the negative correlation with temperature in the same month. It was suggested that *P. uviferum* has a potential as an indicator of regional temperatures. Moreover, the strong link between tree growth and the

ASL opens up possibilities for further studies of the impact of ocean and atmosphere conditions in the Amundsen and Bellingshausen Seas on Patagonian climate. Altogether, the intercorrelation between sites of *P. uviferum* can only be explained by strong climate forcing, encouraging climate studies with this species.

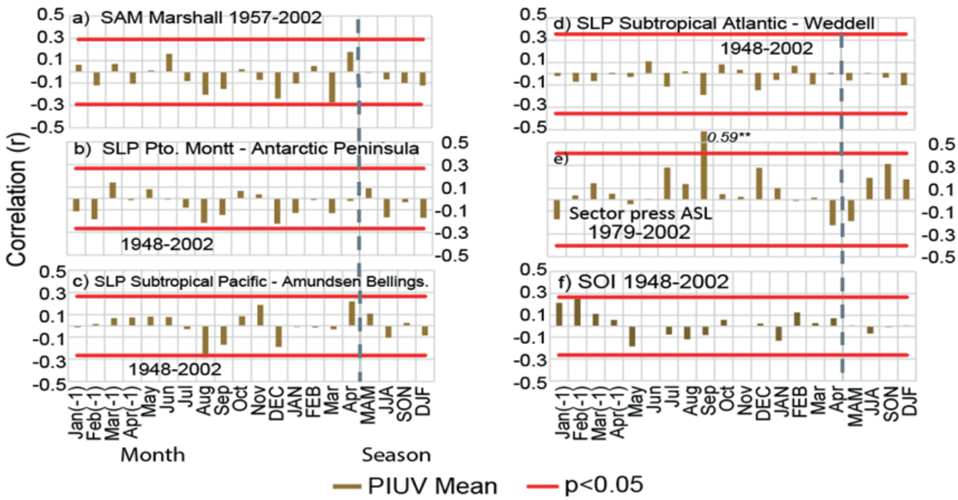

Figure 11. Correlation functions between mean chronology of P uviferum and pressure difference atmospheric indices a) SAM (Marshall, 2003), and local variants b) over the continent and Antarctic peninsula, c) pressure difference over the Pacific d) pressure difference over the Atlantic e) Sector press Amundsen Sea low index (Hosking et al., 2013) f) Southern Oscillation Index (Walker and bliss, 1932; Ropelewski and Jones, 1987).

5. Discussion

5.1. Fennoscandian temperature patterns back in time

The addition of the Rogen BI and the regional reconstruction (papers I and II) led to a better understanding of the temperature evolution in Fennoscandia by providing datasets with higher quality and skills on signal detection with a better southern representation that previous efforts. This is a positive advance considering that the climatic signal of data derived from tree-rings between Scandinavia and the Alps is mostly dominated by precipitation (Seftigen *et al*., 2015; Babst *et al*., 2013), representing a gap in the characterization of temperatures for southern Fennoscandia. Significant improvements of this work were the applications of the RCS methodology for detrending (Briffa, 1992; Melvin and Briffa, 2008), and the implementation of the delta parameters

(Björklund *et al*., 2014). These two factors contribute to an improvement in the detection of the climate signal contained in the tree-rings. Moreover, the reconstructions have improved representation of low-frequency information compared to previous works such as that by Gouirand *et al*. (2008), who applied data-adaptive curve fitting using least squares techniques leading to loss of low-frequency variability (see Cook *et al*., 1995). With the high quality and high resolution, it is possible to make comparisons between the datasets, given that they use the same methodological treatments with only slight differences. It is odd, however, to compare the Rogen reconstruction to the regional one, since that already includes a version of the former. The exercise is still relevant, given the regional features of the second. Figure 12) indicates slightly warmer conditions in Rogen than in the regional reconstruction during 1100-1150, 1360-1400 and 1435-1475 CE, and colder conditions during 1270-1300, 1650-1850 CE and from 1920 to the present. There is a possibility that the differences are locally caused by the modulation of the wind patterns, due to variations in the path and trajectory of the jet stream (Gagen *et al*., 2016) during different periods. The correlations between Rogen and the regional reconstruction with JJA mean temperatures, 850 geopotential height and SST gridded data (Figure 13) indicate the local versus regional signal strength of the reconstructions. The differences in correlations with SST of the two reconstructions suggest a slightly more pronounced influence of the ocean on regional climate, which is in agreement with the findings by Chylek *et al*., (2009).

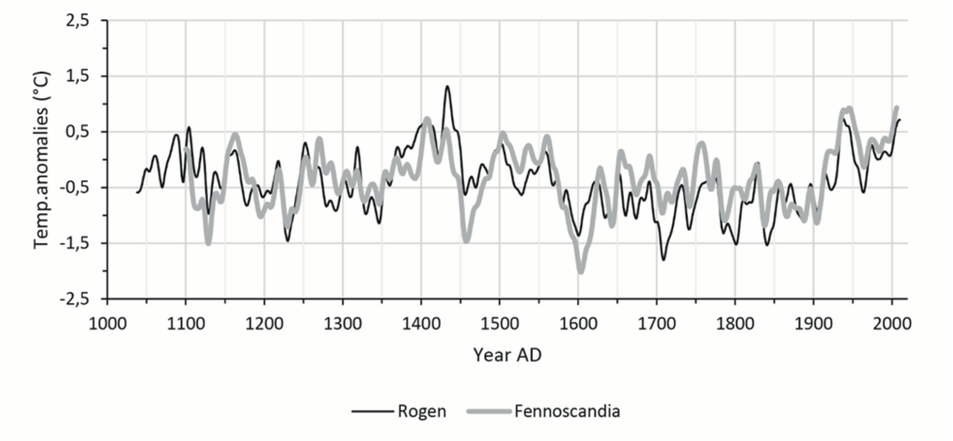

Figure 12. Comparison between local Rogen reconstruction paper I and the regional Fennoscandian reconstruction paper II) a) 20 year Gaussian filter Rogen and Fennoscandian regional reconstruction, Rogen has been scaled to the Regional reconstruction to allow comparison.

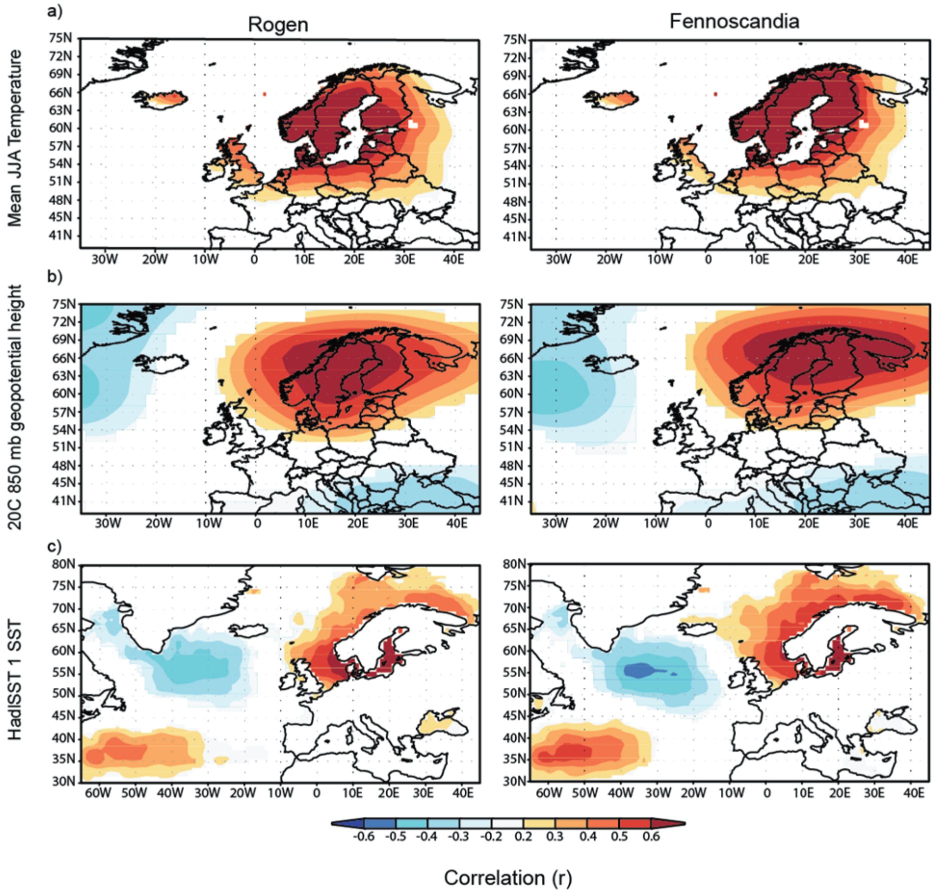

Figure 13. Spatial Correlations between Rogen (left) and Fennoscandian reconstruction (right) with a) CRU TS 3.24.01 0.5° resolution 1901-2010 and 1901-2006 resp. (Harris and Jones 2017); b) 850 geopotential height 20 Century reanalysis data 1901-2010, 1901-2006 respectively (Compo et al., 2006) and c) Sea surface temperature HadlSST1 1870-2010, 1870-2006 respectively (Rayner et al., 2003).

Compared with previous reconstructions (Figure 14), Rogen has the best agreement with C-Scan (Zhang *et al*., 2016). Despite the contrasting methodologies used in the two reconstructions, this was expected, given the good quality of both records and the short distance between them. Further, the differences between Rogen and the other reconstructions suggest dissimilar temperature evolution during the MCA and LIA in central and northern Scandinavia (see Paper I), but also with a record from central Europe (Büntgen *et al*., 2011, hereafter B11) (figure 14). For example, the chronology from southern Finland H14 (Helama *et al*., 2014) indicates warmer conditions from 1000-1100 and 1300-1400 CE and colder during the LIA. These warm periods are well documented since they coincide with the end of the MCA, and colder conditions during LIA are expected, since this chronology is located in an area affected by stronger continental influences than western Scandinavia. The northernmost reconstruction, NSCAN (Esper *et al*., 2012), also

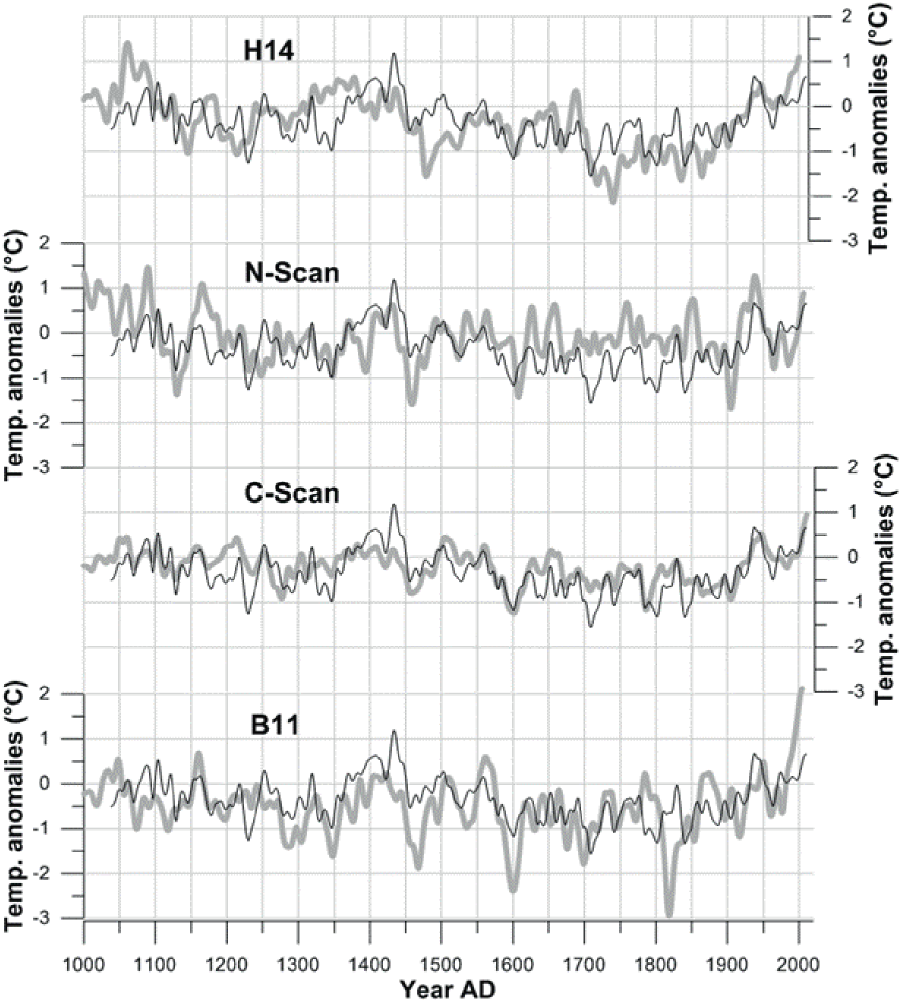

Figure 14. Comparison between the Rogen temperature reconstruction (thin black line) and other reconstructed summer/warm-season temperatures: H14, East-central Finland, May-September (Helama et al., 2014), N-Scan, Northernmost Fennoscandia, June - August (Esper et al., 2012) C-Scan, west-central Scandinavia, April - September (Zhang et al., 2016), and B11 June-August, central European Alps (Büntgen et al., 2011). Rogen was scaled to each of the datasets to allow comparison.

indicates warmer conditions before 1100 CE, and from 1250 to 1325 CE. That Rogen displays colder conditions than N-Scan and C-Scan during the LIA is puzzling, since colder temperatures might be expected at northern latitudes during that period. This is however consistent with the differences found between the regional reconstruction (Paper II) and Rogen. When comparing Rogen with B11, the records seem to be out of phase during some periods (e.g. 1620-1725; 1800 -1900), with B11 indicating colder temperatures during LIA. If the differences are assumed as a product of natural variability, the migration of the polar jet stream could explain the periodical agreements and differences (see Degirmendzic and Wibig, 2007; Hannachi *et al*., 2012; Gagen *et al*., 2016). The apparent disagreements between the northern records and B11 are evidenced by low correlations between the chronologies, indicating different climate regimes in central (southern) Europe and Scandinavia. This highlights the importance for including paleoclimate data from across Scandinavia if the whole of Europe is targeted. Still, the observed differences between the datasets might be caused by different seasonal targets (H14 is MJJA; C.SCAN is AMJJAS), in addition to differences of microclimate conditions together with methodological differences (Frank *et al*., 2007; Wilson *et al*., 2016).

5.2. The temperature evolution in southern Patagonia

Only a few temperature reconstructions exist from southernmost South America (Aravena *et al*., 2002; Villalba *et al*., 2003; Boninsegna *et al*., 2009). However, only two of the new *N. betuloides* records from this study present significant, but low, correlations with temperature, indicating difficulties to provide new information on past temperature in southern Patagonia. The relationship between *P. uviferum*-growth and temperature is more general, with periodically strong significant correlations in summers of the previous growing season, but this relationship is not stable in time, indicating non-significant values if the whole time span 1901-2002 is considered. Possibly, the quality of the station data together with the distance to the sampled sites is the cause of the decay in agreement back in time. Or, it could be a response to climate change, affecting the sensitivity of the trees, e.g. through an increase of the moisture sensitivity (see paper III). Recent studies on climate in the Southern Hemisphere have pointed to an enhanced SAM activity in the last decades, (Thompson *et al*., 2011; Villalba *et al*., 2012; Abram *et al*., 2014), which may have influenced the moisture availability in southern South America and thus having increased the drought signal in the trees.

5.3. Microsites conditions and its relationship to the climate signal

Microsite conditions affect tree-ring networks in both Sweden and southern Patagonia. The former was explicitly investigated and suggests increased precipitation, but a weakened temperature, signal in high-elevation tree growth at moist sites during periods of cooler and/or wetter conditions (Paper III). Moreover, it seems like this effect is more pronounced in RW than in density data. This is an important issue, since it may have impacts on the validities of temperature reconstructions based on both lakeshore and dry-sites tree-ring material, such as the Torneträsk reconstruction, that extends 7400 years (Grudd *et al*., 2002), or the central Scandinavian Mountain record (Gunnarson, 2008), two records which have been of importance when describing the Holocene climate evolution.

In Patagonia, microsite factors can be linked to varying geographical patterns, together with the moisture variability that is regulated by the wind regimes (Carrasco *et al*., 2002; Schneider *et al*., 2003; Garreaud *et al*., 2013), leading to higher heterogeneity in climate signals among sites (paper IV and V). Particularly the westerly winds introduce variability in the local level and homogeneity on the larger scale (Schneider *et al*., 2003; Frank, 2002; Carrasco *et al*., 2002). Moreover, the area south of 50°S is characterized by particular climatic characteristics concerning temperature (Villalba *et al*., 2003), precipitation (Aravena and Luckman, 2007) and wind (Garreaud *et al*., 2013). Whether or not the spatial variability in the climate signal in RW in southern Patagonia is caused by moisture differences alone is still unclear since the sites were far from riparian. Nevertheless, this option cannot be discarded. In previous studies, a positive relationship between the westerly wind flow and precipitation was established for climate stations (Schneider *et al*., 2003), but time-series describing local and general wind patterns do not correlate significantly with the chronologies (not shown). If the precipitation gradient was the main driver, the sites should be organized according to the spatial distribution; those closer to the ocean should display a weaker precipitation signal. But, this is not the case: for example, ALE was located in the outlet of the Magellan Strait and the signal should be influenced by oceanic conditions and characterized as a moist site, but still it displays a drought signal. Higher correlations are, nevertheless, found among the eastern chronologies, both in the vicinity of Lake Fagnano and south of the Perry fjord. There are still clear evidence linking the climate signal in the southern tree-ring network to large-scale patterns of the southern hemisphere.

5.4. Large scale atmospheric patterns and high-latitude tree growth

The large-scale influences on tree growth/climate were assessed in papers I, II, IV and V. Knowing that both study areas are situated close to the ocean, it was expected that SLP and SST information should be contained in tree rings. SLP was assessed in papers I, IV and V. Thus, in paper I, the spatial structure of the correlation functions between ΔBI_{adj} indices and atmospheric pressure patterns indicates a distinct Scandinavian/SNAO pattern. These findings are in line with the findings by Linderholm *et al*. (2009) and Trouet *et al*. (2009), and demonstrates a link between tree-ring data in the area and the large-scale circulation. The Scandinavian Pattern represents blocking situations that can last for weeks. In summer, it is related to warm and dry weather in Scandinavia, and therefore enhanced tree growth in the study area. It was demonstrated to be a stable mechanism at least back to 1659. It has been argued that the Scandinavian blocking operated as far back in time as the Holocene climate optimum at ca. 7000-5000 calendar years BP (Antonsson *et al*., 2008).

SLP was found to be linked to tree growth in southern Patagonia. Previous studies have indicated the influence of SLP on tree growth through large-scale indices such as the SAM and the Transpolar Index (Villalba *et al*., 1997; 2012; Abram *et al*., 2014). But no studies have examined the influence on tree growth of the atmospheric circulation on smaller scales over the Southern Ocean. Such relationships have, however, been identified for tree-ring reconstructions farther north (north of the 40°S) in relationship to moisture variability (Christie *et al*., 2009; Mundo *et al*., 2012) and to precipitation regimes (Aravena and Luckman, 2002; Schneider and Gies, 2004; Quintana and Aceituno, 2012). The relationship between SLP in the southern Ocean and tree-ring data at the study sites is likely related to the westerly wind flow and the positioning of the subpolar jet (Garreaud *et al*., 2009; 2013) modulating advection from the ocean. But these relationships do not seem to be straight forward to interpret: patterns consisting on latitudinal pressure differences may have opposite effects on tree growth according to the intensity of the pressure difference (Paper IV and V).

The SOI signal was assessed in papers IV and V, indicating some association, mainly negative, with tree growth during the warm season for *N. betuloides*. The *P. uviferum* chronologies correlate positively with SOI (lagged one year) being stronger during summer. The findings contrast with previous studies (Garreaud *et al*., 2009; Villalba *et al*., 2007), who argued for limited effects of SOI on southern Patagonian climate. Nevertheless, relationships between SOI and the Southern Ocean, and continental precipitation have been presented before (e.g. Renwick, 1998; Schneider and Gies, 2004; Turner et al., 2013). The SOI signal found in *P. uviferum* was not stationary, and it declines after the 1970s (Paper V), coinciding with increasing significance in the correlations with SAM. This variation in the signal is difficult to explain, but it can be related to the regime change in the Pacific Basin (Hare and Mantua, 2000).

Just like the NAO, the SAM influences various ecosystems and tree growth in the southern hemisphere (Villalba *et al*., 2012; Moreno *et al*., 2014). The *N. betuloides* chronologies correlated weakly, but consistently, with the SAM index (paper IV) while *P. uviferum* showed no clear association with SAM or the regional variants (Paper V). As SAM is characterized by pressure anomalies of different signs organized in latitudinal bands, the pattern is consistent with spatial correlations and the composite maps (papers IV and V). Low correlations between the chronologies and SAM can be explained by the geographical location of the study area. Reconstructions of SAM index with tree rings (Mundo *et al*., 2012; Villalba *et al*., 2012; Abram *et al*., 2014) have been based on sites north from 40°S that experience Mediterranean climate conditions. At these latitudes, the southwards contraction of the westerly wind belt (+SAM) induces draught, contrasting to western sites at higher latitudes where the effects are not clear. Moreover, the SAM mechanism can be understood as the southwards contraction and intensification of the westerly wind-belt at the southern end of the continent, but perhaps may not provoke such dramatic changes of moisture availability at high latitudes as it does north of 40°S. This may be explained by the strength of the westerly and reduced amplitude of the year cycle. Another effect decreasing the detection can be the positive relationship between wind and precipitation (Schneider *et al*., 2003; Carrasco *et al*., 2002; Garreaud *et al*., 2013). In such a scenario, only drier areas such as the Patagonian planes may have consistent SAM signals (see Aravena and Lukman, 2009). Concerning the influence of the SAM on observations at Punta Arenas station, diverging results have been presented; no significant association with precipitation at interannual timescales has been found (Aravena and Lukman, 2009), but the SAM seems to be related to drought frequencies in the area (González-Reyes *et al*., 2017). The spatial patterns observed in the composite maps from extreme tree growth years indicated indeed a SAM structure at 850 geopotential height level.

In Paper V, the influence of the ASL was tested on *P. uviferum*. This index provides information on the longitudinal variations of the lowest atmospheric pressure point in the area of the Southern Ocean from the Ross Sea to the Antarctic Peninsula. This highlights the meridional influence of the hemispheric pattern in the west Antarctica, e.g. the inflow of meridional winds into the Antarctic continent, which contributes to increasing temperatures in the area (Hosking *et al*., 2016, Turner *et al*., 2013). This index has the highest correlation with *P. uviferum* tree-growth in September, consistent with the correlations between *P. uviferum* and temperature (negative). The nature of this relationship is difficult to interpret, since the trees are supposed to be in dormancy at that time of the year. But, it might be connected to pre-setting conditions for the growing season ahead, such as evaporation of the stored water in the mire-like environments where *P. uviferum* grows. This probably provokes an early growth start at the beginning of the growing season (Menzel and Fabian, 1999). All in all, this relationship represents an interesting feature connecting the atmosphere dynamics of the Southern Ocean with tree growth patterns of *P. uviferum* implying a potential use of the species as proxy.

5.5. Volcanic signals

The influence of volcanic eruptions was assessed for both the Rogen and the regional reconstructions (paper I and II), indicating significant impacts of this forcing on temperatures during the last millennium. The response of the temperature anomalies caused by large volcanic eruptions is varied, depending strongly on the forcing data (Paper I, Wilson et al., 2016). However, the response of Blue Intensity data is significant between the year of occurrence to two years after the eruptions. This is in large agreement with the results in paper II, where the response varied from the year after the event to five years later. Similar results have been published elsewhere (Stoffel *et al*., 2015; Wilson *et al*., 2016). The impact on volcanic forcings was tested also on the Patagonian chronologies, but the results were unclear (not shown); for example the response of *P. uviferum* lagged about 10 years (significant at 0.05 level), while no significant response in *N. betuloides* was found. These assessments need to be tested again with datasets that are suitable for the Southern Hemisphere. The general lack of studies assessing the volcanic forcing on tree-ring data in the Southern Hemisphere suggests difficulties to achieve coherent results.

5.6. The influence of sea-surface temperatures

SST was found to be strongly related to tree-ring data in both study areas (Papers II, IV and V). SST influences on interannual to multidecadal scales: North Atlantic climate have been linked to the Atlantic Multidecadal Oscillation (Knight *et al.,* 2005; Sutton and Hodson, 2005) and the SST variations in the Atlantic has been linked to European climate (Frankignoul *et al*., 2003, Rodwell and Folland, 2003; McCarrol *et al*., 2013). This link is shown in paper II, and confirms the potential for using tree-ring records to assess SST back in time. Previous attempts have been made including northern Scandinavian tree-ring records (i.e. Gray *et al*., 2004; Rinne *et al*., 2014). For the purpose of comparison, correlations between SST and the two reconstructions in this work are shown in Figure 13, indicating stronger correlations for the regional reconstruction which encompasses the more northerly datasets. This may indicate a larger oceanic influence on northern latitudes in Fennoscandia, as suggested by Chylek *et al*. (2009).

In Papers IV and V the relationships between tree-ring data and SST were assessed for the Patagonian data, indicating an influence of Southern Pacific Ocean SST on tree growth. This relationship has not previously been explored in tree-rings south of 50°S in the Patagonian archipelago. The spatial correlation patterns between SST and the *N. betuloides* chronologies from DP and NZ indicate a typical ENSO structure, where the El Niño 3-4 and 4 zones are positively correlated with the tree-ring indices. The meridional ENSO SST structure is also partially evident in the spatial correlations for ALE, DF2, ST, VD2, and DP. It was suggested that heat from the Southern Pacific Ocean (the southerly component of the SST ENSO structure) is transported via the westerlies into the study area. This mechanism has previously been proposed relating SST in south Pacific to continental temperature and precipitation regimes for reanalysis data (Garreaud *et al*., 2013). These patterns are not unique to the six new chronologies presented in this work, since they are also found when comparing previously reported chronologies of this species from Villalba *et al*, (2012) south of 50°S (Figure 15).

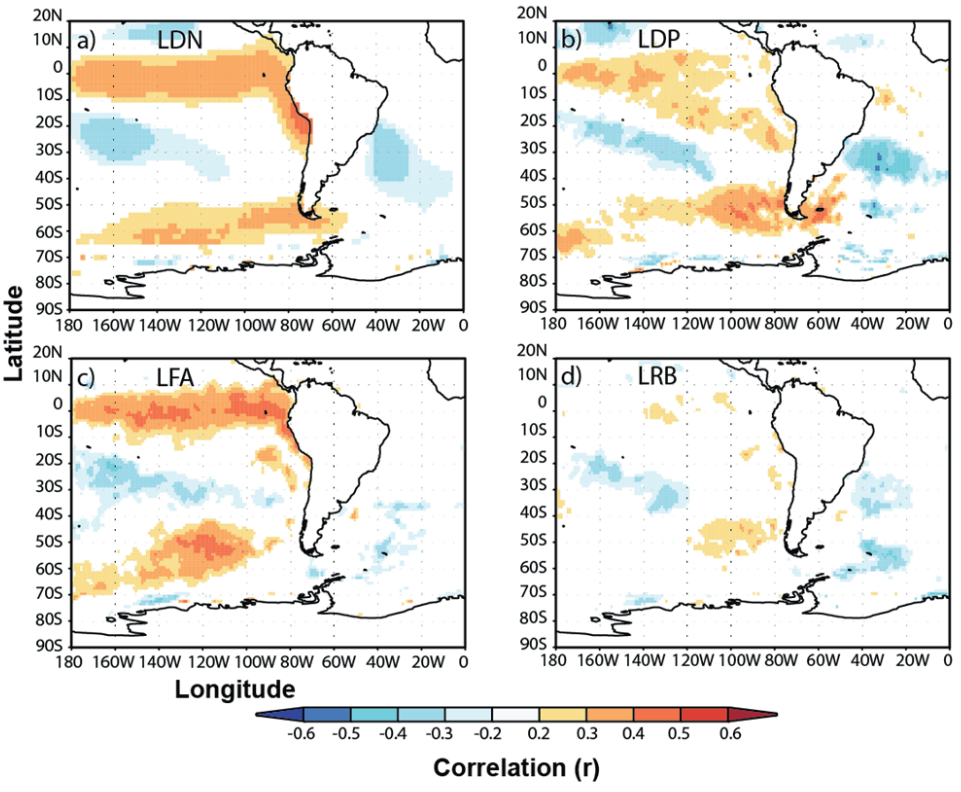

Figure 15. Spatial correlation of N. betuloides chronologies south of 50°S previously reported in Villalba et al., 2012) and SST (HadlSSTL1, Rayner et al., 2003): a) LDN (54°22'S, 68°46'W), b) LDP (54°20'S, 68° 49'W) c) LFA (54°28'S, 68°41'W) and d) LRB. a-c located in the island of Tierra del Fuego, while d is located in Navarino island (54°58'S, 67°41'W).

6. Conclusions

This section summarises the main outcomes of the thesis work in relation to the objectives (section 2)

Objective i) Extension and improvements of chronology networks and proxy development

In Fennoscandia important advances were made by extending the network temperature sensitive tree-ring data to the south. Moreover, using the new Δdensity/BI proxies an improved reconstruction of Fennoscandian summer temperatures was achieved.

In Patagonia, the tree-ring network was extended into the southernmost parts of the region.

Objective ii) Improvement of the knowledge of the temperature evolution in Scandinavia and Patagonia

Using the BI proxy from Rogen, the southernmost high-quality reconstruction of local temperatures was made. This was an important step forward since it facilitates increased understanding from a region from where high-resolution temperature proxies have been lacking. Utilising tree-ring data with larger geographical distribution, it was possible to create a skilful spatial reconstruction of past summer temperatures truly representing most of Fennoscandia.

It was evident that reconstructions of past temperature (or precipitation) based on tree-rings from *P. uviferum* and *N. betuloides* are challenging due to the weak climate signal in the tree-ring data. Further investigations need to be made before reaching this objective.

Objective iii) To provide methodological guidelines to improve the climate signal of the developed chronologies

The new ΔBI_{adj} proxy has the potential to provide robust high-quality temperature information from Northern Hemisphere high-latitude trees, similar to that obtained from the more exclusive densitometric measurements.

The importance of local conditions when assessing the climate signals from the tree-rings was also shown. In the Scandinavian Mountains, it was shown that mixing data from dry and moist sites can have an effect on reconstructed temperatures. In southern Patagonia, the heterogeneity of the landscape implies a local modulation of the climate signal contained in *N. betuloides* RW data. Thus, homogeneous site selection should be applied when collecting material for dendroclimatological analysis of this species.

Objective iv) To assess the link between the new chronologies and large-scale patterns that affect high latitude environments

In Fennoscandia, close, and temporally stable, links between summer atmospheric circulation patterns similar to the Scandinavian pattern and the summer North Atlantic Oscillation (SNAO) and summer temperatures were found. Moreover, significant positive associations between summer temperatures and SST from the Barents and Norwegian Seas, and positive (negative) correlations with the subtropical (subpolar) gyres were found, suggesting a possible link between the thermohaline circulation and summer temperatures in Fennoscandia.

The tree growth of both *N. betuloides* and *P uviferum* was shown to be affected by the SAM, the dominant pattern of extratropical atmospheric circulation in the Southern Hemisphere. In addition, SST variations in parts of the Southern Ocean and the tropical and subtropical Pacific were also found to affect tree growth in the southern archipelago.

7. Future Potentials

The work of the dendrochronology networks in Sweden and South America is far from finished. The Swedish network can benefit from development of blue intensity chronologies for all sites already collected, and with additions of material from southern Norway. Proxy developments must be undertaken for Patagonian material.

In addition, much is to be said on the relationship of RW across Scandinavia, since the signal is extremely coherent, suggesting a common mechanism affecting tree growth in the area. Moreover, through the analysis of the Patagonian material in papers IV and V, a series of mechanisms were found where the area of the Amundsen to Weddell Seas seems to be an important regulator of climate in Patagonia, probably through the modulation of the wind patterns. This area is also related to sea ice, implying a link between tree growth and Antarctic sea ice. These relationships need to be further investigated. Another factor much underrepresented in southern South American research is the influence of volcanic eruptions, and its effects from local to hemispheric scales.

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