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Tree Rings in Archaeology, Climatology and Ecology

Volume 13

Proceedings of the
DENDROSYMPOSIUM 2014
May 6th – 10th, 2014 in
Aviemore, Scotland, UK

Edited by:
Rob Wilson, Gerhard Helle
and Holger Gärtner

Scientific Technical Report STR15/06

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Preface

This publication is a result of the 13th TRACE conference (Tree Rings in Archaeology, Climatology and Ecology) organized by the Department of Department of Earth and Environmental Sciences at the University of St Andrews on May 6th – 10th, 2014 in Aviemore, Scotland, UK.

TRACE is an initiative of the ‘Association of Tree-Ring Research’ (ATR) and seeks to strengthen the network and scientific exchange of scientists and students involved in the study of tree rings. The annual conference provides a scientific platform for young scientists at the cutting edge of tree-ring science.

Around 110 scientists working on tree-ring related topics participated in the conference coming from Belgium, Canada, Czech Republic, France, Germany, India, Netherlands Poland, Slovenia, Spain, Sweden, Switzerland, Taiwan, United Kingdom and the United States. The participants enjoyed about 100 presentations, divided almost equally between talks and posters, organized into six thematic sessions: “Climate”, “Ecology”, “Historical”, “Wood Anatomy”, “Isotopes” and “Tree-Response”.

After review, 18 short papers are published in this volume, giving an overview of the wide spectrum of different fields covered at TRACE. We would like to thank the authors for contributing to this TRACE volume, and the reviewers for their valuable comments on the manuscripts. The organizers of the conference also wish to acknowledge financial support from the sponsors of TRACE 2014:
Beta Analytic Ltd. (United Kingdom), EU COST action STReESS, Forestry Commission Scotland, Regent Instruments Inc. (Canada), Rinntech (Germany) and the Highland Council.

We would finally like to thank all participants of TRACE 2014 and hope the Scottish flavor of the conference will provide good lasting memories.

Rob Wilson
Gerhard Helle
Holger Gärtner

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SECTION 1

ARCHAEOLOGY

The Impact of Dendrochronological Dating on the Interpretation of Vernacular Architecture in Wales

M.C. Bridge

Oxford Dendrochronology Laboratory, Mill Farm, Mapledurham, Oxfordshire RG4 7TX, U.K.
and Institute of Archaeology, UCL, 31-34 Gordon Square, London WC1H 0PY, U.K.
E-mail: martin.bridge@ucl.ac.uk

Background

Whilst dendrochronological dating has been used extensively in England for many decades, much less has been carried out in Wales until relatively recently. Although individual important buildings had been dated from at least the 1990s, the first major organised study was of houses in Radnorshire (reported in Suggett 2005), followed by a project in the small community around Beddgelert in the Snowdonia region. The success of this latter project enabled funding to be raised to look at further buildings, especially at first in north-west Wales, although the geographical coverage is expanding rapidly. The current body commissioning most of the dendrochronological and building survey work is known as ‘Dating Old Welsh Houses’ and a major collaborator in this project, and indeed in commissioning similar dating work throughout Wales, is the Royal Commission on the Ancient and Historic Monuments in Wales (RCAHMW). The current situation is that some 220+ phases of building have been dated, mostly in the north of the country (Fig. 1). All the dated material is of oak (*Quercus* spp.) although elm (*Ulmus* spp.) is sometimes found in buildings and cannot routinely be dated.

Accumulated data

The 220+ phases that have been dated up to now show a superficially similar distribution pattern to the 2500+ building phases that have been dated in England, with most examples falling into the period from the early 15th century until the start of the 17th century. Later buildings rarely get dated as they are generally better known and often have documentary evidence supporting their history, whilst earlier buildings tend to be less common. The buildings investigated are specifically chosen and do not therefore represent a random cross-section of the building stock. Most of the Welsh dendrochronologically dated buildings have been chosen either because they are thought to represent early examples of particular building styles, or because they are thought to represent typical buildings of this style, or because there is an important cultural link either with the building itself, or an important inhabitant, e.g. the house belonging to the first person to translate the Bible in Welsh. Bearing in mind this sampling bias, there are nevertheless some interesting observations that can be derived from this relatively small data set. There are no domestic buildings that have been dated from before 1350, whereas many have been found in England. The only dated buildings in Wales from before this date are two churches, a cathedral and a castle. Another finding is that the styles of carpentry and joinery used appear ‘old-fashioned’ to someone used to having worked in England, as shown by one example, Hafod Isbyty below.

As in other regions, there do seem to be ‘pockets’ where the material seems to be less suitable for dating. In the north of Wales, two areas have been recognised as yielding fewer datable timbers than others. The first is the Llyn peninsula (Fig. 1) and, to a lesser extent, the Isle of Anglesey – where some timbers may even be of Irish origin.

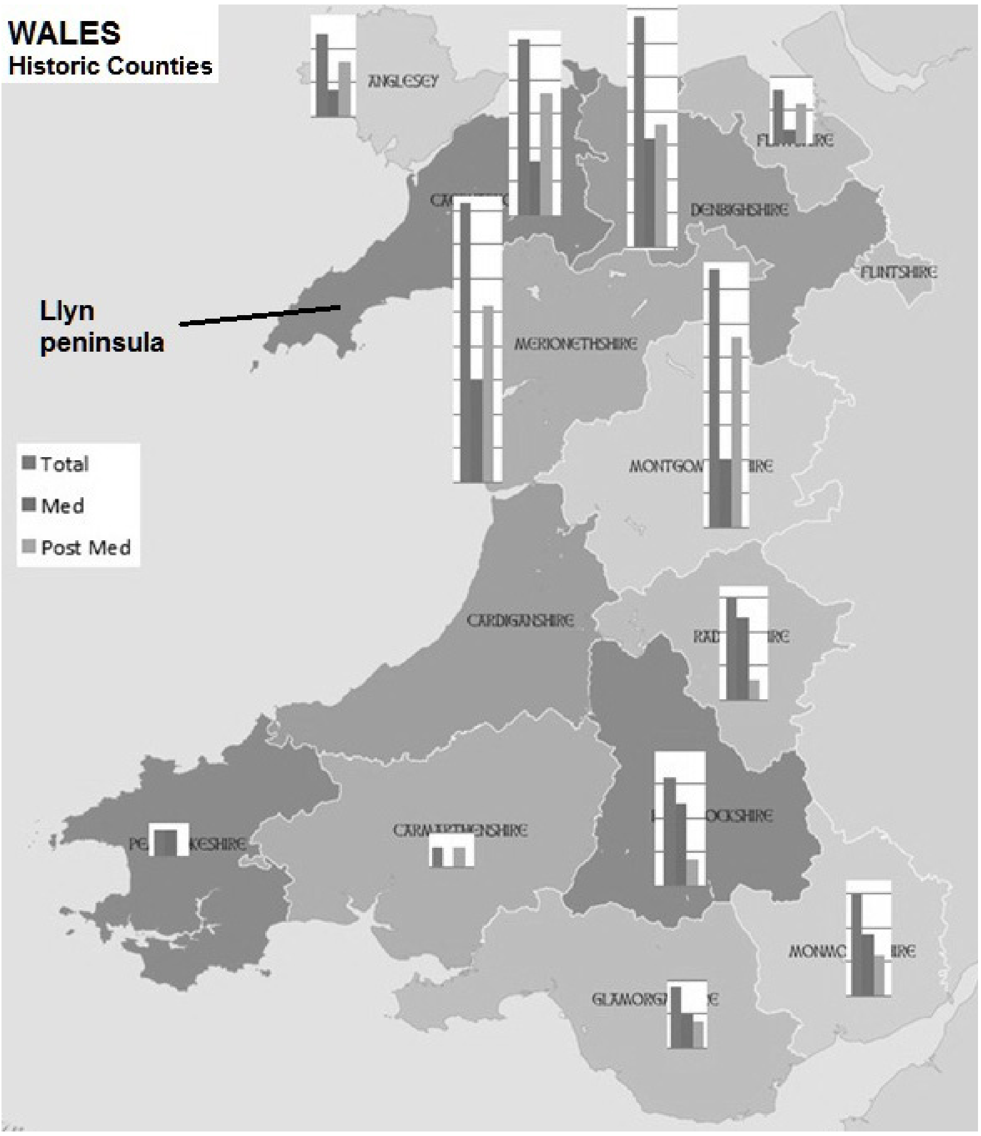

Figure 1: The historical counties of Wales, showing the relative numbers of building phases dated in each of the counties.

Examples of Dated Sites

Four examples are given of sites that have yielded dating results of interest:

Hafod Isbyty

This long low building is typical of a group of upland hall-houses in north-west Wales that had domestic quarters at one end, with animal sheltering at the other. It is a three-unit hall-house of 'gentry' type with a two-bay hall with central, open truss with cusped apex and double-pegged archbrace. The two-door dais-end partition survives. Although it does not look particularly interesting from the outside, inside there is some fine decorated carpentry with cusping to the braces, indicating that this was a quite high status building when built. This cusping and heavy arch-bracing (Fig. 2) appears 15th-century to English eyes, but the timberwork was dated to the period 1509–33 and shows that this decoration carried on into the 16th century here.

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Figure 2: Cusped bracing and fine carpentry at Hafod Ysbyty.

Cae Canol Mawr

This fine ‘Snowdonian’ style house (Fig. 3) is thought to be an early example of the type, as suggested by its downslope siting on a relatively elevated position (*c*330m amsl) and its hall remaining open to the roof. Like Hafod Isbyty, the use of cusping is here found on the windbraces. The dating of 1532 is therefore useful in setting a period for the early use of this style.

Figure 3: Cae Canol Mawr, an early ‘Snowdonian’-style house on an elevated site, dated 1532. The building to the right is a later addition.

Bryn Rodyn

In contrast to the last site, this is considered to be a typical fully-developed ‘Snowdonian’-style house (Fig 4). It is floored through, and has a post-and–panel cross-passage, with the stair going around beside the fireplace. An extension to the rear was thought to be much later in date, but was of unknown age. The dendrochronological dating produced three felling dates covering the seasons from winter 1555/56 to summer 1557, showing that this fully-developed house was built only a generation after the early example of Cae Canol Mawr. The extension to the rear contained several timbers of similar date plus timbers felled in 1640.

Figure 4: Bryn Rodyn, a fully-developed ‘Snowdonian’-style house dated to 1557.

Ffinnant

This is from a more lowland site than the previous examples, situated closer to the border with England. This site consists of a large farmhouse (Fig. 5) which has several phases, an original cruck-framed house, with a box-framed enlargement and heightening of the roofline. On the same site is a long barn, consisting of a cruck-framed unit which has evidence of having been built as a dwelling, and a box-framed extension (Fig. 6). The dendrochronological dating gives a fascinating insight into the development of this site. The original cruck dwelling (now part of the barn) was built in 1550, but the cruck part of the current farmhouse was built only a couple of years later from trees felled in the winter of 1552/53. The extension to the current house was built from trees felled winter 1583/84, whilst the box-framed extension to the barn was made from trees felled in winter 1609/10.

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Figure 5: Ffinnant farmhouse, showing the cruck-framed unit on the left with a later heightened roofline, and the later box-framed extension to the right.

Figure 6: The barn at Ffinnant, with the cruck-framed unit, originally a dwelling, in the foreground, and the later box-framed extension behind.

Conclusions

While the number of dates for building phases obtained in Wales is less than a tenth of the number so far obtained in England, the results are showing some interesting differences, e.g. the lack of early domestic buildings, and they are having a profound effect on the understanding of the vernacular architecture of the country. A much better understanding of the rate of development of styles of building has been reached, and an invaluable set of dated reference sites have led to a much better application of stylisitic dating where dendrochronology cannot be carried out, or is yet to be undertaken. Important differences can be noted between the date ranges for stylistic elements in Wales and in neighbouring England. The interpretation of multi-phase sites has also been radically improved by the ability to attribute dates to particular phases.

Acknowledgements.

I would like to thank my colleague Dan Miles for sharing his extensive work in the region from the time before I joined with him on the Welsh material, Margaret Dunn of 'Dating Old Welsh Houses' and its predecessor groups who arranged and funded many of the studies, and Richard Suggett of RCAMHW who has been intimately involved with much of the work.

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A millennium of change: Dendrochronology in Scotland's built heritage and cultural landscapes

C.M. Mills

Department of Earth & Environmental Sciences, University of St Andrews, Scotland
E-mail: cm212@st-andrews.ac.uk

This presentation reviewed the dendrochronological evidence from Scottish historic buildings, archaeological sites and cultural landscapes, using tree-ring data which cover a 1000 year period developed by several analysts over the last 40 years or so (e.g. Baillie 1977; Pilcher & Baillie 1980; Mills & Crone 2012; Crone & Mills 2013; Wilson et al 2012). This evidence records a millennium of enormous change in the timber supply and the woodland resource in Scotland (Fig. 1).

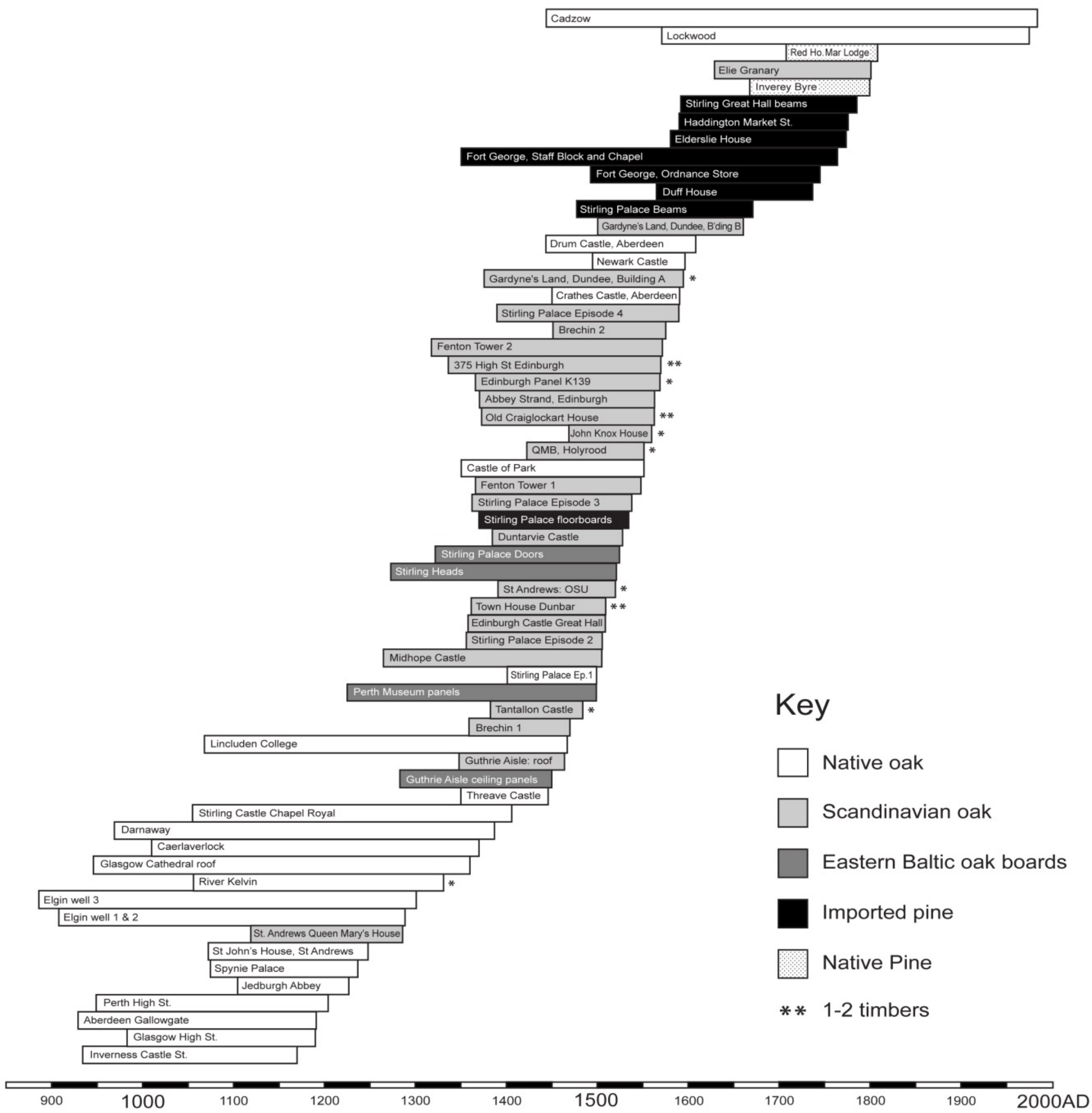

Figure 1: Summary bar diagram of all dated tree-ring chronologies from Scottish buildings and archaeological sites in 2010, for the last millennium. Some key living tree native oak chronologies are also included (modified after Fig 2, Crone & Mills 2013).

Prior to about AD 1450, native oak timber dominates the record, much of it slow-grown long-lived material, as shown in Fig 1. The predominance of long-lived oak in the medieval record is not necessarily a good sign; it suggests that much timber is being taken from old growth sources and not from woodland being managed for timber production, where a younger age profile would be expected. The reasons for the late-medieval demise of native Scottish oak timber supplies are complex but may be postulated to include inadequacies in resource management in the face of a worsening climate, the onset of the Little Ice Age perhaps undermining the various attempts through Acts of Parliament to redress the situation (Smout et al. 2007, Mills & Crone 2012).

From the mid 15th century, there is an enormous shift in much of the country to imported oak timber, which persists until the 17th century. At this time, Norway, one of the key exporters to Scotland, cuts off its oak supplies and imported pine becomes predominant thereafter in Scottish buildings, although its provenance shifts through time, with Scandinavian pine initially and then a switch to eastern Baltic sources in the mid-18th century (Crone & Mills 2013). The tree-ring evidence for the changes in the timber supply in Scotland over the last millennium are more fully related in Mills & Crone 2012.

However, the picture so far revealed is admittedly incomplete: Scotland has had relatively few sites analysed dendrochronologically compared to many other European countries and the sites studied are skewed towards certain species, regions and periods. Recent work indicates a probable under-recognition of native timber in post-medieval Scottish buildings, which is being tackled by the development of more regional chronologies for oak, pine and other native species used in construction.

Figure 2: Jedburgh townhouse, native oak felled AD 1667/8

Figure 3: Dalkeith old oaks, deadwood sampling

As an example of recent developments, a townhouse in Jedburgh, in the eastern Scottish Borders, was found to have been built with young native oak felled in AD 1667/8, thereby becoming the most recent example of a historic building with Scottish oak timber (Macfadyen et al. 2014). The roof of Drum Castle mansion house, in north east Scotland, was previously the latest known example (Fig. 1), built with local oak felled in the very early 17th century. Dating and provenancing the Jedburgh oaks was difficult due to the limited reference data available for Scottish oak in south east Scotland and for the post-medieval period. Dating relied on matches with the old oaks at Cadzow (Baillie 1977, Pilcher & Baillie 1980), which have a more westerly, wetter situation, and with a range of northern English building chronologies. Work is now underway on developing a reference chronology from the ancient oak wood at Dalkeith near Edinburgh, which in turn should help to identify and date other native oak buildings in south east Scotland. The tree ring evidence will also contribute to a wider understanding of the history of this remarkable old woodland, a rare relict of a wooded medieval park.

This is just one of a number of inter-disciplinary studies of wooded cultural landscapes in Scotland which have been undertaken in recent years to extend our understanding of woodland history as well as providing new tree-ring reference data for species used in construction. For example, old coppices and wood pastures in the Trossachs have been sampled and analysed, work which discovered some very old ash trees of pollard form, the oldest originating in the late 17th century and associated with the remains of pre-improvement farming (Mills et al. 2009). Ash was regarded as a very useful species historically and ash crucks were used in some vernacular buildings in the southern Highlands. With a little more replicated ash data, it should become possible to date such buildings. It is becoming increasingly apparent that local native timber was widely used for construction in many rural inland parts of Scotland in the post-medieval period, with oak, pine, ash and elm amongst the species used (Crone & Mills 2011), while imported oak and pine timber is more prevalent in coastal, urban and high-status settings (Mills & Crone 2012, Crone & Mills 2013).

In Scotland there is a particularly good reason to develop the dendrochronology of Scots pine because the Caledonian pinewoods of the Scottish Highlands are viewed as the descendents of extensive natural post-glacial pine forests and have a long history of exploitation for timber. The need to develop native pine dendrochronology was recognised around the turn of the millennium (Crone & Mills 2002) and work on Scottish pine buildings was then started under NOAP (the Native Oak And Pine project) with Anne Crone (Crone & Mills 2011, Mills & Crone 2012, Crone & Mills 2013) which focussed on north east Scotland specifically. Historic pine buildings across the country are now being investigated further under the Scottish Pine Project, at the University of St Andrews, which has both climate reconstruction and cultural heritage objectives (Mills et al. 2014 infra). The NOAP project began to develop the network of native living pine reference chronologies, using some long-lived Caledonian pine woods like Ballochbuie, Glen Derry and Glen Loyne (Mills 2008). Since then, the Scottish Pine Project has added many more native pine sites to the network, using a combination of living, historical and sub-fossil material, and as more fully explained in our poster (Mills at al. 2014 infra), it has become possible through this expanding network to provide the first dendro-dates for native pine structures in Scotland and indeed in Britain. Dating can be challenging given the network of native pine chronologies is still being built, and because relatively young timbers were used in many of the surviving Highland pine buildings, but the prospects for dating are improving all the time as more reference chronologies and new techniques are developed (Wilson et al. 2012, Mills et al. 2014 infra).

In conclusion, tree-rings have revealed a complex and changing story of timber supply and woodland resources in Scotland over the last 1000 years, and going forward there are great opportunities for new work to expand Scottish tree-ring coverage geographically, chronologically and for other useful native species, so that we can date and provenance more historic timbers, and contribute to the wider understanding of Scottish woodland history. Given documentary evidence that Scottish pine was also exported historically, these developments may also contribute to dendrochronology elsewhere.

Acknowledgements

The review related the work of a number of dendrochronologists on Scottish material over the last few decades, especially Mike Baillie and Anne Crone, as mentioned in the references, but also including the chair of the TRACE archaeology session, David Brown of Queen's University, Belfast. Many other dendro colleagues across Britain, Scandinavia and continental Europe have assisted the development of Scottish dendrochronology, especially with regard to identifying imported material. Numerous funding bodies and supporters have been involved along the way, but Historic Scotland has funded much of it. The emerging bigger picture has only been possible because of the many individual owners and managers who have generously granted permission to sample.

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Historic timber: Augmenting Scotland's native pine chronologies

C.M. Mills, M. Rydval, C. Wood, S. Averill & R. Wilson

Department of Earth & Environmental Sciences, University of St Andrews, Scotland
E-mail: cm212@st-andrews.ac.uk

Introduction to SCOT2K

The SCOT2K Project* aims to establish a continuous native Scottish pine tree-ring record for the last 2000 years, for climate reconstruction and cultural heritage objectives, and is part of the wider Scottish Pine Project (Wilson et al. 2011). Historic timber has an important role in augmenting the records in the periods where greatest woodland exploitation occurred, sub-fossil replication is poor and where the common growth signal has been affected by exploitation disturbance. Native pine was used extensively in the past, especially in buildings near the Caledonian pinewoods. These Highland areas relied less on imported timber which supplied many other parts of Scotland from the mid-15th century onwards. SCOT2K builds on previous work by Anne Crone and Coralie Mills (Mills 2008; Mills & Crone 2012; Crone & Mills 2013) during the Native Oak and Pine Project (NOAP, funded by Historic Scotland).

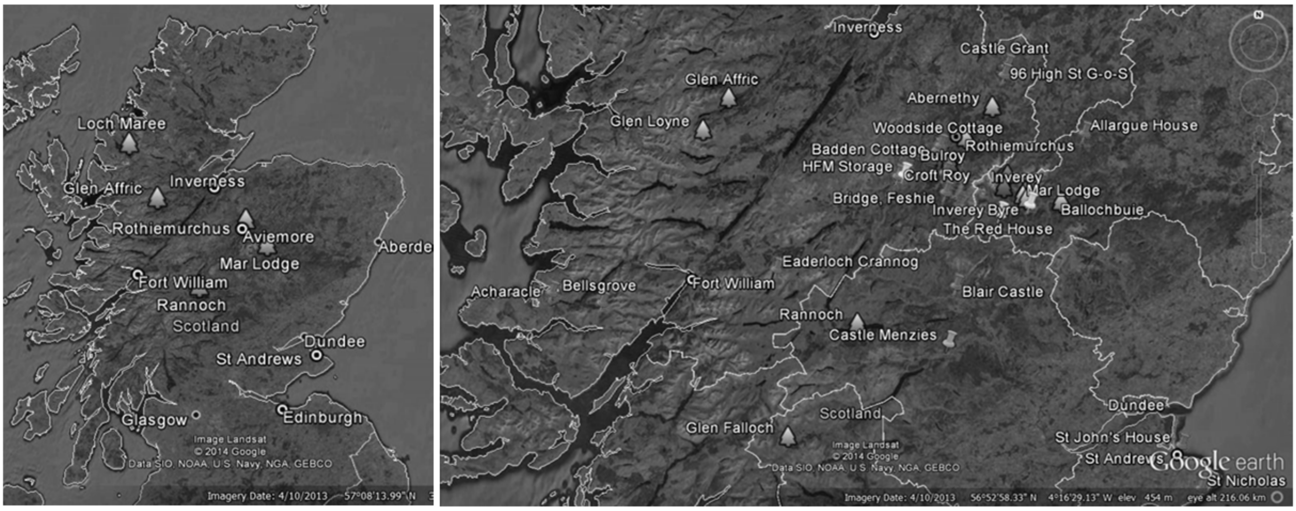

Figure 1: Maps (L) Scotland overview (R) Scottish pine selected sample sites: Pin symbols - buildings; Tree symbols – selected living pine chronologies.

The priority for SCOT2K is to analyse historic timbers from structures in areas where natural pine records are being developed from living trees and sub-fossil material extracted from lakes (Fig. 1). The focus in Year 1 has been the Cairngorms: sampled structures range from cruck-frame cottages to castles (Fig. 1). Reasonable numbers of vernacular pine buildings with local timber survive, but many were built with young timber with fewer than 100 rings, and often less than 50-60 rings. These structures mostly post-date 1745, because many buildings in the Highlands were destroyed during the 18th century, either after the Jacobite risings or through the massive improvement-era changes on Highland estates. Occasionally, earlier higher status buildings with pine have survived in the Cairngorms, like Castle Grant (Fig. 1), but these are rare.

Figure 2: (L) Badden Cottage, Kincraig; (Middle) Badden Cottage roof; (R) Castle Grant, Grantown-on-Spey

Pine buildings in the Highlands

Sampling and analysis of Highland pine buildings is ongoing. So far five native pine structures have been dated; Inverey Byre and the Red House in Upper Deeside (through NOAP), Badden Cottage (Fig. 2) in Badenoch & Strathspey, and two timbers from the Highland Folk Museum (HFM Storage on map) from buildings elsewhere in the Highlands. All are from cruck frames and have felling dates in the late 18th/early 19th century. Dating earlier material, such as Castle Grant (Fig. 2) and Eaderloch crannog, depends on the ongoing extension back in time of the tree-ring record using sub-fossil material. We are currently analysing Year 1 historical samples from a number of sites, mostly from the northern Cairngorms, including those from Croft Roy (Newtonmore) and a ruined bridge in Glen Feshie (Fig. 3). It is hoped that these will date against the ever-expanding network of living and sub-fossil chronologies being developed in this region, including Rothiemurchus, Abernethy and Glen Feshie. The project is also investigating buildings from other native pine source regions (e.g. upland Perthshire and Glen Affric down to the Beauly Firth), together with some so far undated material sampled in the NOAP project.

Figure 3: (L-R) Inverey Byre; ruined bridge in Glen Feshie; Croft Roy; old timbers in storage at Highland Folk Museum.

Early 'export' sites

While use of native pine timber was mostly local, it was sometimes transported longer distances, floated down rivers and shipped around the coast. Although exploitation was most intensive from the 18th century, records show this occurred back into medieval times. The potential for native pine to survive in older buildings outside the Highlands is being tested, for example at St John's House, in St Andrews. Given the relatively rare survival of earlier native pine buildings in the Highlands, such 'export' timber sites could be important for constructing the medieval Scottish pine tree-ring record although provenancing such material may be a challenge.

Chronology extension, exploitation phases and woodland dynamics

SCOT2K aims to augment the tree-ring record for periods where the natural living tree and sub-fossil pine record is thin or disturbed, often as a consequence of past exploitation (Fig. 4). As more data accumulate, these patterns across Scotland are likely to resolve more clearly, and indicate periods of felling and regeneration. Disturbance influences are evident in the 19th century data from our study area in the northern Cairngorms, at Rothiemurchus and Abernethy/Green Loch, where coherence between the ring-width chronologies is weak and end dates of dated sub-fossil samples (with associated axe/cut marks) clearly indicate a period of timber extraction which is especially pronounced in the early 19th century (Fig. 4). This period of exploitation is known from the documentary record, coinciding with increase in demand for Scottish grown timber brought about by the Napoleonic Wars. Woodland history is particularly well researched for Rothiemurchus through the work of Chris Smout (1999) and also benefits from a first-hand account by Elizabeth Grant of Rothiemurchus who candidly describes the estate's debts and difficulties which led to large scale exploitation from the early 19th century (Grant 2006, first published 1898). By the late 1830s the forest was almost entirely clear-felled but with some small stands surviving and much regeneration (Smout 1999, 70), all of which fits well with the impacts indicated by the data in figure 4.

However, the history of native pine use at Rothiemurchus, and in Scotland more generally, is much longer. Tree-rings will allow us to explore that longer story, for times and locations not represented in the documentary record. As well as the period of timber extraction during the early-mid 19th century at Rothiemurchus, Figure 4 clearly indicates a similar exploitation period at the end of the 17th century (panels C and E) with associated regeneration afterwards (panels D and F). In fact, taking into account replication, the 1680s event appears more substantial than that of the 1810s/20s. The Rothiemurchus pine woods were already a well-used resource for timber from before the mid-17th century, when records become reasonably plentiful for the historian's work (Smout 1999). From then until about 1800, two types of exploitation are evident, with a traditional pattern of cutting and selling of timber by local people, largely under licence from the laird, being overlaid by spasmodic attempts by outsiders to exploit the woods on a larger scale commercially, usually unsuccessfully (Smout 1999, 60). The first such documented arrangement is when in 1658 an English merchant, Benjamin Parsons, secured contracts to cut in both Rothiemurchus and Abernethy; he obtained a 13 year lease for 'the whole fir woods' at Rothiemurchus with permission to build sawmills locally, but before the end of that contract he had run into debt, being pursued in 1671 by the laird of Rothiemurchus for sums owed (Smout 1999, 61). Smout says 'it remains a mystery how much timber he was able to extract from Rothiemurchus in his thirteen-year tack, but there is no evidence that it was a vast amount' (Smout 1999, 61). This could indeed be the case as this contract does appear to be a little earlier than the 1680s impact seen in Figure 4. Smout does not mention any contracts in the 1680s, the next being in the early 18th century, although it would be worthy of further research in the records at this specific time. We may be identifying an unknown episode of intense exploitation, and would expect to find that some of that material was used in Scotland's buildings at the time. More generally, the timbers we sample from old buildings and archaeological sites are expected to assist climate reconstruction by augmenting the tree-ring data available for these weak signalled and low replicated periods of exploitation in the living and sub-fossil pine records. This is a slow step by step process, requiring simultaneous and iterative work on both the natural and archaeological material.

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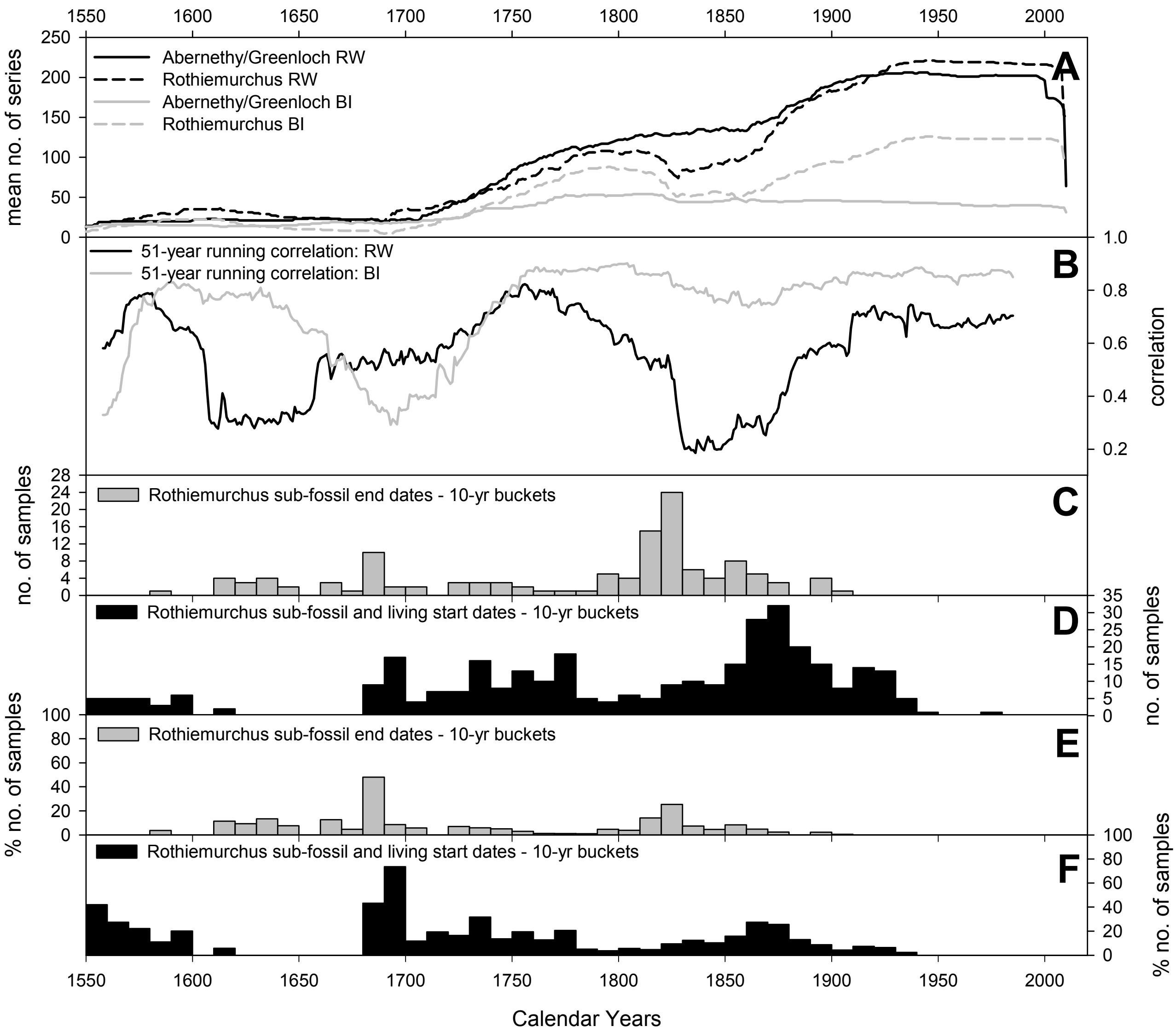

*Figure 4: **A -** RW and BI series replication for Rothiemurchus and Abernethy/Greenloch; **B -** running 51-year correlations between the Rothiemurchus and Abernethy/Greenloch regional chronologies for RW and BI ; **C -** histogram of end dates for Rothiemurchus sub-fossil. As most of the samples had axe/cut marks, their end dates reflect timber extraction and not natural die-off; **D -** histogram of start dates for Rothiemurchus living and sub-fossil material; **E** and **F -** As C and D, but the counts have been calculated as percentages relative to the replication (Panel A).*

New methods for historical material

Alongside conventional ring-width cross-dating methods, the Blue Intensity (BI) variable (Rydval et al. 2014) is being explored in SCOT2K to (a) assess its ability to facilitate dating of historic pine timbers, and (b) allow historic material to be used for dendro-climatic reconstruction. BI measurements have already been used to confirm the dating of Inverey Byre, and BI will be applied routinely to all SCOT2K historic samples alongside ring width.

Acknowledgements

SCOT2K is funded by NERC (NE/K003097/1) and is part of the Scottish Pine Project: more information here: http://www.st-andrews.ac.uk/~rjsw/ScottishPine/
We are grateful to the owners and managers who have generously granted permission to sample.

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SECTION 2

CLIMATOLOGY

Dendroclimatic evaluation of climate-growth relationships of *Pinus kesiya* Royle ex Gordon in subtropical forests of Manipur, northeast India

N. Dhirendra Singh[1], N. Venugopal[2] & P.S. Yadava[1]

[1]*Centre of Advanced Study in Life Sciences, Manipur University, Canchipur, India*
[2] *Centre for Advanced Study in Botany, North Eastern Hill University, Shillong, India*

Introduction

Tree-ring research in India was initiated with the application in the field of forestry research, growth rate determination, wood productivity and quality. Various studies have been made to find out the dendroclimatic potential of different trees growing in the Indian peninsular and Western Himalayan region. Many of the studies show the relationship between climate and annual growth ring formation in trees of Kashmir region (Pant, 1979; Hughes and Davies 1987, Bhattacharyya et al. 1988). A considerable number of studies focus on the reconstruction of the pre-monsoon temperature based using tree-ring width indices of *Cedrus deodara* and *Pinus wallichiana* which revealed century scale negative temperature anomalies which could be due to a regional impact of the Little Ice Age (Borgaonkar et al. 1996; Yadav and Singh 2002). Other studies using *Taxus baccata* and *Abies spectabilis* reveal the sensitivity of these species on pre-monsoon temperatures (Yadav and Singh 2002). Tree-ring research has been extended to the eastern and northeastern regions of India and has proved the dendroclimatic potential of the trees growing in this region (Chaudhary and Bhattacharyya 1999, 2002). Drought sensitive tree stands of Tibet showed their dendroclimatic potential (Brauning 1999). Stream flow reconstruction have been carried out from tree rings of Larix grafithiana from north Sikkim, North east Inida (Shah et al. 2014). Climate induced elevational species richness changes were observed in the Himalayan region by Telwala et.al. (2013). However, there is scarcity of studies pertaining to seasonal cambial activity and growth ring formation in relation to climate, especially in northeast India. Except for the works of Chaudhary and Bhattacharyya (2000, 2002); Dhirendra (2002), Venugopal and Liangkuwang (2007); Dhirendra and Venugopal (2011), no documentation has been carried out which climate factors plays major roles in the process of growth ring formation. Therefore the present study was conducted on *Pinus kesiya* Royle ex Gordon which is considered as one of the most important species in terms of reforestation of watershed areas as well as from a conservation point of view. The study focused on intra-annual variations of monthly cambial growth within a growing season as well as the long term response to climate. Two objectives were set for the present study-1) to compare the seasonal cambial activity among trees of similar age with climatic factors, and 2) to describe the influence of climate on annual growth by using dendrochronological tools.

Materials and methods

Study area and general climate.

The present study was conducted at the Langol Reserve Forest under Imphal West District of Manipur. The soil is loam, reddish brown in colour and lateritic in origin. The ‘pH’ ranges from 5.9-6.2 (Singh 1996; Porwal et al. 2000). Climatologically this study area belongs to the sub-tropical moist climatic regions (Champion and Seth 1968). This region receives abundant southwest monsoon rainfall. Highest rainfall was recorded with 427 to 422mm during the months June and July. During winter, mean temperature ranges from 2°C to 12°C and in the spring season (March to April) from 20°C to 25°C (Fig. 1). During winter, the monthly mean precipitation is below 50mm and the soil moisture content is around 30-40% (Porwal et al. 2000; Brady and Well 2002; Triparthi 2002; Pandey 2004). Tree-ring samples were collected from 34 trees during September 2012 at breast height by using 18" Hagolf three thread corers. Two cores were extracted from each individual tree.

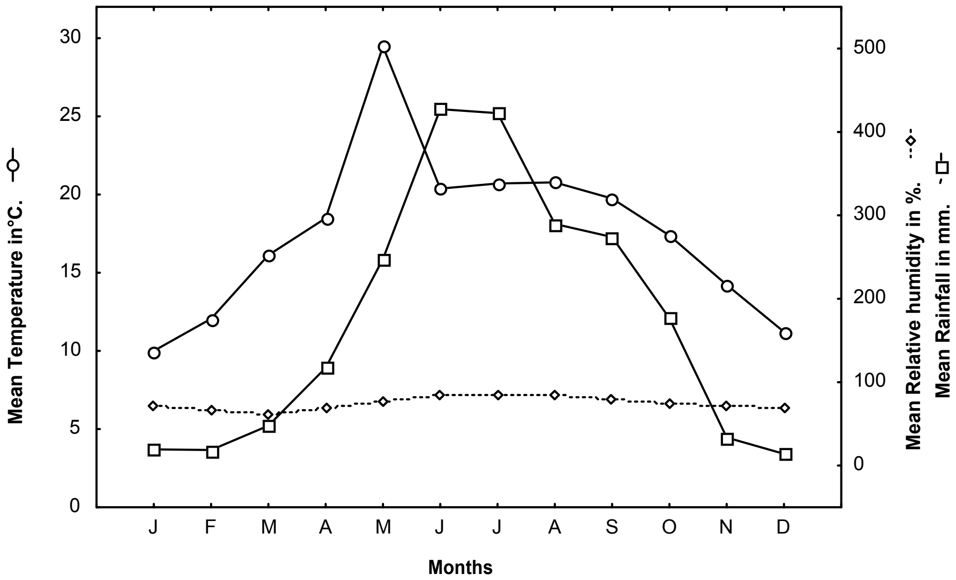

Figure 1: Annual distribution of rainfall, temperature, and relative humidity.

Tree-ring analysis and cross-dating

The extracted cores were processed following standard procedures of tree-ring analysis (Fritts 1976). Careful examinations were made before identifying the exact calendar year of formations of each ring. All cores were mounted, sanded, and visually cross-dated as described by Eckstein et al. (1984) and Pilcher (1990). Sanding was done on each core using different grades of sand paper. Ring width measurements were checked for possible measurement or dating errors using the computer program COFECHA (Holmes et al. 1983). Rechecking of certain core segments was done if COFECHA identified issues. Standardization of measurement series was performed using the program ARSTAN (Cook 1985). Measured ring width series were detrended by applying negative exponential curve plus 32 years cubic spline. After synchronizing the individual series, a standard chronology was constructed by averaging all cores.

Response function analysis

For studying the growth response of *P. kesiya* to climatic factors, the program RESPO (Lough 1984) was used. It performs a simple correlation analysis and a stepwise multiple regression analysis using orthogonalised monthly mean rainfall and mean temperature against the standardized chronology. Climatic variables were procured from IMD Pune, includes total monthly mean rainfall, monthly mean temperature. Fifteen months from July of the previous year to September of the current year were used for the response function analysis. Coefficients were calculated from a 38-year period extending from 1962 to 1999, which was the common period between the climate records and the chronologies.

Results

The growth rings were markedly distinct by the radially compressed late wood xylem elements. A chronology covering the period from 1880 to 2012 (132 years) was developed (Fig.2). The strength of cross dating among the trees was reflected by a correlation among all radii of 0.32 and a mean correlation between trees of approximately 0.31. The signal to noise ratio is 4.26;

agreement to population chronology is 0.8 and variance explained by the first eigenvector is 39.24% indicating suitability for dendroclimatic studies (Table 1). The mean sensitivity of the standardized chronology (0.25) indicates its suitability to obtain accurate results with correlation function methods.

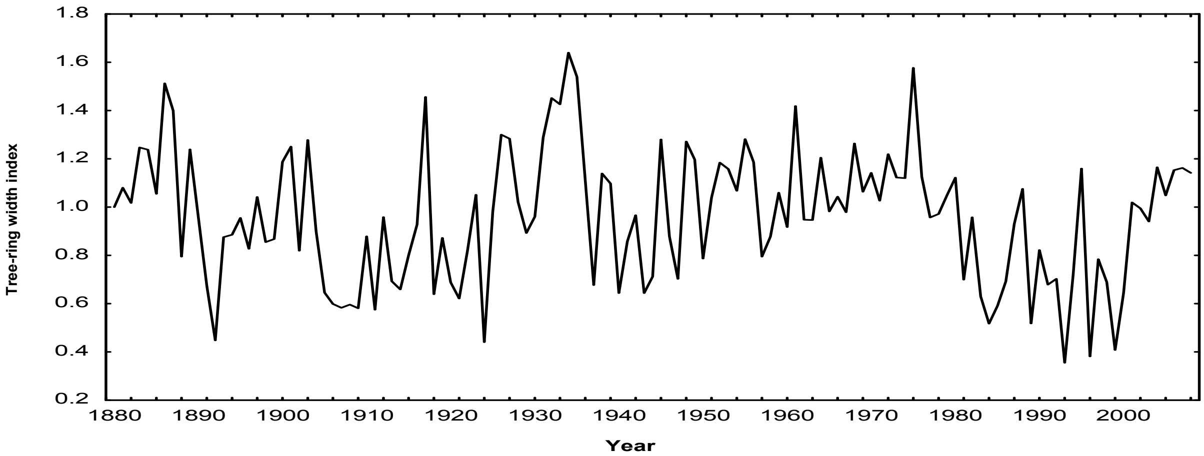

Figure 2: Tree-ring width indices of Khasi pine standardized chronology

Table 1: General statistics for standard chronology of *Pinus kesiya*.

Mean sensitivity	0.25
Correlation among all radii	0.32
Correlation between trees	0.31
Signal to noise ratio	4.26
Agreement to population chronology	0.80
Variance due to first eigenvector	39.24%

Tree-ring growth of *P. kesiya* responded positively with monthly mean temperatures of April through September of the current year growth (Fig. 3A), with lower correlations during April and May. Current year June and September mean temperature shows significant correlation with tree growth (Fig. 3A), however, current year March mean temperature shows a significant negative correlation (Fig. 3A). A positive response was also observed with mean temperature during July to December of the previous year (not shown). Ring width responded negatively with precipitation during January to April of the current year, but positive correlations were observed during May to July of the current year (Fig. 3B). A negative response was observed with rainfall in the months of the previous year except for July.

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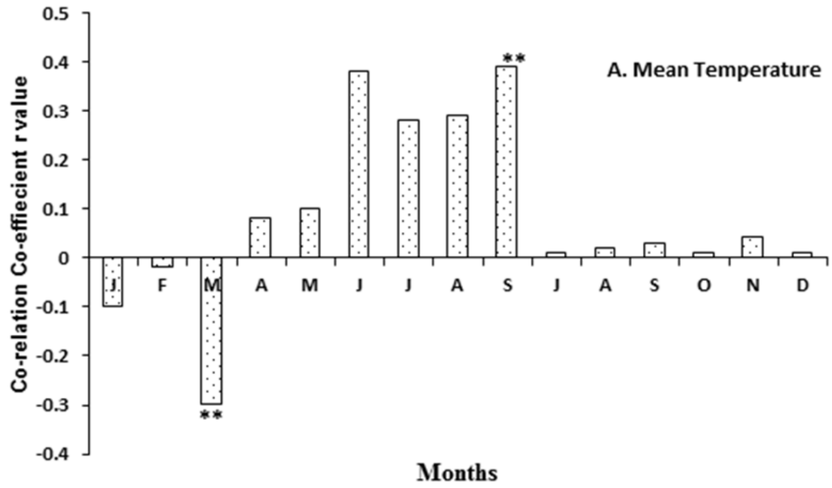

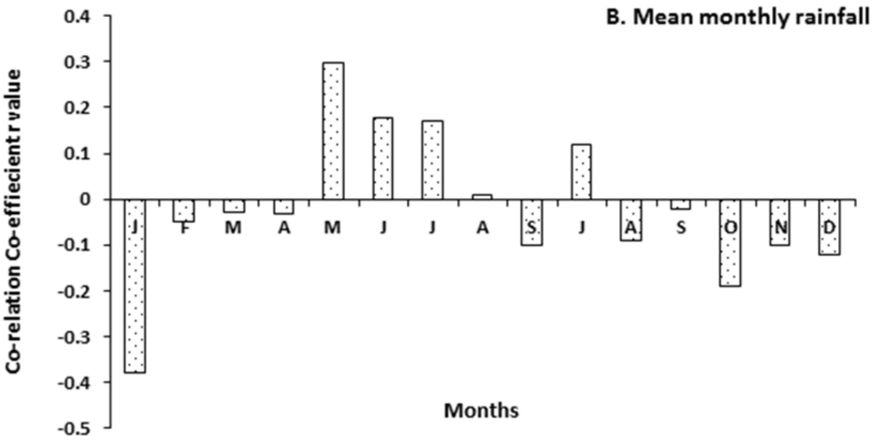

Figure 3: Correlation function of Pinus kesiya growth and A mean monthly temperature, B mean monthly rainfall. Coefficients significant at 0.05 level are identified by double asterisk.

Discussion

The significant correlation among individually standardized tree ring series showed synchronicity in inter-annual variation in ring-width patterns. The observed signal to noise ratio and the expressed population signal, as well as the percentage of variance accounted for by the first eigenvector of the standardized tree ring indices indicated that all trees share a strong regional common signal (Table 1). The mean sensitivity of the standardized chronology shows the possibility of getting a good correlation with the climatic factors. The tree growth showed positive response to mean temperatures of April through September of the current year growth. Other dendroclimatic studies in Northern India also displayed a similar response to climate (Borgaonkar et al. 1996). The negative response of mean temperature observed during the months of January to March of the current year is also in accordance with the observation of Borgaonkar et al (1999). A slight increase in temperature during the month of February is an important factor to initiate the reactivation of cambium. Moreover, during February the sprouting of new buds, needles, and branches of *P. kesiya* could be related to the reactivation of vascular cambium after winter dormancy. Both the mean maximum and mean minimum temperature influence is in a similar trend with that of mean temperature to the ring growth of *P. kesiya*. However in the present study, rainfall during the months of January to April of the current year growth responded negatively, indicating that rainfall during the dormant and spring period does not play a role for wood formation. The observed positive response between ring width and rainfall during current May to August reflects the influence of the Southwest monsoon on growth of the species, as higher rainfall is conducive to cambial reactivation in several plants growing especially in the tropic and the semi-arid climates. The significant response of September mean temperature could be stated that from this month onward the formation of late wood elements occurs with the accumulation of photosynthate for the use of next year growth. These assimilates may be used for the early next year growth, provided if there is no physical and physiological stress. The activation of cambium and its dormancy is associated with the accumulation of maximum and minimum starch in the xylem elements (Parker 1960; Sauter 1966; Tsuda and Shimaji 1971; Riding and Little 1984; Essiamah and Eschrich 1985). Larson (1967) reported that the early wood development depends on stored reserves of the previous years; while the late wood is dependent on current year assimilate that available for an extended growing season. In the present study a weaker correlation was observed with mean temperatures of the previous year to the growth of *P. kesiya* suggesting previous year temperature did not influenced much to the growth. The observed difference to the present study could be due to the elevation of the sampling site as well as higher rainfall. Studies on cambial activity in relation to climatic factors in *P. kesiya* (Dhirendra Singh 2002) and *Dellinia indica* Linn (Venugopal and Liangkuwang 2007) from this study site showed significant temperature response to mean and minimum temperature rather than other factors. The present study clearly revealed that *P. kesiya,* growing in north east India, is suitable for tree-ring analysis because of its clear and datable ring sequences and synchronicity in growth pattern. The present study concludes that the annual growth rings of *P. kesiya* are datable because of its early wood and late wood demarcation among the yearly rings. The tree-ring growth is influenced by the regional environmental factors. Temperature plays a significant role for the growth of the species. Further studies on other coniferous trees growing in this region will be undertaken to explore whether a common climate force operates on all the species of conifers in this region. It can be concluded that the tree-ring width sequences of *P. kesiya* serves as a reliable source for further dendroclimatic studies.

Acknowledgements

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High frequency coherence of temperature and solar radiation reconstructions over the past millennium in northern Fennoscandia

E. Düthorn[1], S. Holzkämper[2] & J. Esper[1]

[1]Department of Geography, Johannes Gutenberg University, Mainz, Germany
[2]Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden
E-mail: E.Duethorn@geo.uni-mainz.de

Introduction

Tree growth is a complex process influenced by many different factors (Fritts 1976). Especially at extreme sites, with limiting climatic factors, the production of wood and the carbon isotope fractionation notably depends on external influences, e.g. vegetation period temperatures, precipitation, snow cover, or radiation variations. Due to the measurement of various parameters, including tree ring width (TRW), maximum latewood density (MXD) and stable isotope ratios ($\delta^{13}C$, $\delta^{18}O$), trees offer the possibility for multi-proxy analyses (McCarroll et al. 2013). In northern Europe, MXD and carbon isotope records have been used to reconstruct several climate parameters over the last millennium (Esper et al. 2014, Esper et al. 2012, Gagen et al. 2011, Loader et al. 2013, Melvin et al. 2013, Young et al. 2012). All these reconstructions display the variability of a climate parameter over at least the last 1000 years. Studying the association between these might improve our understanding of the complex interaction between tree growth and atmospheric conditions. The relationship between radiation, estimated by using sunshine hour and cloud cover reconstructions, and temperature has been discussed in several recent papers (Gagen et al. 2011, Loader et al. 2013, Young et al. 2012). These studies indicated temperature versus cloud cover homogeneity at higher frequencies, but also a decoupling between these elements at lower frequencies, enabling reconstructions of prolonged periods with sunny and cold as well as cloudy and warm conditions, respectively. We here build on these results and compare summer temperature reconstructions, derived from MXD time series, with reconstructions of solar radiation (cloud cover and sunshine hours), derived from $\delta^{13}C$ time series. We assess inter- and intra-proxy similarities focusing on high and low frequency domains as well as possible effects of macro-climate conditions.

Data and Methods

In northern Europe, several climate reconstructions have been developed, based on long tree-ring records, with annual resolution, and covering the last millennium (Overview in McCarroll et al. 2013). Beside multi-proxy analyses, also intra-proxy relationships are important to understand. A recent study showed the similarity between the MXD based temperature reconstructions from Torneträsk (Melvin et al. 2013, Schweingruber et al. 1988) and northern Fennoscandia (Esper et al. 2012). They combined the two time series to a single record representing summer temperature variations in northern Europe (N-Eur; Esper et al. 2014).
There are two long term carbon isotope records with an annual resolution from Torneträsk and Forfjorddalen (Loader et al. 2013, Young et al. 2012). Both records are proxies for solar radiation, with the Torneträsk isotopic data representing summer sunshine hours, and the Forfjorddalen data representing cloud cover changes.
All proxy records cover the last millennium (1000-2001AD). Standardization over this common period allows comparisons between the reconstructions. For inter-proxy comparisons we use the N-Eur temperature reconstruction. Cloud cover and sunshine hours are inversely connected to each other: if it is cloudy, the sunshine hours are reduced. Hence, the cloud cover record was

inverted enabling the comparability of the reconstructions. The low-frequency relationship between the two climate parameters was tested by calculating residuals between the temperature and the radiation record. A 10-year spline spots periods of positive and negative alterations. For tests on high frequencies we calculated the first differences of the reconstructions. This method allows us to test the relationship on a year-to-year perspective. 51-year running correlations with a centrally weighted filter help to detect the constancy of the high-frequency relationship over time.

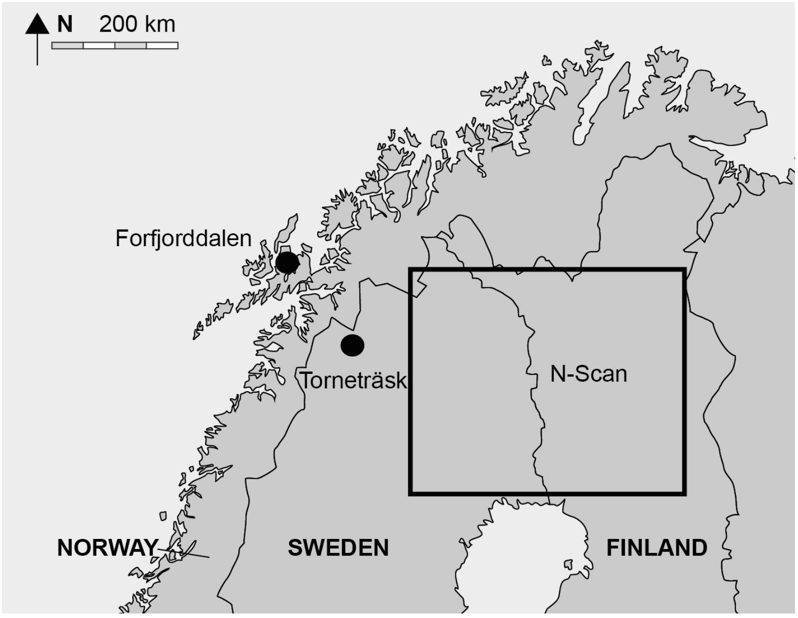

Figure 1: Map of northern Fennoscandia. Dots display sites of millennial long tree-ring records. N-Scan (black box) cannot be determined with one point due to a large extension of the different sampling sites over this northern region.

Results

The described homogeneity of the Torneträsk and N-Scan temperature reconstructions is displayed in the upper panel of figure 2 and the correlation coefficient of 0.72 over the last millennium highlights this close relationship. The radiation records (Fig.2, bottom panel) correlate at 0.48 over the past millennium, though include periods of obvious coherence (e.g., 1600-1800) and divergence (e.g., around 1100 and 1500).

The inter-proxy relationship at lower frequencies is shown in figure 3. The residual time series indicate periods with dominating warm and cloudy conditions, alternating with cool and sunny conditions. Considering the Torneträsk record, the residuals show warmer conditions at the beginning of the last millennium followed by a colder/sunnier period in the 13th century. The most distinct and persistent era of cooler and sunnier conditions is around the Little Ice Age (LIA) in the 17th and 18th century. The results are quite similar with the residual time series derived using the Forfjorddalen record. The key periods are the same as with the Torneträsk data, but there are more distinct warmer periods (e.g., around 1400 AD), as well as clearer changes in the atmospheric conditions in the early 12th and mid-15th century when the climate turned cool and cloudy.

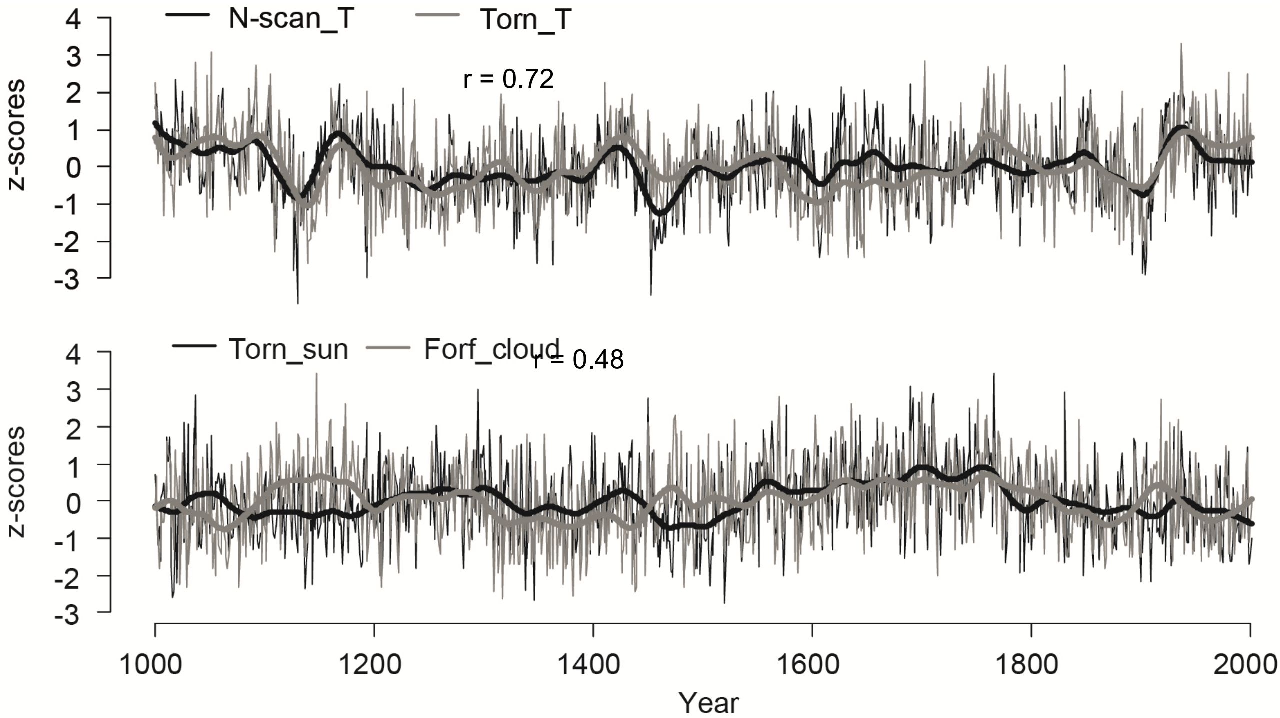

Figure 2: Millennial long climate reconstructions with annual resolution in northern Fennoscandia. Upper panel shows summer temperature reconstructions based on MXD chronologies. Lower panel shows sunshine hour/cloud cover reconstructions. The common period is 1000 - 2001 AD. All data were z-transformed over this common period. The cloud cover reconstruction is inverted to simplify comparison with the other reconstructions. Thicker lines are 50 year spline.

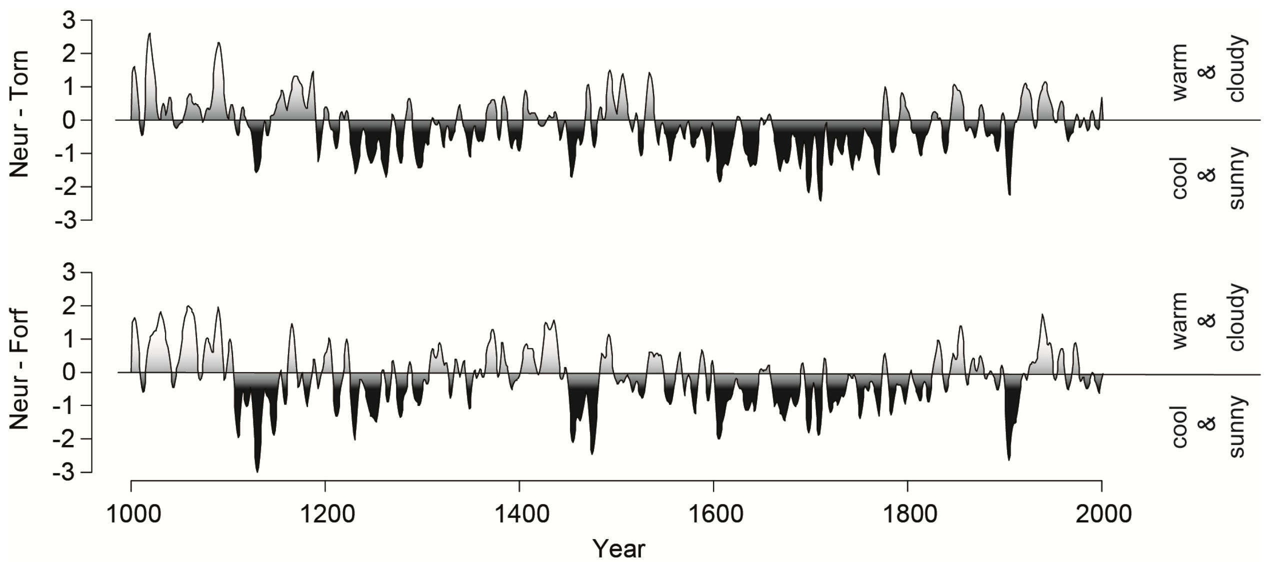

Figure 3: Relative differences between the combined temperature reconstruction (N-Eur) and sunshine hour/cloud cover reconstructions (upper panel: Torneträsk; lower panel: Forfjorddalen). Differences are smoothed with a 10 year spline. Warm and cloudy conditions are represented by positive values (grey), negative values indicate cool and sunny atmospheric conditions (black).

51-year running correlations indicate similar patterns among the three records (Fig.4). The relationship between temperature and radiation (sunshine/cloud cover) is positive throughout the entire millennium and varies around 0.5. The most striking deviation occurred in the late 16th century when correlation drop below 0.2 in all cases. The correlation drops in the 11th century using Torneträsk data, though this feature is not revealed in the Forfjorddalen data nor in the combined record (bottom panel in Fig.4)

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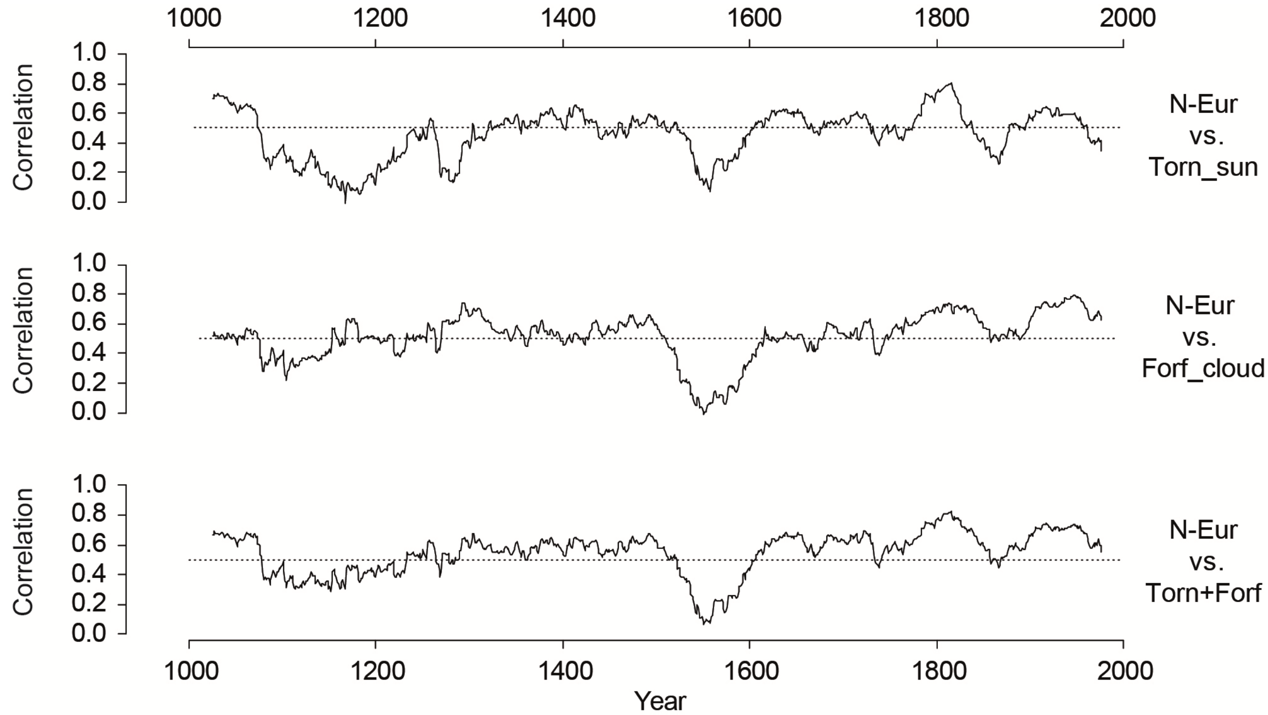

Fig.4: Inter-proxy high frequency analysis. 51-year running correlation of the first differences of temperature and radiation reconstructions. Upper (middle) panel shows the correlations of N-Eur and Torneträsk (Forfjorddalen). Lower panel shows the running correlations of a combined record of Torneträsk and Forfjorddalen versus N-Eur. Dotted line is r= 0.5.

Discussion

The similarity of the MXD-based temperature reconstructions (Torneträsk and N-Scan) enables merging these records into a single temperature reconstruction for northern Fennoscandia (Esper et al. 2014). A similar combination of the stable carbon isotope-based radiation reconstruction (sunshine hour and cloud cover) from nearby Forfjorddalen and Torneträsk would increase replication and likely advance the spatial expansion of the radiation signal. In general, discrepancies between these records (see lower panel in Fig.2) could be related to the location in the luv (Forfjorddalen) and lee (Torneträsk) of the Scandinavian Mountains. The coastal site is influenced by a higher atmospheric moisture content due to the Atlantic Ocean. The Scandinavian Mountains serve as orographic border where the air masses rise. During the movement the air masses are transformed into precipitation, fog and clouds (Young et al. 2012). The phenomenon of the foehn provides drier and warmer conditions in the continental Torneträsk area (Holmgren and Tjus 1996). While these site effects appear important to understand differences between the carbon isotope records, the overall coherence is still striking. Also the spatial importance is unclear due to the strong effect of macro-climatic influences.

Changing connections of temperature and radiation proxies at differing frequencies (Fig.3 and Fig.4) have already been addressed by Gagen et al. (2011) detailing co-variance at high frequency and divergence at decadal to centennial time scales. We here provide more detail on these changes. First of all the relationship between temperature and sunshine hour is positive over the last millennium (Fig.4), indicating that warmer temperatures coincide with more hours of sunshine (Loader et al. 2013). This positive relationship on a high frequency level is accompanied by an opposite relationship at lower frequencies. The residual time series (Fig.3) point out changing conditions and a decoupling of the positive relationship between temperature and sunshine hours during the last 1000 years. As the high frequency shows robust results of a positive relationship, we will discuss the possible causes for the divergence at lower frequencies.

Next to annual information tree-rings also store low frequency trends. Depending on the measured parameter and the statistical treatment, the low frequency capacity of the time series could vary.

The low frequency content in the temperature reconstructions depends on the detrending method of the raw MXD measurements. The applied detrending technique on the MXD-measurements is the RCS detrending as it is known to keep the low frequency in the tree-ring data (Briffa et al. 1996, Esper et al. 2003). MXD-data also shows similar frequencies as the target parameter and is very suitable for temperature reconstructions (Franke et al. 2013). Some studies propose that carbon isotope records also contain low frequency information even without detrending (Young et al. 2011) but the relationship of the frequencies of the proxy and target data is unclear and depends strongly on the trend caused by the CO_2 corrections of the carbon isotope data (Konter et al. 2014). These differences also could bias the low frequency relationship between temperature and radiation, as well as the link of MXD and carbon isotope records, respectively.
Another approach to explain the divergence of temperature and radiation over time was discussed by Loader et al. (2013). They point out that a change of the dominant air masses could cause this divergence. Their results are based on the residual time series (Fig.3) where on the one hand positive differences are indicated to be warm and cloudy and on the other hand negative values point out cool and sunny conditions. This simple way to calculate differences is not very robust as it does not consider the extreme years of the climate reconstructions and therefore a misinterpretation could be the consequence. Hence, a more complex analysis of differences and of the low frequency relationship is needed to verify if there is a change in the air masses.
The high frequency relationship of temperature and radiation is very stable over the last millennium. A decoupling between both proxies is only indicated by the drop of running correlations shown in figure 4. The positive relationship between the first differenced temperature and sunshine hour time series breaks down in the 16th century. We exclude an error of dating of the temperature time series as it fits quite well to other existing independent temperature reconstructions in this area. Dating problems of the radiation records are also unlikely due to the appearance of the drop at both sampling sites. Also woodland clearance as a factor for the decrease in correlation appears unlikely. Even if this effect would result in more light and increased growth, the thinning must have taken place at both sites. Helama et al. (2009) reconstructed a dry period around 1500 AD, indicating that increased drought stress could have influenced tree growth in the North and affected the temperature signal in the MXD measurements. Furthermore, this also could affect the radiation reconstructions as they are established under the condition that the carbon isotope fractionation takes place in moist environments and that the photon flux (Hari et al. 1981) is responsible for the assimilation in the tree-rings. But very dry years can change this main factor for carbon fractionation and stomata conductance controls the fractionation (McCarroll and Loader 2004). Therefore, in dry years water availability and not sunshine is influencing the signal in the carbon isotope time series.

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Memory effects in tree-ring width and maximum latewood density in response to volcanic eruptions: evidence from northern Fennoscandia

J. Esper

Department of Geography, Johannes Gutenberg University, 55099 Mainz
E-mail: esper@uni-mainz.de

Introduction

Large volcanic eruptions, injecting aerosol into the stratosphere, are an important component of the global climate system (Cole-Dai 2010). The aerosols scatter the incoming, shortwave radiation and absorb the outgoing, longwave radiation, thereby warm the lower stratosphere and cool the earth surface (Robock 2000). Estimates of this post-volcanic surface cooling are constrained by the limited number of stratosphere-injecting eruptions during the period of large-scale instrumental measurement (Kelly & Sear 1984, Robock & Mao 1995). This limitation is overcome by using tree-ring based climate reconstructions (Briffa et al. 1998, Cook et al. 2013, Esper et al. 2013a), though the proxy-derived temperature estimates typically explain only a fraction of the variance of surface temperature variability (Frank et al. 2010).

It has recently been suggested (Anchukaitis et al. 2012) to use maximum latewood density (MXD) instead of tree-ring width (TRW) data for assessing the climatic fingerprint of large volcanic eruptions. The rationale for this suggestion is related to potential physiological memory effects inherent to TRW (Cook and Kairiukstis 1990, Fritts 1976) that might blur the signal of distinct cooling or disturbance events and produce temporally extended response patterns (D'Arrigo et al. 2013, Esper et al. 2007, 2010, Krakauer & Randerson 2003). However, the only detailed assessment revealing distinctly differing, parameter-specific, response times to a major volcanic eruption has been presented in Frank et al. (2007a; see their figure 2) indicating a substantially extended TRW decline following the 1815 Tambora eruption, compared to MXD and summer temperature data from the European Alps (see also reviews in D'Arrigo et al. 2013, Anchukaitis et al. 2012). We here evaluate this topic, using the recently developed N-Scan MXD and TRW data from northern Fennoscandia (Esper et al. 2012a), and assess the typical patterns in these tree-ring parameters in response to annually dated volcanic eruptions over the past 750 years.

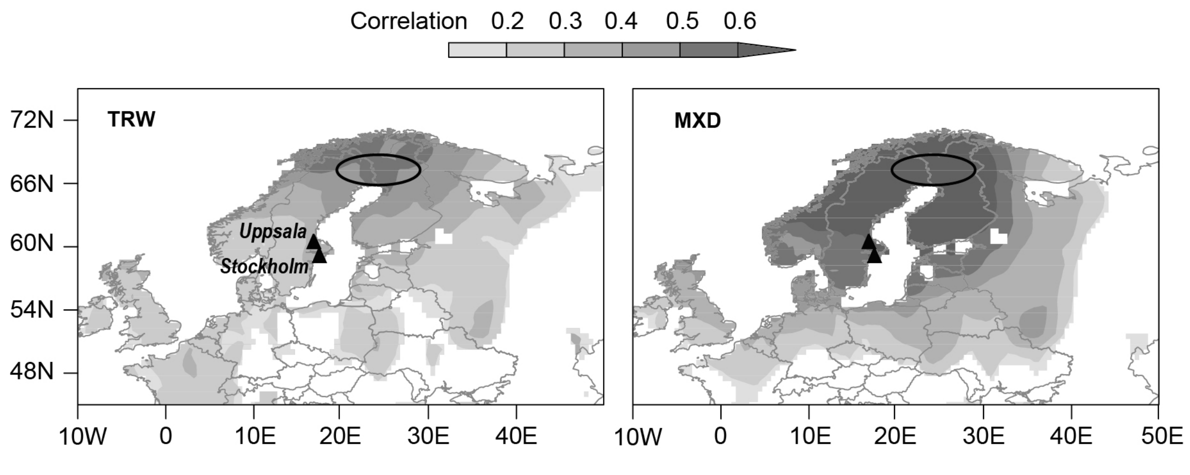

Figure 1: TRW and MXD temperature fields. Location of the N-Scan sampling sites (circle), and spatial correlation patterns of the TRW (left) and MXD data (right) with gridded (0.5° resolution) summer temperatures calculated over the 1901-2006 period. Triangles indicate the location of the long-term temperature stations in Stockholm and Uppsala.

Material and methods

Scots pine data

Five hundred eighty seven TRW and MXD measurement series from lakeshore (Düthorn et al. 2013) and sub-fossil (Eronen et al. 2002) *Pinus sylvestris* L. from northern Finland and Sweden are used in this assessment of potential memory effects. The MXD collection was previously used to reconstruct summer temperatures over the Common Era revealing a millennial scale cooling trend of ~ 0.3°C in northern Fennoscandia due to long-term changes in orbital forcing (Esper et al. 2012b). However, also the TRW data contains a reasonable climate signal explaining ~ 25% of regional summer temperature variance (Fig. 1), making it – in the absence of MXD measurements – a useful paleoclimatic proxy. While the original N-Scan dataset spans more than two millennia, we here only use the past 750 years during which a number of annually dated volcanic events are available.

Age trend removal and chronology building

TRW and MXD data contain entirely different age trends (Fig. 2). While *Pinus sylvestris* MXD measurement series typically increase from ~ 0.5 to ~ 0.7 g/cm^3 during the first two decades of the trees' lifespans, this juvenile trend is followed by a small and fairly gradual decrease of less than 0.1 g/cm^3 up to tree ages > 300 years. In contrast, TRW measurement series are characterized by a steep age trend from ~ 1.2 mm to ~ 0.6 mm over the first eight decades, followed by a still substantial but less severe decrease by another ~ 0.3 mm up to tree ages of 300 years and beyond.

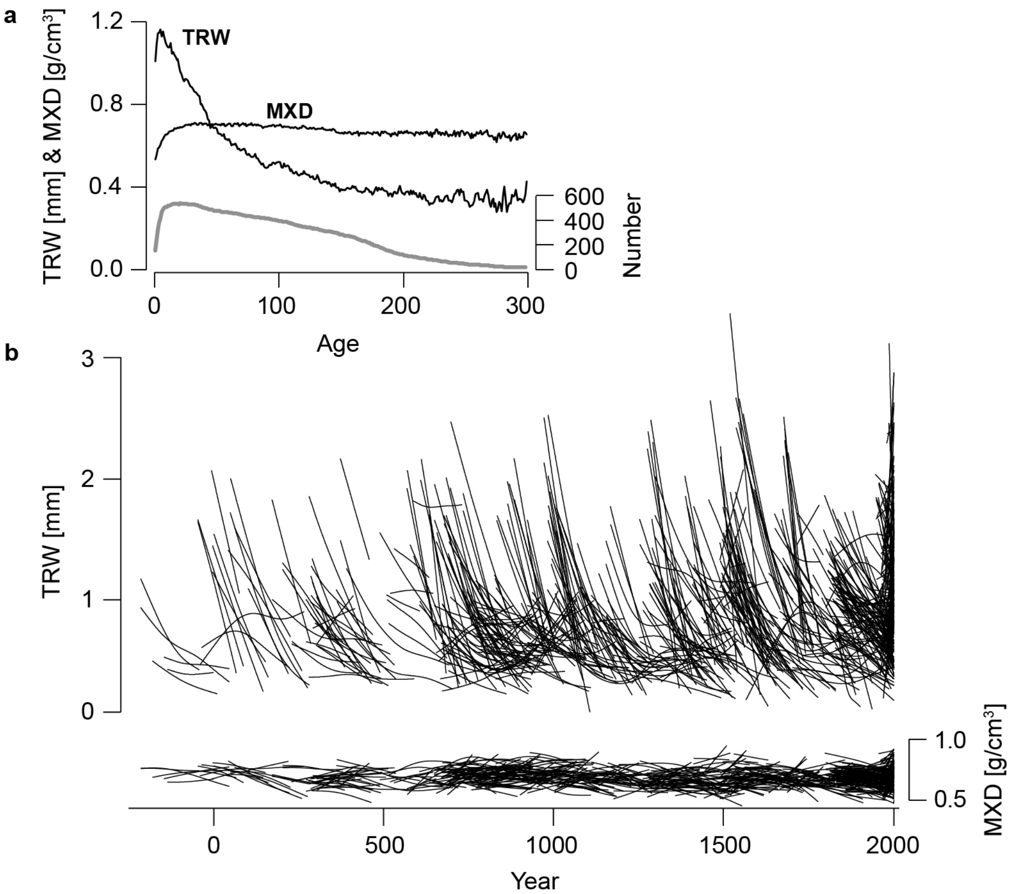

Figure 2: TRW and MXD age trends. ***a****, Arithmetic means of the age-aligned TRW and MXD data shown together with sample replication (bottom panel) declining to 20 measurement series at 300 years.* ***b****, 300-year low-pass filters fitted to the N-Scan TRW (top) and MXD (bottom) measurement series.*

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Visualizing these differing age trends over the past two millennia (Fig. 2b) might help emphasizing the much-increased changes that occur when detrending TRW data, compared to MXD. We here applied three approaches (Regional Curve Standardization, RCS; Negative Exponential Standardization, NegExp; and 100-spline Standardization, 100spl) to study the relative contribution of detrending methodology to the estimation of post-volcanic memory effects. In RCS, the regional curve was produced using a 10-year fixed spline, and ratios between the raw measurement series and the regional curve calculated (details in Esper et al. 2003). In the individual series detrendings, we first power transformed the original measurement data (Cook & Peters 1997), and then calculated residuals from NegExp and 100spl functions (Cook & Kairiukstis 1990). No positive slope was allowed in the NegExp detrending to avoid removing long-term increasing trends. In all detrending methods, chronologies were calculated using the arithmetic mean, and variance was stabilized using 300-year splines (Frank et al. 2007b).

Calibration and transfer

The detrended chronologies were calibrated (1876-2006 period) against instrumental June-August (JJA) temperature data recorded at the stations Karasjok, Sodankyla, and Haparanda in northern Fennoscandia. Correlations ranged from 0.43 to 0.53 for TRW, and from 0.72 to 0.77 for MXD, with the RCS detrended chronologies always scoring highest and the 100spl chronologies lowest. The chronologies were transferred into estimates of summer temperature variability by scaling the records (i.e. adjusting the mean and variance; Esper et al. 2005) to the target instrumental data (Fig. 3), and the Expressed Population Signal (EPS) was calculated to estimate the skill of the 100spl detrended chronologies back over the past 750 years (Wigley et al. 1984).

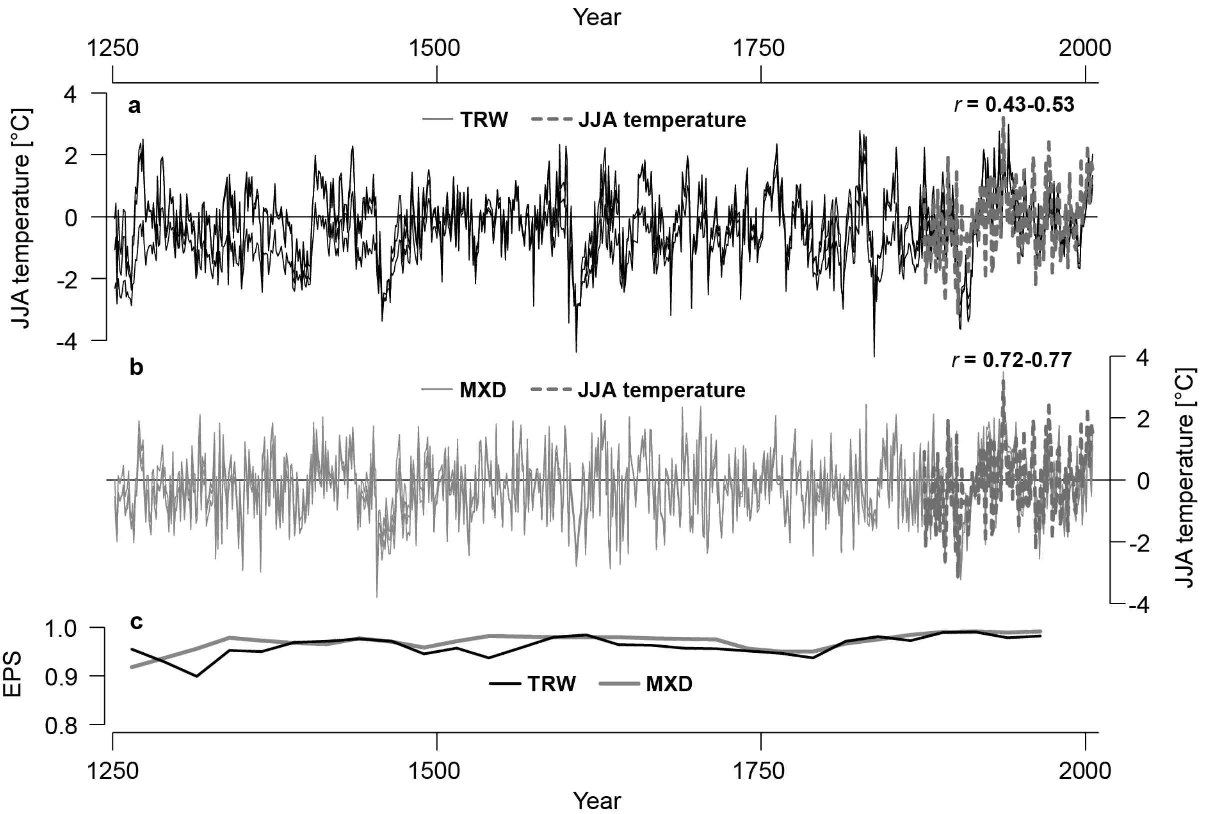

*Figure 3: TRW and MXD derived JJA temperature estimates. **a**, Differently detrended (RCS, NegExp, 100spl) TRW chronologies scaled against regional JJA temperatures (dashed curve) over the 1876-2006 period. **b**, Same as in **a**, but for the MXD chronologies and JJA temperatures. **c**, EPS curves of the 100spl detrended TRW (black) and MXD (grey) chronologies.*

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Autocorrelation and SEA

To assess the temporal persistence inherent to the TRW and MXD data, lag-1 to lag-20 autocorrelations of the detrended chronologies, as well as a long instrumental temperature record, were calculated over 1756-2006. The long instrumental record integrates summer temperature readings of the stations in Stockholm and Uppsala in southern Sweden reaching back to the mid 18th century (Moberg & Bergström 1997). While these stations are located towards the southern limit of the proxy correlations fields (particularly for TRW; see Fig. 1) the exceptional length of these data allow an additional assessment of volcanic eruptions fingerprinted in regional temperature data, and comparison with proxy evidence.

Post-volcanic cooling and persistence in TRW and MXD data were estimated using Superposed Epoch Analysis (SEA; Panofsky & Brier 1958). The method comprises aligning the proxy (and instrumental) data by pre-defined dates of large volcanic eruptions, and assessing the estimated temperature deviations prior and subsequent to these events. The eruptions considered here are derived from Esper et al. (2013b) listing 34 events exceeding a volcanic explosivity index (VEI) of 4 over the 1111-1976 period. Three additional, post-1976 events were added here (St. Helens in 1980, El Chichon in 1982, and Pinatubo in 1991) as the N-Scan data reach into the 21st century. We also ran a second SEA including only the ten VEI ≥ 5 events since 1756 that caused substantial cooling (> -0.5°C) in the long Stockholm/Uppsala temperature record, and used these for an additional comparison of observed with TRW- and MXD-estimated cooling patterns.

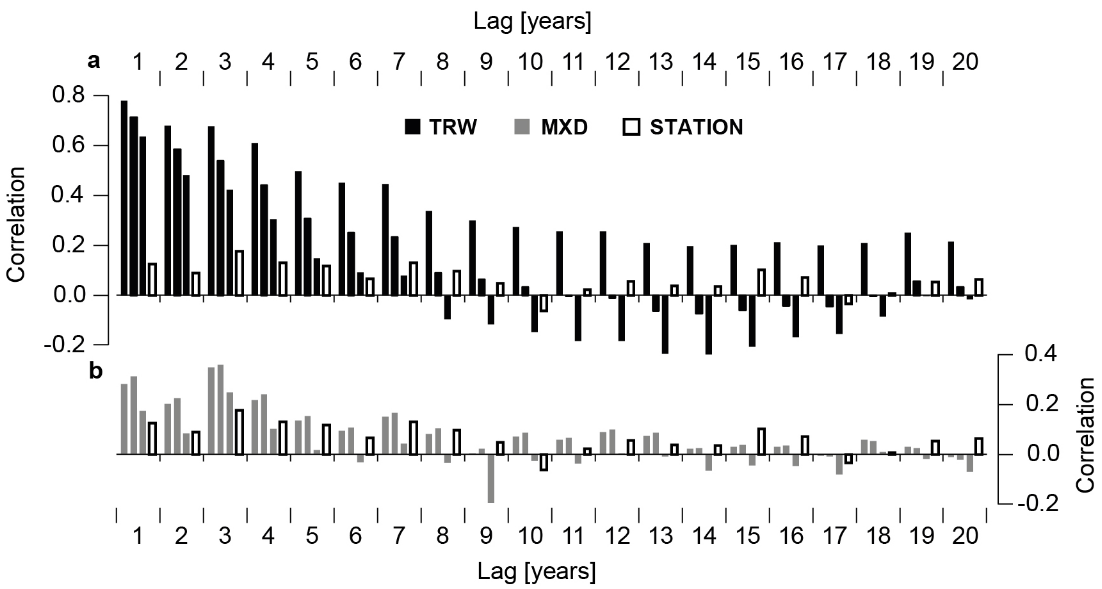

*Figure 4: TRW, MXD, and station data autocorrelations. **a**, Lag-1 to lag-20 autocorrelations of the differently detrended N-Scan TRW chronologies (black bars: left = RCS, middle = NegExp, right = 100spl), and the combined Stockholm/Uppsala summer temperature station data over the 1756-2006 period. **b**, Same as in **a**, but for MXD and the station data.*

Results

The detrended TRW chronologies contain much more autocorrelation than the MXD chronologies (Fig. 4). TRW chronology lag-1 autocorrelations range from 0.78 in the RCS to 0.64 in the 100spl detrended timeseries. Autocorrelations also decline faster with increasing lag in the 100spl chronology, approaching zero at lag-7, whereas the RCS chronology is characterized by positive autocorrelations up to lag-20. In contrast, the MXD chronologies only contain autocorrelations ranging from 0.31 (NegExp) to 0.17 (100spl) at lag-1. MXD autocorrelations shrink at lag-5, and subsequently fluctuate around zero up to lag-20. Interestingly, the long summer temperature data recorded at Stockholm/Uppsala contain properties similar to the MXD data, including positive autocorrelations ranging from 0.09 to 0.18 up to lag-5, and subsequently minor deviations around zero up to lag-20. Similar to the MXD data, the observational record contains much less memory compared to the TRW timeseries.

The SEA considering 37 annually dated VEI ≥ 5 volcanic events over the past 750 years (Fig. 5a) reveals substantial differences in the response structure of the N-Scan TRW and MXD chronologies. While both parameters indicate strongest post-volcanic cooling at year T+2, in line with evidence from other MXD sites in Scandinavia (Esper et al. 2013b), the MXD data fluctuates back to > 0°C at year T+4, whereas the TRW chronologies continue showing below zero temperature anomalies for another 3-4 years. The 100spl detrended TRW data (the lowest of the three black curves in Fig. 5a) indicates negative values up to T+7 and bounces back to positive temperature anomalies at T+8.

This delayed response pattern in TRW is supported by the SEA applied to only the most significant volcanic eruptions of the past 250 years, during which also long instrumental station data are available (Fig. 5b). In this assessment, average cooling at year T+2 reaches -1.11°C in the instrumental JJA data, a finding in line with the cooling estimated by the MXD chronologies (-1.04 to -1.26°C at T+2). The TRW chronologies show less cooling at T+2, ranging from -0.37°C (RCS) to -0.76°C (100spl). However, while both the station and MXD data bounce back to positive temperatures at T+3, the TRW chronologies indicate below average temperatures up to T+6. This latter feature is evident in all three, differently detrended TRW chronologies.

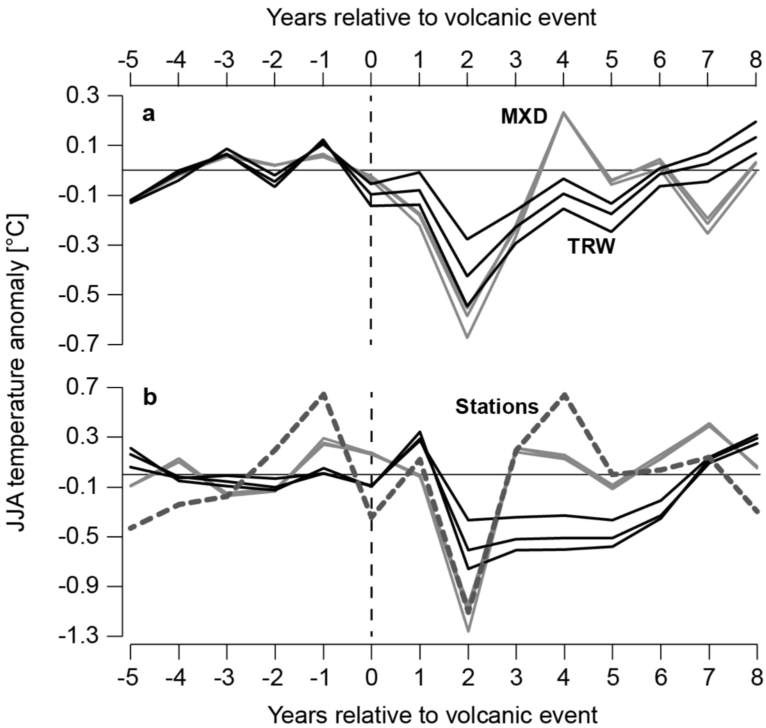

*Figure 5: SEA of the TRW, MXD, and long instrumental station data. **a**, Summer temperature estimates derived from differently detrended TRW (black) and MXD (grey) chronologies during five years prior and eight years after 37 annually dated VEI ≥ 5 volcanic eruptions since AD 1250 in the Northern Hemisphere and Tropics. For a complete list of volcanic events, see Esper et al. (2013b). **b**, Same as in **a**, but for the 10 volcanic eruptions coinciding with a > -0.5°C summer temperature drop at year T+2 in the Stockholm/Uppsala station record since AD 1756. Station data results are shown with a dashed curve.*

Discussion

Studying the effects of large volcanic eruptions on regional climate is a key objective in dendroclimatology. The development of long, tree-ring based temperature reconstructions enables aligning greater numbers of volcanic events from periods prior to large-scale temperature

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observations, and thereby reducing uncertainties in post-volcanic cooling estimates (Briffa et al. 1998, Cook et al. 2013, D'Arrigo et al. 2013, Esper et al. 2013a). The analysis of temporal persistence in northern Fennoscandian *Pinus sylvestris* chronologies presented here, revealed substantially larger autocorrelations (up to 0.77 at lag-1) and prolonged post-volcanic cooling (up to 6 years) in TRW data, compared to MXD. The pine MXD chronologies match the autocorrelation structure and post-volcanic cooling pattern retained in the instrumental temperatures recorded since 1756 in southern Sweden. Both the MXD and instrumental data revealed post-volcanic cooling persisted over 2-3 years following large, stratosphere-injecting eruptions. The TRW chronologies, on the other hand, indicated this post-volcanic cooling lasted for another 3-4 years, a finding that is rather related to biological memory effects than actual cooling.

Needle longevity (~ 3-7 years in case of the northern Fennoscandia pines), and storage of starch and protein in parenchyma cells, from previous-year vegetation periods, are likely the key drivers of the increased persistence inherent to the TRW chronologies. Yet the post-volcanic cooling estimates derived from MXD appear to be unaffected by these biological constraints, supporting suggestions to consider this tree-ring parameter for studying the impact of large eruptions on the climate system (Anchukaitis et al. 2012, Briffa et al. 1998, D'Arrigo et al. 2013, Esper et al. 2013b). These findings are in line with evidence from the European Alps indicating a prolonged cooling (by ~ 6 years) in regional TRW data of four conifer species following the VEI 7 Tambora eruption in 1815 (Frank et al. 2007a). Alpine MXD and instrumental temperature data again indicated that the post-Tambora cooling lasted only 1 year.

The Fennoscandian *Pinus sylvestris* TRW data contain a weaker climate signal, compared to MXD, though still pick up post-volcanic cooling centered at T+2 as revealed in both the instrumental and MXD timeseries. The increased memory in TRW chronologies has been considered in some paleoclimatic reconstructions by adjusting the proxy persistence and matching the memory inherent to target instrumental data (e.g., Cook et al. 2002). Among the pine TRW chronologies studied here, we found greatest autocorrelations in the RCS detrended data, compared to the NegExp and 100spl detrendings. The increased memory in the RCS TRW chronology is likely related to the composite detrending approach, in which each measurement series is compared with the mean of all series (Esper et al. 2003). Interestingly, this increased persistence is not translating into an extended post-volcanic cooling, which is most prolonged (up to 6 years) in the 100spl detrended, rather than the RCS detrended, TRW chronology. Explanation of this feature requires further tests including different detrendings applied to MXD and TRW data as well as consideration of additional sites and species.

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Hydroclimatic variability of the Tibetan Plateau during the past millennium

J. Wernicke[1], P. Hochreuther[1], J. Grießinger[1], H. Zhu[2], L. Wang[3] & A. Bräuning[1]

[1]*Institute of Geography, Friedrich-Alexander University Erlangen-Nuremberg, Germany*
[2]*Institute for Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China*
[3]*Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China*
E-mail: jakob.wernicke@fau.de

Introduction

The water availability in one of the most populated regions of the world is directly (river discharge) and indirectly (melt water discharge) dependent on time and duration of Summer Monsoon driven water supply (Vuille et al. 2005). Contrary to its importance, relatively few hydroclimatic studies have been conducted on the Tibetan Plateau (TP), especially on the eastern TP.
Numerous authors demonstrated the potential of stable oxygen isotopes in tree-rings for the reconstruction of moisture properties (McCarroll et al. 2004, Roden et al. 2000, Saurer et al. 1997). On the TP reliable climate reconstructions, based on stable isotope chronologies of tree-ring cellulose, have been conducted during the last decade. The results reveal a heterogeneous picture of moist and dry phases on the TP over the past millennium. Grießinger et al. (2011) detected for the central part of the TP highest amounts of August precipitation during the Little Ice Age (LIA) and lowest sums during the termination of the Medieval Warm Period (MWP). Similar moisture patterns were confirmed for the southern Himalayas (Sano et al. 2011, Sano et al. 2013). Reconstructions for the southeastern TP were focused on cloud cover but show a similar moisture decline trend (Liu et al. 2013). A robust, stable oxygen isotope based, precipitation reconstruction for the western margins of the TP demonstrated an opposite moisture trend during several periods of the past 1000 years (Treydte et al. 2006). Although their results capture a clear westerly signal, tree-ring width based moisture reconstructions for the northeastern TP show similar fluctuations (Yang et al. 2013).
However, apart from a relatively short summer moisture sensitive time series (An et al. 2014), only little is known about the palaeohydroclimate in the transition zone of the East Asian (EAM) and the Indian Summer Monsoon (ISM), at the eastern TP (Morrill et al. 2006). Furthermore, only review studies with focus on the most recent hydrological change of the TP were conducted so far (Yang et al. 2014, Yao et al. 2013). We therefore established a 800-year long stable oxygen isotope chronology derived from tree-ring cellulose, calibrated the results with recent climate data and achieved a reliable reconstruction of relative humidity during the summer season. Additionally, we present a review of important long term hydroclimatic studies over the entire TP.

Material and Methods

Study site

The study site –Lhamcoka- is located on the eastern TP (see Figure 1). Increment cores of 16 living *Juniperus tibetcia* trees (two per tree) were collected during a field campaign in 1996. The samples were taken from a steep slope with southern exposition in an elevation of 4350m a.s.l. (39°49'N/99°06'E). The chronology spans from 1193-1996 AD (804 years). Due to the slope steepness (slope angle more than 30°) and well drained substrate properties, we suppose negligible influence of groundwater uptake by the root system. The climate is characterized by maxima of temperature and precipitation during the summer season, which categorizes the Monsoon climate type. The study site is located 50km east of climate station Derge (see Fig. 1).

We applied our proxy/climate calibration model with the meteorological record from that climate station.

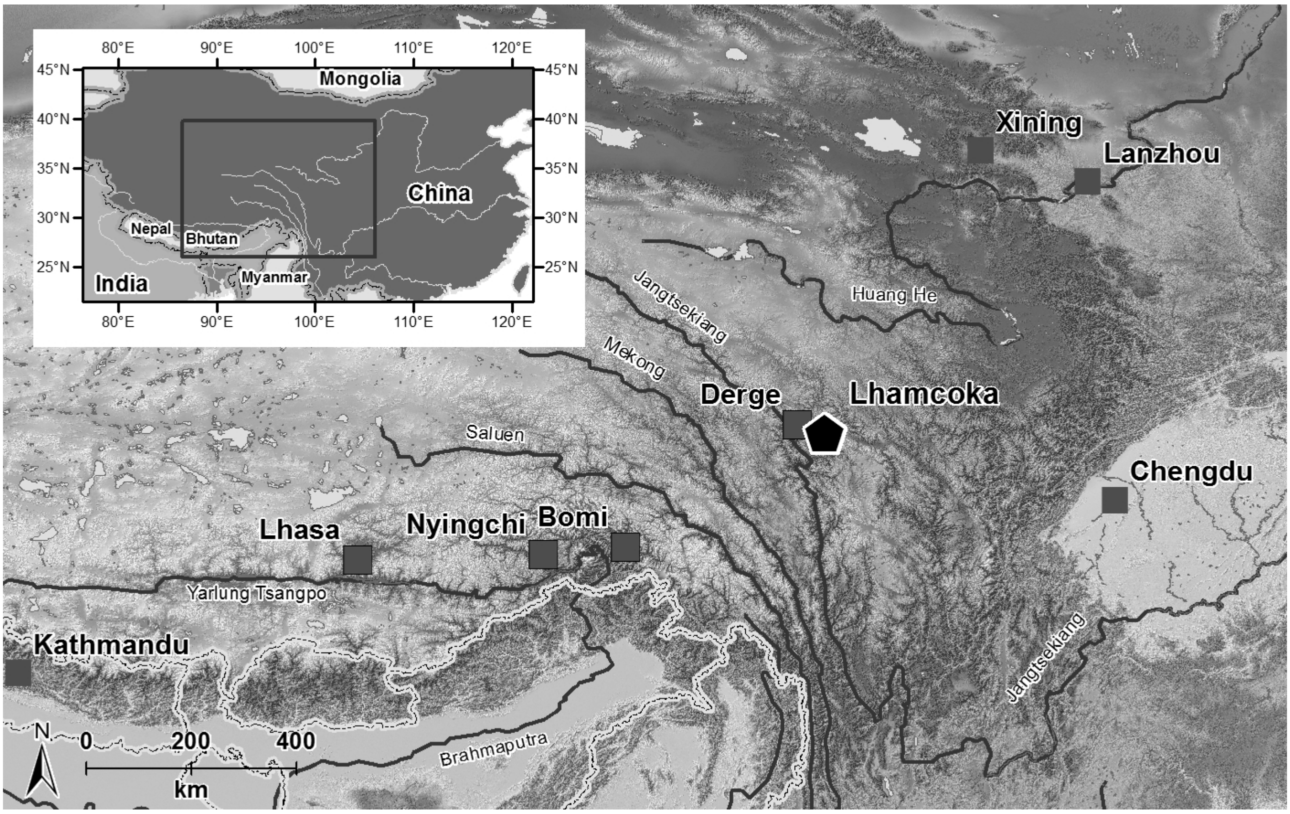

Figure 1: Location of the study site (pentagon) and location of cities with climate stations (rectangles).

Sample preparation and stable oxygen isotopes in tree-ring cellulose

We chose five cores of different trees according to (i) maximum age, (ii) high inter-tree ring-width correlation and (iii) the avoidance of growth asymmetries due to slope processes. We used the tree-ring width master chronology of Bräuning (2006) in order to date each annual ring precisely. Single years were cut with a razorblade under a microscope. We applied the shifted block pooling method to obtain sufficient amounts of material at sections with extremely narrow rings (Böttger et al. 2009). The samples were chemically treated according to the procedure presented in Wieloch et al. (2011). After freeze drying, α-cellulose was homogenised with an ultrasonic unit in order to achieve completely mixed ring-width cellulose (Laumer et al. 2009).

The ratio of $^{18}O/^{16}O$ is a representation of the abundance of light isotopes relative to heavy isotopes. The enrichment of heavy isotopes, in comparison to soil water, evoked by gas exchange on leaf level, is controlled by the opening width of the stomata (no fractionation during the water uptake of the root system). Due to the water vapour deficit, which is related to relative humidity and temperature, a shift towards higher/lower ratios has been observed. In reality, the fractionation process is more complex and includes the Péclet effect, and the fraction during the sugar transport within the vascular bundles and cellulose formation (Sternberg 2009). For the purpose of this study the knowledge of basic mechanism is sufficient. Hence, we expect a negative relationship of high/low $\delta^{18}O$ ratios with a low/high water vapour deficit and thus low/high relative air humidity.

Results and Discussion

Our $\delta^{18}O$ chronology is characterized by a mean value of 21.27‰ and global minima/maxima of 18.24‰/24.83‰, respectively (see Fig. 2). The global EPS is 0.88 and among the single radii we determined a highly significant GLK of 0.57 (*p < 0.01*). Thus, we found a strong common signal within the five individual trees. At "plateaus" (parts with extremely narrow rings, ring width < 0.2mm) we applied shifted block pooling. Therefore the presented chronology is smoothed by a five years running mean. As illustrated in Figure 2 the chronology oscillates around the mean value and shows an abrupt increase towards heavier isotope ratios since approximately the 1870s. Lowest $\delta^{18}O$ values were found in the early part of the chronology, while we achieved generally heavier ratios since the 19th century.

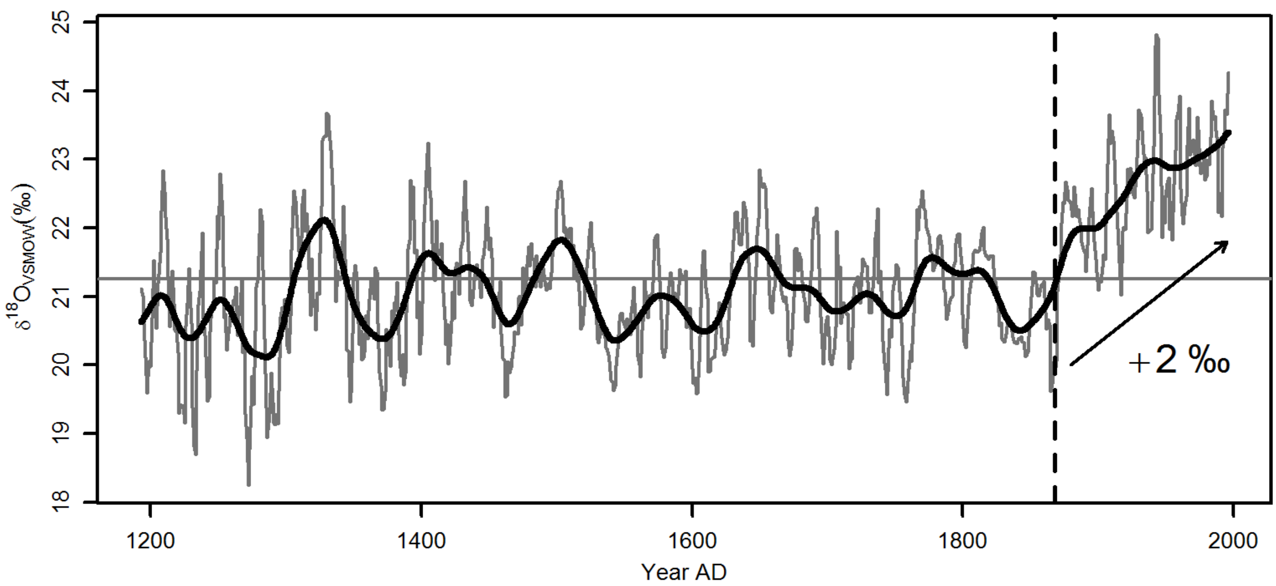

Figure 2: Lhamcoka tree-ring $\delta^{18}O$ chronology comprised of five individual trees, spanning the period 1193-1996 AD (804 years). Black bold line represents a 50 years smoothing spline. Dotted vertical line emphasis the turning point towards heavier isotope ratios ~1870 AD.

During the calibration period (1956-1996 AD), we revealed highest negative correlations with relative humidity in July (r = -0.73, p < 0.01) and August (-0.65, p < 0.01) but also with precipitation in July (see Tab. 1). Although highest correlations were obtained with single months, the reconstruction was established for the summer season, as the mean relative humidity of July and August.

*Table 1: Correlation coefficient (r) and explained variance (R²) between $\delta^{18}O$ chronology and different climate elements within the calibration period 1956-1996 AD. Abbreviations: J-July, A-August, JJ-June/July, JA-July/August.*** represents the 99.9% (p < 0.01) and ** the 99.5% (p < 0.05) significance level.*

	precipitation				relative humidity			
month	J	A	JA	JJ	J	A	JA	JJ
r	-0.58***	-0.20	-0.55***	-0.49***	-0.73***	-0.65***	-0.71***	-0.28**
R²	0.34	0.04	0.30	0.24	0.53	0.42	0.50	0.08

We employed a linear transfer model for the reconstruction of summer relative humidity over the past 800 years. The model was validated according to standard procedures (Cook et al. 1990, Cook et al. 1994). Due to the short calibration period of only 41 years we applied the leave-one-out validation method. We achieved a *Reduction of Error* (RE) and a *Coefficient of efficiency* (CE) of 0.45, respectively. The coefficients indicate that our reconstruction is better than the calibration period mean and that our transfer model is suitable for a reconstruction. The model is described as: RH_{JA}: -2.3*δ^{18}O + 125.3 (RH_{JA}, expressed in %) and accounts for the summer relative humidity at Lhamcoka (see Fig. 3).

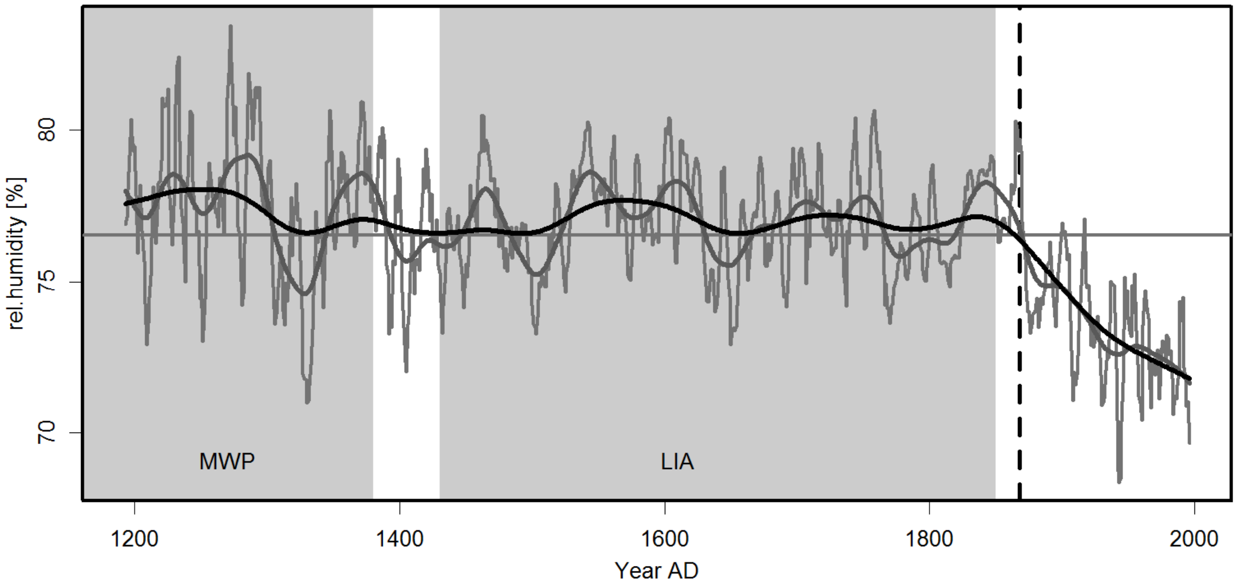

Figure 3: Reconstructed relative summer humidity (1193-1996 AD) at Lhamcoka. Dark grey and black solid lines represent 50 and 150 years smoothing spline, respectively. Black dotted line marks turning point toward drier conditions (~1870s). The Medieval Warm Period (MWP) and Little Ice Age (LIA) are emphasized by grey areas.

The reconstruction reveals moister conditions at the termination of the MWP, slightly oscillating relative humidity values around the long-term mean during the LIA and a remarkable decrease towards drier conditions since the 1870s. The driest summer was detected in 1943 (RH_{JA} = 68.4%) and the wettest summer in 1272 (RH_{JA} = 83.5%), respectively. Similar moisture conditions during the MWP were confirmed for Inner Asia and the northern TP (Pederson et al. 2014, Yang et al. 2013), but not for central Tibet (Grießinger et al. 2011). The moderate moisture variations during the LIA contrasts results from different parts of the TP (Grießinger et al. 2011, Shao et al. 2005, Yao et al. 2008). The abrupt moisture change since the 1870s is in good accordance to results from southeastern TP (Liu et al. 2014, Xu et al. 2012, Zhao et al. 2006).

We assign the abrupt moisture decline to the reduction of the thermal gradient between the tropical and north Indian Ocean (Xu et al. 2012). As a consequence, the land-ocean temperature difference is lowered and the northward motion of the Innertropical Convergence Zone is diminished. It is plausible that either strengthened solar activity or rising global mean temperatures induced the weakening of the monsoon circulation and thus cause drier conditions at Lhamcoka since the mid-19th century (Duan et al. 2000, Mann et al. 1999).

We assembled different moisture sensitive archives, to achieve a complete view on the moisture variability over the entire TP during the past millennium. Each combination of dark and light grey bars in figure 4 illustrates the change between considerable dry/wet conditions at the specific location. The joined moisture reconstructions (precipitation (liquid and solid), relative humidity, cloud cover or Palmer severity drought index) are specified by author and archive type (see Fig. 4). The graphic clearly illustrates opposite moisture patterns between the humidity reconstructions on the northern and southern (southeastern) TP. Especially the mid-19th century moisture decline on the southeastern TP is accompanied by a moisture increase on the northern and western TP. Moreover, the southern drying is more pronounced in greater distance to the Bay of Bengal than close to that major source of summer precipitation (Sano et al. 2013). We may address that finding to a decreasing monsoonal influence and an increasing effect of the westerlies affecting the northern/western parts of the TP. Additionally, the transition towards dry/moist conditions is phase

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shifted. The more western located reconstructions are prone to be earlier affected by wetter/drier conditions than the more eastern located study sites.

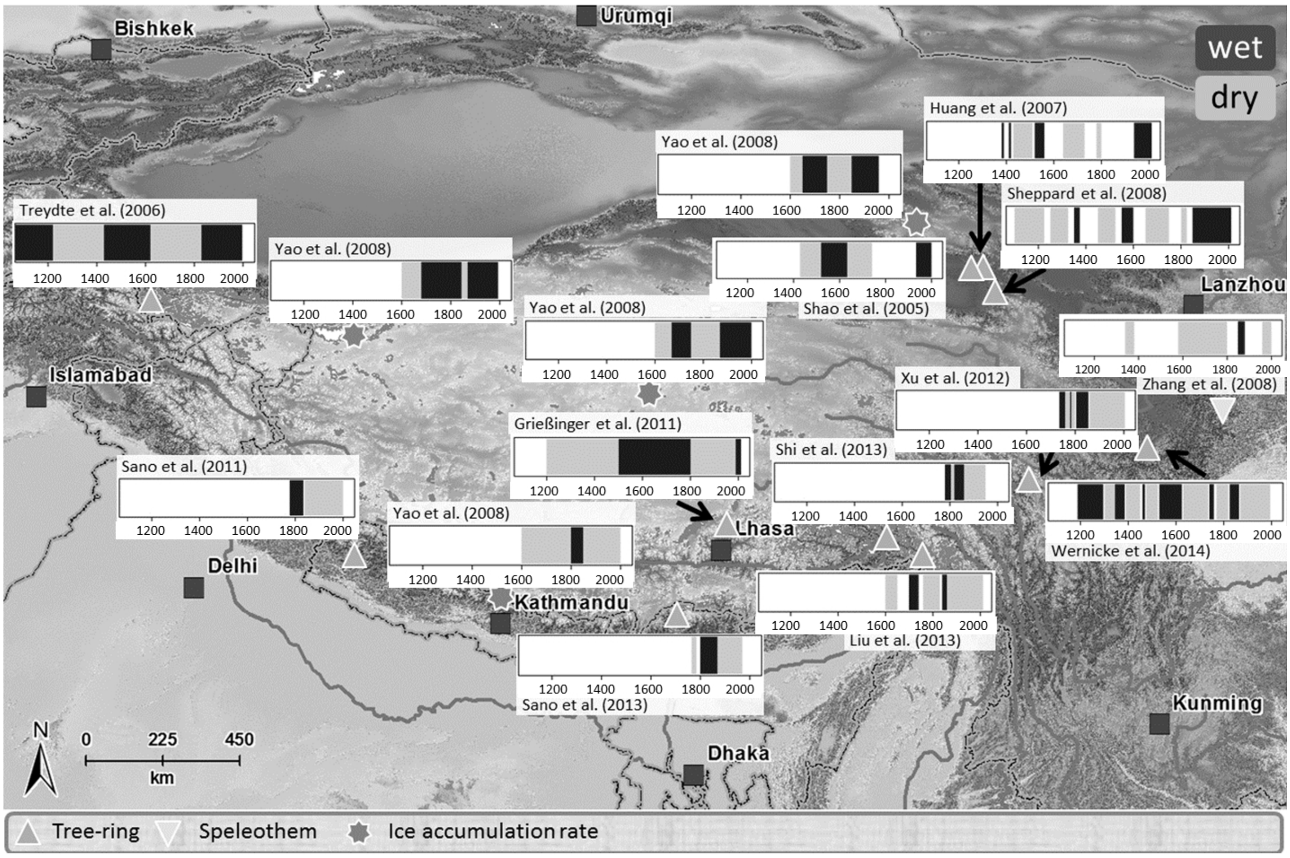

Figure 4: Summary map of humidity reconstructions from several archives on the TP. Dark grey bars representing wet, light grey dry conditions, respectively. For details and explanations please see text.

Conclusions

We presented and discussed a new 800-year long, well replicated $\delta^{18}O$ chronology from the eastern TP. The chronology is sensitive to relative humidity and is suitable for reconstructing summer relative humidity. We found that the termination of the MWP was the wettest period of the entire record, while the driest period occurred during the mid- 19th century. When comparing moisture reconstructions across the TP, clear opposing trends between the southern and northern TP were observed. Especially the mid-19th century moisture decline on the southern TP is simultaneously characterized by a moisture increase on the northern (western) TP. Moreover, we detected a phase shift in the hydroclimatic changes between western and eastern located study sites. However, the hydroclimatic history of the TP is still incomplete. Especially the descriptions of mechanistic processes behind the results are still fragmentary. Thus a strong need for further evidence and explanation attempts persists.

Acknowledgements

We thank the German Federal Ministry of Education and Research (BMBF) for the financial support of the project “Climate variability and landscape dynamics in Southeast-Tibet and the eastern Himalaya during the Late Holocene reconstructed from tree-rings, soils and climate modelling (CLASH)”. We also thank Roswitha Höfner-Stich for her efficient and precise work at the mass spectrometer.

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Tree rings of *Pinus cembra* L. in the Tatra Mts as a proxy of significant volcanic eruptions in the last 280 years

K. Janecka & R.J. Kaczka

Faculty of Earth Science, University of Silesia, Sosnowiec
E-mail: karolinaejanecka@gmail.com

Introduction

Stone pine *Pinus cembra* L. constitutes a good proxy of climate (Bednarz 1976, Oberhuber 2004) and due to its longevity (Carrer & Urbinati 2004, Popa 2009) as well as sensitivity to summer temperature, this species is frequently used in dendroclimatological research, especially for climate reconstruction (Rolland et al. 1998; Büntgen et al. 2007). Volcanic eruptions inject a huge quantity of gases and dust into the atmosphere. As a result they cause a decrease in the solar radiation reaching the Earth's surface and therefore they lower air temperature (Robock 2000). In the past, numerous large eruptions affected the climate of different places all over the world, for example: Huaynaputina (*Peru, 1600*), Tambora (*Indonesia, 1815*), Krakatu (*Indonesia, 1883*), Katmai (*Alaska, 1912*), Agung (*Indonesia, 1963*) and Pinatubo (*Philippines, 1991*) (Sigl et al. 2013). The information about the character of volcanic events, their size and impact on climate can be obtained from: a) direct observations and measurements, b) reconstruction based on historical records and c) volcanic deposits lodged in ice covers in Greenland and Antarctica (Gao 2008). Apart from these sources, tree rings are also considered a good tool for detecting volcanic events. In addition to classical dendrochronological analysis of tree ring width, pointer years and the anatomical anomalies of both earlywood - frost rings (La Marche et al. 1984) and latewood- pale/light/moon rings (Briffa et al. 1998; Esper et al. 2013) are often employed. The latter are characterized by a lighter colour of latewood, not entirely formed cell walls and an increase in cellulose and lignin (Tardif et al. 2011).

The aim of the study was to determine the changes of Stone pine growth in the Tatra Mts caused by four largest volcanic eruptions in the last 280 years. The strongest eruption occurred in the 19th century – Mount Tambora located on Sumbawa Island in Indonesia (8°14'S 117°57'E) (Fig. 1). It erupted in April 1815 and the effects of the eruption were observed for the next months and years throughout the world. Finally it brought about several years' cooling in the Northern Hemisphere among which the year 1816 was particularly cold and wet. Due to this, it was named 'the year without summer' (Stommel & Stommel 1983, Stothers 1984, Harington 1992, Briffa & Jones 1992, Bednarz & Trepińska 1992, Robock 1994, 2000). At the beginning of the 20th century, in June 1912 Novarupta (Katmai) volcano in Alaska (58° 3'N 155° 2'W) (Fig. 1) erupted causing untypical summer cooling in Central Europe (Esper et al. 2013), while winter warming in the Northern Hemisphere resulted from stratospheric volcanic clouds (Robock et al. 1992).

In January 1976 the Alaskan Augustin volcano (59°21'N 153°26'W) (Fig. 1) erupted causing less perceptible climatic changes in comparison to the above-mentioned eruptions, but injecting huge amounts of gases and ashes into the atmosphere. The strongest eruption in the last 30 years took place at the end of the 20th century - Mount Pinatubo located on the Island of Luzon on the Philippines (15° 08'N 120° 21'E) (Fig. 1) erupted in June 1991, making the 1991-1992 winter very cold in the Middle East and anomalously warm in North America and Eurasian mid-latitudes (Robock et al. 1992).

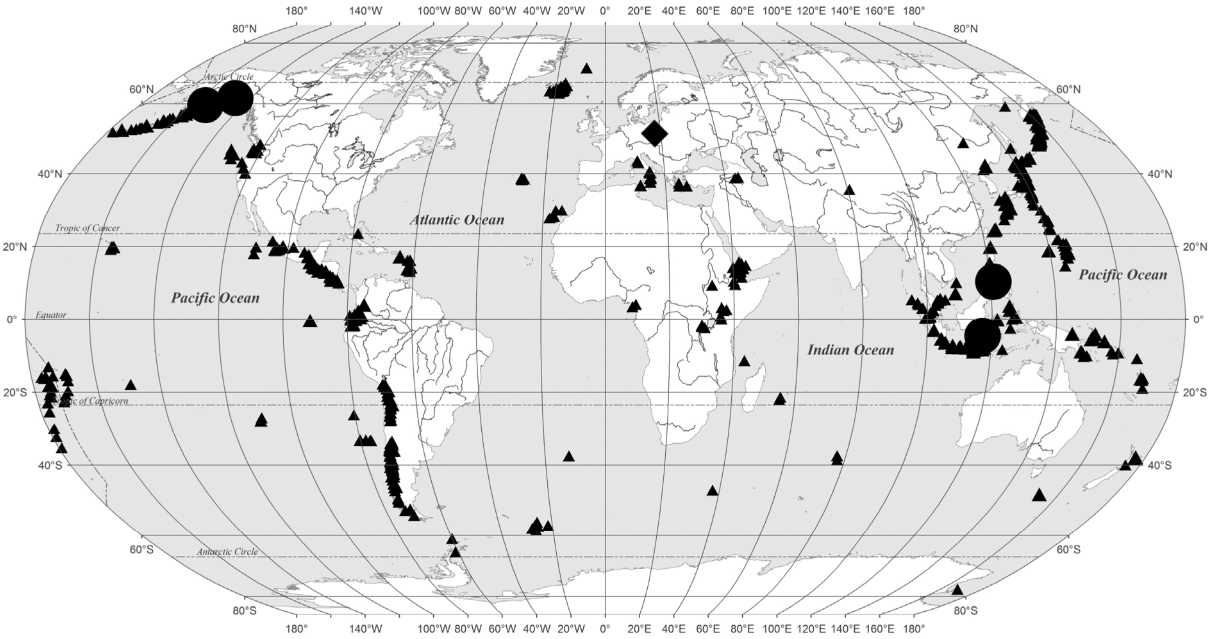

Figure 1: Location of 470 major volcanic eruptions which took place in the last 3 centuries (triangle), 4 studied eruptions (circle) and the studied site (rhomb).

Study area

The research was carried out in the upper part of the Rybi Potok Valley in the Tatra Mountains, Western Carpathians (Fig. 1) above the timberline which is composed of Norway spruce. The sampling site represents the natural habitat of Stone pine, at the elevation of about 1559 m a.s.l. on the slopes with western and eastern exposure. It belongs to the upper timberline ecotone (Guzik 2008) in which the growth of trees is determined by climate - mainly temperature (Bednarz 1982, Schweingruber 1996, Speer 2010). The studied region is characterized by typical mountain climate with altitudinal changes of temperature from 5 degrees Celsius at foothills to -0.6 degrees Celsius on the summit, precipitation from 1100 mm in Zakopane (855 m a.s.l.) to 1830 mm at Kasprowy Wierch (1986 m a.s.l.). It results in the development of a vertical vegetation zone which is similar to the one in the Alps but located at a lower altitude. Stone pine grows in the zone of the annual temperature fluctuating around +2 to +4 degrees Celsius and about 1570 mm sum of precipitation (Hess 1974). The studied area is built of the granite rocks covered with initial soils, mainly Haplic Regosols and Albic Podzols (Skiba 2002). Pinus cembra grows in Pino cembrae-Piceetum forest (Myczkowski & Lesiński 1974).

Materials and methods

The following proxies: tree ring width (TRW), pale rings and blue intensity (BI) were used in order to identify the influence of volcanic eruptions on the climate in the Polish Tatra Mountains. 352 trees were sampled with an increment borer. The collected samples were prepared applying standard dendrochronological techniques and scanned in a high image resolution (2400-4800 DPI). Tree ring width and blue intensity measurements were obtained with CooRecorder 7.7 software provided by Cybis Elektronik & Data AB (www.cybis.se). The quality and synchronicity of measurement series were determined on the basis of visual (CDendro software) and statistical (Cofecha software) analyses. Two chronologies were constructed with the use of ARSTAN software: tree ring width (TRW) and blue intensity (BI).

The study included the analyses of positive and negative pointer years calculated for TRW and BI time series. For this purpose the skeleton plotting method was applied (Cropper 1979), while positive and negative years were computed using Weiser software (Gonzalez 2001). In order to identify wood anomalies 51 samples were selected and used to create pale ring chronology. Each selected sample had to meet the proper age criterion (minimum 220 years). Moreover, the samples had to be free from rotten and reaction wood, otherwise it would prevent noticing the analysed anatomical features. Altogether 13 500 tree rings were visually examined with special attention paid to the anatomical features typical of pale ring (thin cell walls, small size and round shape of latewood cells) (Fig. 2.). The dendroclimatic analyses for the 1901 – 2009 period were based on CRU TS3.21 gridded data of temperature and precipitation (Harris et al. 2013). Furthermore, the climate data from two different climate stations were employed: i) from the nearest mountain station Zakopane in the foothils of the Tatras (49°17′N 20°57′E, 855 m a.s.l.), covers 1901-2000 period and ii) from the nearest mountain station with long records (1781-1981) – Hohenpeissenberg in the German Alps (47°48′N 11°00′E, 986 m a.s.l.).

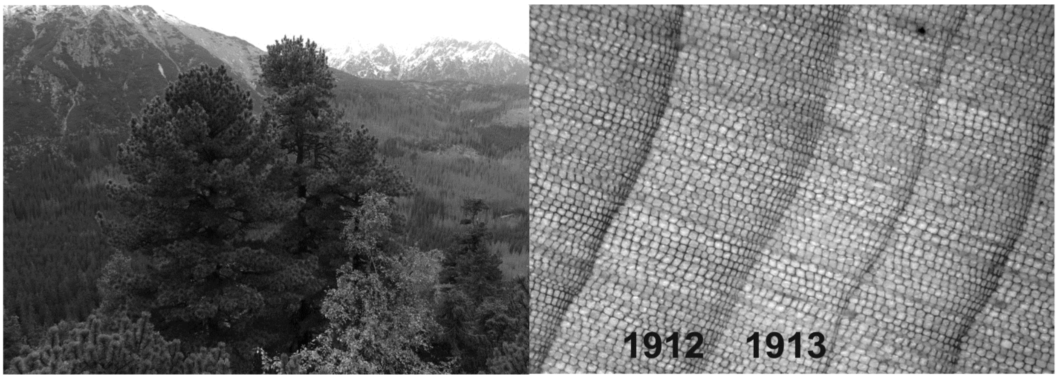

Figure 2: Pinus cembra L. in the Tatra Mts and pale rings in 1912 and 1913.

Results

TRW chronology covers the period from 1726 to 2013 and BI chronology from 1732 to 2013. The analyses show that the TRW residual chronology corresponds very well with the mean temperature for July (CC=0.44) and the June – July (CC=0.41), June – August (CC=0.38) periods. Precipitation has a negative influence on the growth (June – July CC=-0.34). The results of BI correlation with climatic series indicate that the most significant correlation coefficient values for temperature occur in July (CC=0.45), August (CC=0.48) and the June – August (CC=0.47) and April – September (CC=0.44) periods. The outcome of the analyses of precipitation/BI response is similar to the TRW results.

In the course of TRW chronology development 5 deep reductions are visible, 2 of which are connected with the considered eruptions. A reduction in growth for several years caused by the Tambora event in 1815 is the most distinguished. The growth reduction is related with the average summer temperature (June-August) decrease in the German Alps station. In 1815 the temperature lowered by about 1.4 degrees Celsius compared with the temperature for the 1781-1981 period (13.7 degrees Celsius) and reached 12.3 degrees Celsius. Nevertheless, the lowest temperature was recorded in 1816 and reached the value of 11.4 degrees Celsius (Fig. 3.).

A very severe reduction could be observed one year after Katmai eruption, which took place in 1912. A drop of the temperature was visible in both stations in 1912 and 1913. In the year of the eruption the temperature lowered by about 0.6 degrees Celsius in Zakopane and 0.9 degrees Celsius in Hohenpeissenberg. As a result the temperatures reached the values: in Zakopane 13.4 degrees Celsius in comparison to the average summer temperature for period 1901-2000 (14.03 degrees Celsius) and 12.8 degrees Celsius in the German station. Similarly to the Tambora event, the lowest temperature was recorded one year after Katmai eruption and reached 11.6 degrees Celsius in Zakopane and 11.8 in the German Alps (Fig. 3.) The growth reduction after two more

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studied eruptions, of Mt Augustine in 1976 and Mt Pinatubo in 1991 was not noticeable, as well as the temperature decrease (Fig. 3).

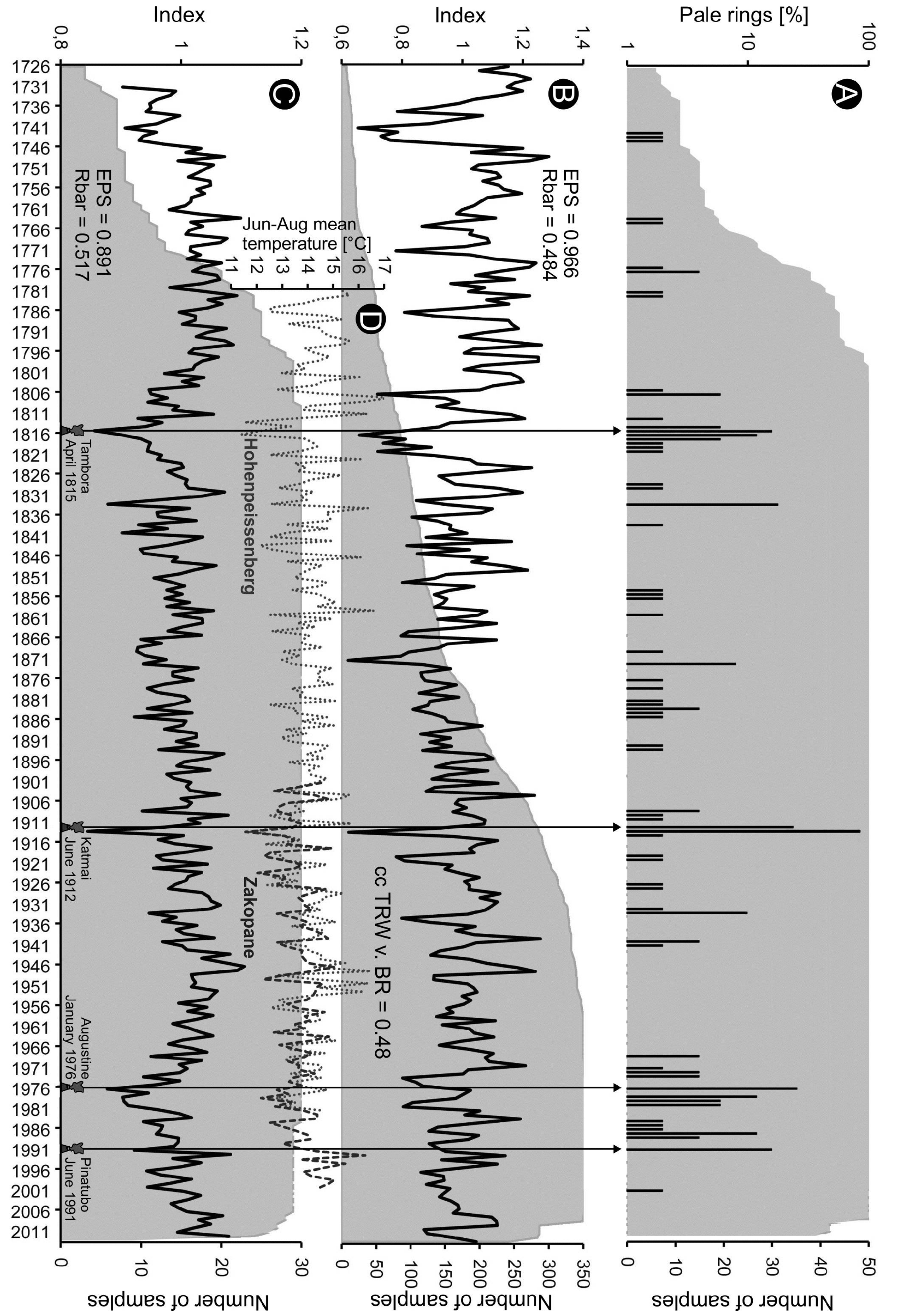

Figure 3: The synchronicity of four big eruptions with the occurrence of pale rings (A), tree ring width chronology (B), blue intensity chronology (C) and June-August mean temperature for Hohenpeissenberg in the German Alps and Zakopane in the south of Poland (D).

Further analyses show that the four volcanic events are recorded by reduced Blue Intensity. A one-year-long BI reduction is the most apparent one after the Katmai and Tambora events, however in case of Katmai the strongest signal occurs similarly to TRW, i.e. one year after the eruption (Fig. 3) It may be assumed that a one-year lag in the reaction of *Pinus cembra,* contrary to *Picea abies* L. Karst from a similar location in the Tatras (Kaczka & Czajka 2014) is typical only for this spices.
Based on these results, a typical year of a strong stratovolcanic eruption is characterised by a cold and wet vegetation period. It is confirmed by historical data, especially for the Tambora eruption, when 'the year without summer' was observed also in the Tatras (Bednarz & Trepińska 1992).
In the analysed samples the highest number of pale rings connected with the studied eruptions was identified for the following years: 1815 (15%) and 1816 (11%) - Tambora, 1912 (24%) and 1913 (84%) – Katmai, 1976 (25%) - Augustine and 1991 (16%) - Pinatubo (Fig. 3). The pale ring chronology for Norway spruce from the Tatra Mts shows that the volcano-climate-trees reaction was more instant for that species and occurred in 1912 (Biczyk & Kaczka 2014), which is similar to the BI chronology. Both eruptions from the end of the 20th century (Augustine and Pinatubo) were recorded also in the decreased blue reflectance values.
The analyses reveal 7 positive and 10 negative pointer years for TRW. Only the Katmai eruption is detected by a negative pointer year. The analyses of BI pointer years indicate 13 positive and 14 negative ones, 3 of which were connected with the following eruptions: Tambora, Katmai, Pinatubo.

Conclusions

As the Tatra Mountains are located far from any regions of volcanic activity, their climate is sensitive only to volcanic eruptions of global importance. For the analyzed events the summer temperature decreased by maximum 1-2 degrees Celsius.
Volcanic eruptions leave a rather distinct mark on Stone tree rings. However, the presence, strength, time and duration of volcanic signal vary depending on individual characteristics.
Wood density-related proxies are the best archive to preserve volcanic signals. For both proxies (blue reflectance and pale rings) the strongest signal was caused by the Katmai eruption (6.06.1912). This event was recorded in Stone pine in the form of a one-year lag.

Acknowledgements

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Exploring blue intensity - comparison of blue intensity and MXD data from Alpine spruce trees

A. Österreicher[1], G. Weber[1], M. Leuenberger[2] & K. Nicolussi[1]

[1]Institute of Geography, University of Innsbruck, Innsbruck, Austria
[2]Climate and Environmental Physics, University of Bern, Bern, Switzerland
E-mail: kurt.nicolussi@uibk.ac.at

Introduction

Blue intensity (BI) / blue reflectance has been recognised as a proxy to acquire wood density of conifers, but in an easier and cheaper way as with classical radiodensitometric analyses (McCaroll et al. 2002, Campbell et al 2007). As maximum density values (MXD) of tree-rings are strongly related to summer temperature, an easier approach facilitating the development of such records has a high potential for dendroclimatic studies (e.g. Trachsel et al 2012, Björklund et al 2013, 2014, Rydval et al 2012, Wilson et al 2014). However, BI is a relatively new proxy and its potential but also possible problems are not fully evaluated. The number of studies that directly compare BI and MXD data from the same trees are limited (e.g. Björklund et al 2013, 2014, Rydval et al 2014, Wilson et al 2014). Interestingly, most studies so far focussed on scots pine (*Pinus sylvestris*), whereas other species got less attention.

Here we compare BI with MXD data established on parallel cores from living spruce (*Picea abies*) trees in the eastern Alps. The MXD series have already been dendroclimatologically analysed (Esper et al 2007) and were used in palaeoclimatic studies (Battipaglia et al 2010, Trachsel et al 2012). We also evaluate an additional methodological approach to produce BI values, i.e. cutting and using microscope photography instead of the traditional sanding and scanning of wood samples.

Material and methods

Three cores from 21 living spruce trees were taken at two sites (Mauchele, Winterstallen) in two neighbouring valleys (Pitztal, Ötztal) of the eastern Alps at about 1900 m a.s.l.. Two cores were used for radiodensitometric analyses (Esper et al 2007), and the third core, samples parallel to one of the others, was used for BI analysis. These cores were first stored in pure acetone for 72 hours to remove resins (Rydval et al 2014). Then, an exactly planed surface was produced utilizing the WSL core microtome (Gärtner & Nievergelt 2010). To overcome possible shade effects in the open tracheids, their lumen were filled using white chalk (Rayher, Dustless Chalk White MPS-12W).

We applied microscope photography utilizing a Jenoptik ProgRes C5 camera to acquire images for the BI analysis. The resulting uneven illumination was corrected by the software ProgRes CapturePro 2.7. Exposure was controlled by making use of a classical Kodak grey card. The used magnification of 0.7 results in an image resolution of about 5000 dpi. The application of microscope photography instead of scanning leads to higher resolved images, which is an advantage especially with regard to often relatively small latewood sections of alpine tree rings. Comparisons with scanner images confirm the higher quality and resolution of the microscope images (not shown).

A series of images were created for each core with defined, but relatively small overlaps that are necessary for the following combination of the images. A colour card was also enclosed and photographed to control the following BI measurements. For the image production, the software i-Solution (Image & Microscope Technology) was used to combine the single images into one picture per sample. The BI data were established by utilizing a version of the software LignoVision (Rinn 2014) that allows the selection of the blue colour channel only. For comparison, we also applied the software CooRecorder (version 7.6) on some images. For the LignoVision-CooRecorder comparison, both maximum BI (MXBI) series were established as averages of repeated measurements on slightly different tracks to minimize possible data differences just due to somewhat diverging analysis tracks (Fig. 1). According to Björklund et al. (2014), δBI series were calculated by subtracting BI mean values of the earlywood (EWBI) from MXBI data. MXD and BI series from the same tree but of different length that occasionally resulted from slightly different tree-ring coverage of the different cores were shortened to the overlapping period. Chronologies for comparisons of the MXD and BI data were established by averaging the raw single series using the arithmetic mean, i.e. without applying any detrending. For this comparison, the MXD as well as the BI chronology was converted into z-scores (Fig. 3).

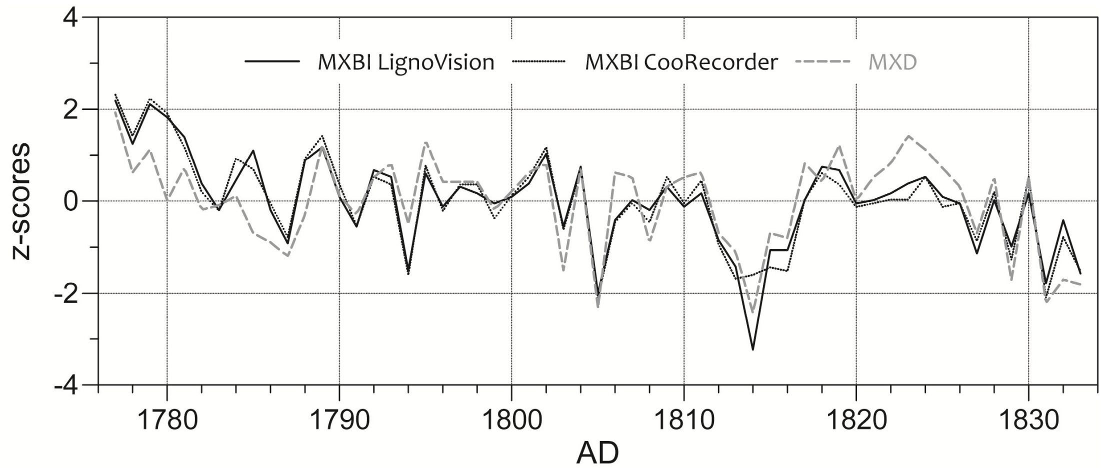

Figure 1. MXBI data measured with LignoVision and CooRecorder compared with MXD data of the same tree (mau-14). Note: The BI curve from CooRecorder is displayed with reversed y-axis.

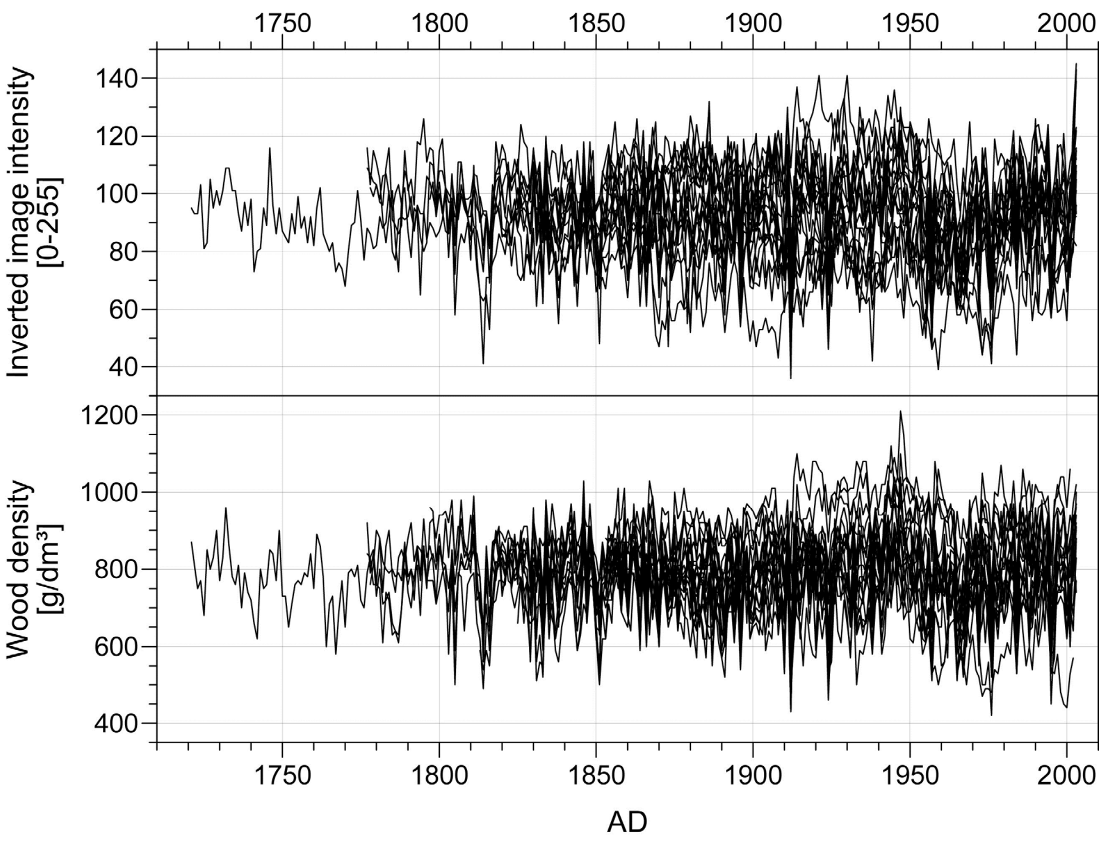

Figure 2. Raw data series of MXBI (above) and MXD (below) of all analysed spruce cores.

Results

Comparison of the BI data obtained using LignoVision and CooRecorder revealed no major differences. Figure 1 shows the results for the tree mau-14 for the time period around 1800 in comparison with the MXD series from the same tree. For a better comparison the series are given in z-scores. The raw data of the two MXBI series (not shown) are usually on different data levels, i.e. CooRecorder gives higher (after inversion) values than LignoVision, but the course of the series is nearly identical (Fig. 1). The largest deviation is recorded for the year 1814 when both the LignoVision-MXBI as well as the MXD series indicates a very low value. The MXD series shows higher deviations but this is to be expected because the core was not the same. However, the differences between the MXD and MXBI series could also partly be due to the differing analysis techniques.

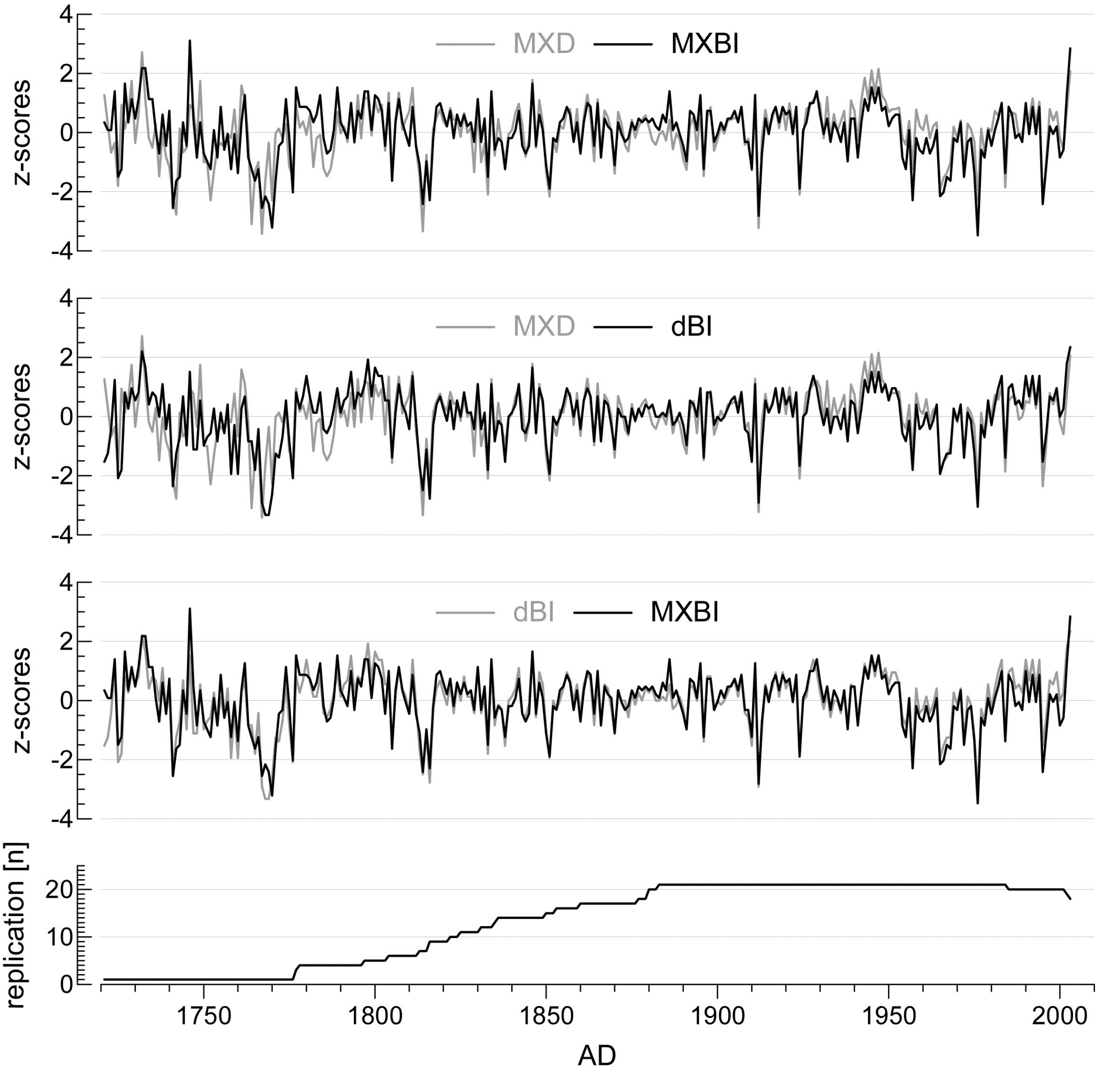

Figure 3. Comparison of MXD, MXBI and δBI chronologies established as average series of the raw single series (Fig. 2) and plotted in z-scores. The chronologies (1721-2003) are based on up to 21 single series.

The 21 BI and MXD series cover the period 1721 to 2007, a sample depth of more than 5 series is available from 1804 onwards (Fig. 2). The single series of both datasets show weak or even missing age related growth trends. Comparisons of the mean MXD series with the MXBI/δBI chronologies reveal high similarities even in the period 1721 to 1777, when just one tree is available (Fig. 3). This is underlined by correlation results of the raw data chronologies calculated for the period with a sample depth > 5: r=0.89 (MXBI-MXD) and 0.91 (δBI-MXD). The first differenced series correlate at 0.95 and 0.94, respectively.

A nearly linear correlation between MXD and δBI and especially MXBI data can be shown based on the data pairs of each tree and year (Fig. 4). Earlywood density (ED) and MXD data as well as BI data show nearly normal distributions (Fig. 5). EWBI and MXBI data show hardly any overlay and the shape of their data distribution are quite similar to the density data.

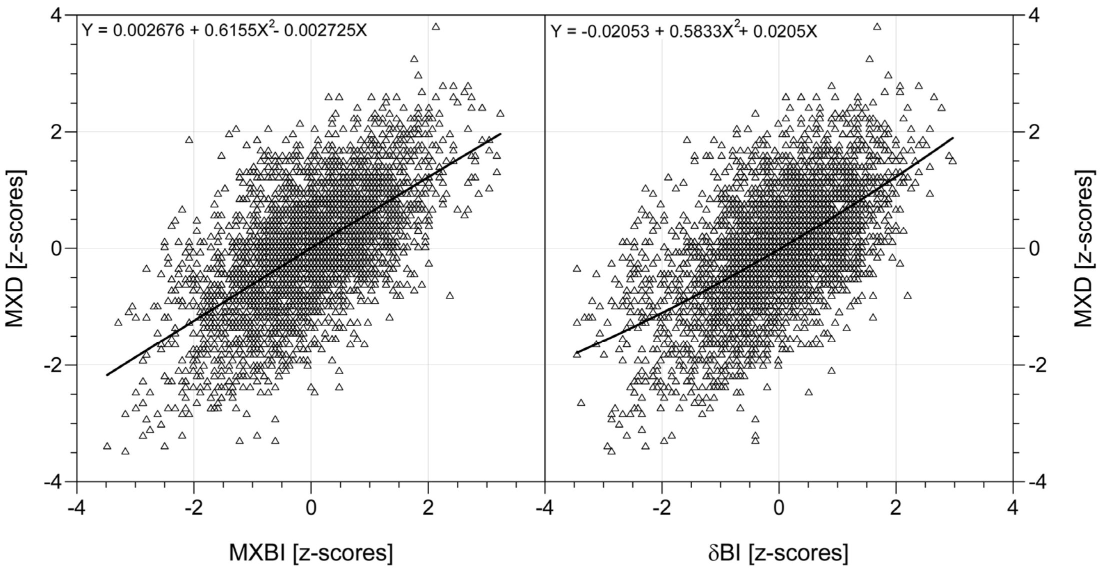

Figure 4. Regression diagram of MXD and MXBI (left) / δBI (right) values based on the data pairs of the single series (n=3731), with polynomial trend lines (2nd order).

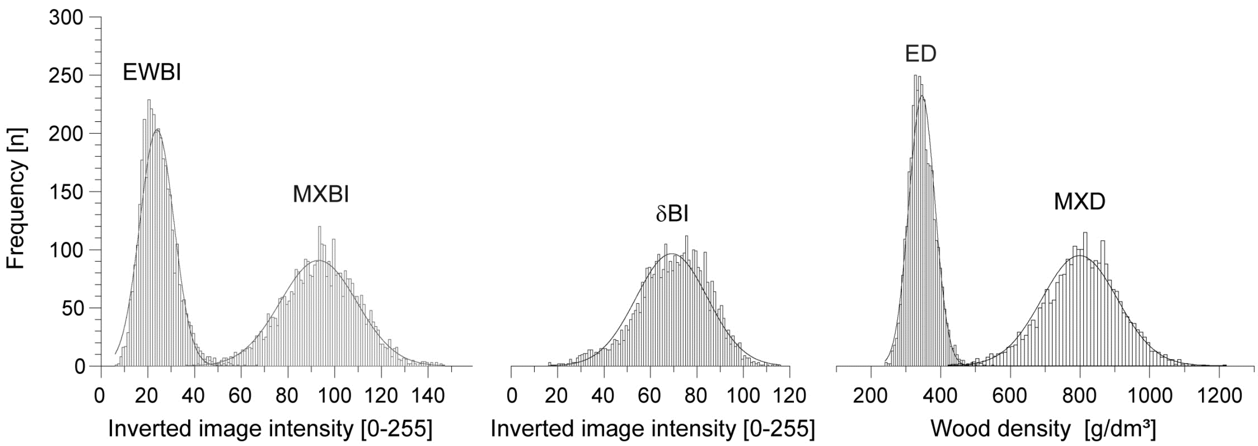

Figure 5. Frequency distribution of BI and density data with normal distribution curves. EWBI/ED and MXBI/MXD data show similar distribution shapes and even the differences between the EWBI and MXBI as well as the ED and MXD data, respectively, are comparable.

Discussion

A comparison of the software tools LignoVision and CooRecorder based on the same sample photos shows no significant differences in the variability of MXBI data. However, the absolute data levels differ substantially: CooRecorder produced higher values (after mirroring the data) than LignoVision. We selected LignoVision for our analyses because LignoVision produces simultaneously earlywood, latewood and total-ring width data as well as four BI values (minimum and maximum values for earlywood and latewood, respectively, as well as mean values for both) for each analysed tree-ring. The established EWBI data provide the base for the δBI calculations.

The chosen sample preparation procedure – cutting, usage of chalk and microscope photography, instead of sanding and scanning – is different to the protocol suggested by Campbell et al (2011), but performed satisfying results if the MXD data from the same trees are considered as a benchmark. Microscope photography has high potential especially in the analysis of narrow rings, which are typical for alpine trees, because the magnification can easily be adjusted. The usage of chalk leads to a clear differentiation of the EWBI from the corresponding MXBI values. However, the workload of our preparation and analysis procedure is somewhat higher than the approach applied so far. Cutting instead of sanding is admittedly faster, but the usage of microscope photography and the stitching of the images as well as the utilization of LignoVision instead of CooRecorder is more time consuming.

Data distributions of the BI data are quite similar to the corresponding radiodensitometric data (Fig. 5). This is a clear difference to the BI data distributions after sample preparation by sanding (Björklund et al 2014). Moreover, MXD data show largely linear relationships to the corresponding MXBI data. In contrast the δBI / MXD relationship seems not to be completely linear.

Comparisons of the MXD with the MXBI / δBI chronologies reveal high correlations. This was found despite MXD and BI data being measured from different cores. At least in the case of spruce samples from living trees, BI analyses seems to be able to replace classical radiodensitometric analyses. However, spruce does not have discoloration of the heartwood as other species do, e.g. scots pine. Further tests of the BI approach are necessary on more challenging species, e.g. larch (*Larix decidua*) or cembran pine (*Pinus cembra*), but also on discolorated wood like subfossil samples from peat bogs.

Conclusions

- Parallel cores of living spruce trees, for which MXD data were available, were used for BI analyses.
- A different preparation protocol (resin extraction, cutting of the wood, preparation with chalk, microscope photography) was applied.
- The established MXBI / δBI chronologies show high similarities with the corresponding MXD chronology.

Acknowledgements

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Spatiotemporal variations in the climatic response of *Larix decidua* from the Slovakian Tatra Mountains

O. Konter[1], K. Rosner[1], T. Kyncl[2], J. Esper[1] & U. Büntgen[3,4,5]

[1]*Department of Geography, Johannes Gutenberg University Mainz, Germany*
[2]*Moravian Dendro-Labor, Brno, Czech Republic*
[3]*Swiss Federal Research Institute WSL, Birmensdorf, Switzerland*
[4]*Oeschger Centre for Climate Change Research, Bern, Switzerland*
[5]*Global Change Research Centre AS CR, Brno, Czech Republic*
E-mail: o.konter@geo.uni-mainz.de

Introduction

Understanding past climate variability is crucial for the assessment of recent warming. Only a few millennium-long temperature reconstructions, mainly from Northern Scandinavia and the Alps, have so far been developed in Europe (Büntgen et al. 2011, Esper et al. 2012). For the Eastern part of the continent, dendroclimatological studies extending back into medieval times are, however, restricted to a single tree-ring width (TRW) record from historical timbers and living individuals of *Larix decidua* Mill. from the Slovakian Tatra Mountains (Büntgen et al. 2013). The Tatra comprises two sub-regions: In the High Tatra, trees grow under treeline conditions up to 1500 m asl in a subalpine environment, whereas the Low Tatra lacks alpine and treeline characteristics due to lower maximum elevations of 1100 m asl. A combined TRW dataset integrating samples from both sub-regions displayed a distinct May-June (MJ) summer temperature signal (Büntgen et al. 2013). Most of the historical timbers sampled in this region were, however, used in buildings in lower elevations. The provenance of this historical material could not clearly be identified, though it seems reasonable to assume that the timbers used in lower elevations originate from lower elevation forest sites. Changing climate-growth response patterns as a function of altitude are, however, a well-known feature in alpine settings (Hartl-Meier et al. 2014) and have also been reported for various species across the Tatra Mountains (Büntgen et al. 2007).

Here, we assess the variability of site-specific climate signals of *Larix decidua* Mill. as a function of altitude and time. TRW data from site in the High and Low Tatra were separately analyzed to obtain a better understanding of the underlying climatic controls of tree growth in different altitudes. Temporal robustness of the incorporated climate signals is also tested throughout the 20th century (1901-2009), while focusing on variations in the best-responding seasonal windows within the vegetation period.

Material and methods

Sampling sites and strategy

All TRW sampling sites were selected within the Slovakian Tatra Mountains (Fig. 1), the northwestern part of the Carpathian arc. Continental dry air and local insolation effects (i.e. high summer temperatures subject to exposure angle), in combination with advective humid air masses, predominantly following trajectories from the Atlantic, characterize the local climate. The Siberian High strongly impacts the cold and dry winter season, while summers are influenced by low-pressure cells which provide precipitation maxima in June (Niedzwiedz 1992, Büntgen et al. 2007).

A total of 181 cores were extracted from 69 living *Larix decidua* Mill. trees in November 2012, either around 1550m asl (Mlynicka Dolina: H12; 37 trees; 3 cores per tree) or 850m asl (Vernar: L12; 32 trees; 3 cores per tree) (Fig. 1). Samples were combined with material from nearby locations, previously published (H04, L08, L11) (Büntgen et al. 2007, Büntgen et al. 2009, Büntgen et al. 2013), to increase replication back in time and to extent until present, i.e. 2012. The newly developed chronologies thus span the 1657-2012 and 1634-2012 periods for the high- and low-elevation site, respectively, at a minimum replication of 5 cores per site.

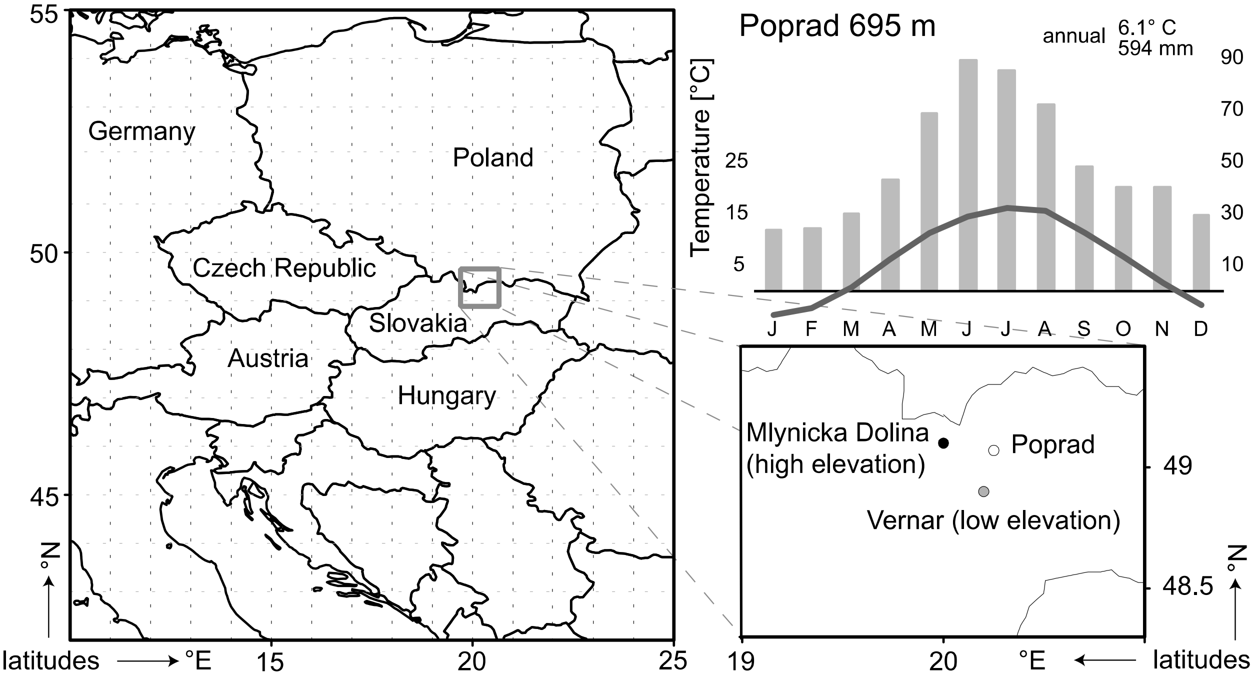

Figure 1: Map of the study region and climate diagram of the Poprad meteorological station (1951-2012). Grey curve is temperature, bars are precipitation.

Data treatment

TRW was measured and crossdated using commonly applied software, such as COFECHA (Holmes 1983) and ARSTAN (Cook 1985). The age trend was removed by detrending with two different methods to address varying frequency domains: 30-year cubic smoothing spline standardization (Cook & Peters 1981), and negative exponential standardization (Fritts 1976). Prior to detrending all TRW data were power-transformed (Cook & Peters 1997), and the resulting chronologies were variance stabilized (Osborne et al. 1997, Frank et al. 2007). All data were high-pass filtered by calculating residuals between the original data and its corresponding 10-year cubic smoothing splines to retain only high-frequency variations. Running correlations, rbar and EPS statistics are denoted with a 31-year moving window and 30-year overlap (Wigley et al. 1984).

Table 1: Site and chronology statistics (negative exponential standardization)

Code (altitude in m)	*Period*	*oldest/ youngest tree*	*MSL (years)*	*AGR (mm)*	*Number of cores*	*Series Inter-correlation*	*rbar*	*EPS*
L12 (850)	*1698-2012*	*374/ 29*	*202*	*0.54*	*81*	*0.712*	*0.50*	*0.95*
L11 (950)	*1883-2011*	*152/110*	*121*	*1.63*	*31*	*0.676*	*0.51*	*0.97*
L08 (800)	*1634-2008*	*402/45*	*173*	*0.47*	*36*	*0.658*	*0.51*	*0.93*
H12 (1550)	*1669-2012*	*383/177*	*231*	*0.61*	*100*	*0.764*	*0.59*	*0.97*
H04 (1450)	*1676-2004*	*342/19*	*165*	*0.56*	*64*	*0.719*	*0.58*	*0.96*
L (<1000)	*1634-2012*	*402/45*	*178*	*0.59*	*164*	*0.644*	*0.47*	*0.96*
H (>1400)	*1657-2012*	*383/19*	*205*	*0.56*	*148*	*0.746*	*0.57*	*0.98*

Meteorological data and calibration trials

Since instrumental temperature and precipitation station readings in the immediate surrounding of the sampling sites are scarce and do not extend prior to 1951, monthly temperature means, precipitation totals (CRU TS3.1; Harris et al. 2014), and drought indices (van der Schrier et al. 2006) were derived from gridded data (accessible via KNMI Climate Explorer: http://climexp.knmi.nl) of the two best-fit grid points (high elevation: 49°25N, 19°75E; low elevation: 48°N, 20°75E), covering the longer 1901-2009 period. The assessment of climate signals focused on calibrating the TRW chronologies against climate data over the 1901-2009, and two split periods (1901-1954 and 1955-2009). Degrees of freedom were adjusted considering the timeseries' autocorrelation in order to calculate reliable confidence limits (Konter et al. 2014).

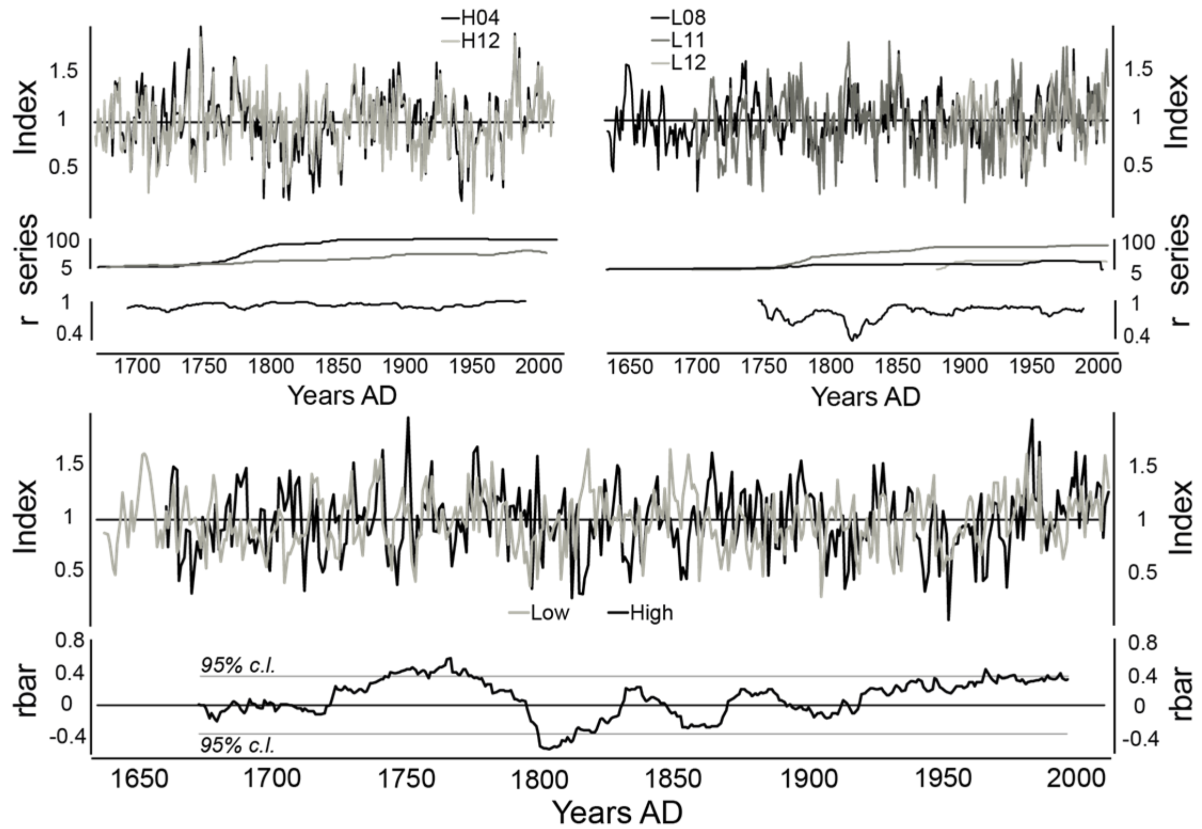

Figure 2:Tatra Mountain tree-ring chronologies (negative exponential detrending). Upper left: H04 and H12 high-elevation chronologies (top panel), number of TRW series (middle), and running correlations (bottom). L08, L11, and L12 low-elevation chronologies, number of TRW series, and running correlations. Bottom panels show the combined site-chronologies (low-elevation in grey and high-elevation in black) and running correlations (black) together with 95% confidence limits (grey). All running correlations calculated in a 31-year window with a 30-year overlap.

Results and Discussion

Intra- and inter-site coherence

Between-tree correlations and site chronology statistics exceed commonly accepted thresholds (Tab. 1; Fig. 2, upper panel). Correlation values between the two high-elevation chronologies ($r_{1698\text{-}2004}$=0.92, p<0.001) are clearly higher in comparison to the low-elevation sites ($r_{1698\text{-}2004}$=0.70, p<0.001), supporting the general assumption of more distinct climate-growth associations at higher elevations (Büntgen et al. 2007). Inter-site correlations display more ambiguous results ($r_{1657\text{-}2012}$=0.097): Running correlations between the two site chronologies oscillate from significantly positive (~1750 AD) to significantly negative (~1800 AD). 20th century running correlations are positive ($r_{1901\text{-}2012}$=0.25, p<0.05) due to synchronizing low-frequency trends in both chronologies

(Fig. 2, lower panel). A significant correlation is displayed after high-pass filtering the data ($r_{HP1657-2012}$=0.13, p<0.05). TRW data of both sites share variance in the high-frequency domain, but appear less synchronized in the lower frequency domain ($r_{LP1657-2012}$=0.04).

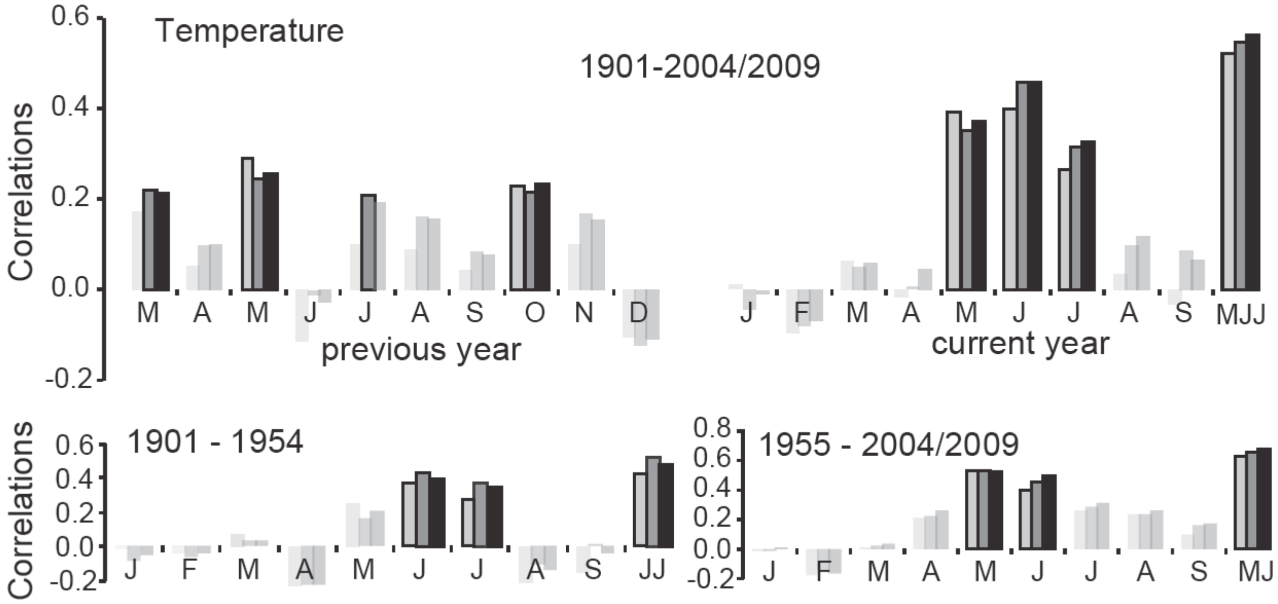

Figure 3: Climate-growth relationships of the high-elevation TRW data (negative exponential standardization). Monthly and seasonal correlations between TRW chronologies (single chronologies in grey scales, combined site-chronology in black) and temperatures. Significant correlations (p<0.05) framed in black.

Climate Signals

Tree growth at higher elevations is mainly controlled by variations in May-July (MJJ) summer temperatures (Fig 3), and non-significant relationships are found when calibrating TRW against precipitation data (not shown). The best seasonal response ($r_{1901-2009}$=0.56, p<0.001), however, varies over time, shifting from a June-July signal ($r_{1901-1954}$=0.48) to an early summer (May-June, $r_{1955-2009}$=0.68) signal.

Climate signals incorporated in TRW from low-elevations appear to be less distinct (Fig. 4). Correlations between temperatures and TRW reveal minor impact on tree growth. Only one of the low elevation chronologies displays significant values (p<0.05) for May (r_{H04}=0.20) and August temperatures (r_{H04}=-0.25). Calibration against precipitation totals reveals indistinct results. July precipitation shows significant positive results (r_L=0.23, p<0.05), while September is associated with significant negative values (r_L=-0.24, p<0.05). The analysis of the scPDSI, integrating temperature, precipitation, and soil information, provides a clearer pattern, though correlations remain overall quite low. The most distinct seasonal response is detectable for the March-July season (r_L=0.23, p<0.05). Additionally, previous year’s drought conditions impact current year’s growth to a greater extent than conditions of the actual year, exacerbating a clearer interpretation of this climate parameters control mechanism on tree growth.

Generally, correlation values reported from calibration trials using TRW from low-elevations are much lower with the highest values with July precipitation (r=0.23, p<0.05) and April scPDSI (r=0.23, p<0.05), complicating a clear interpretation of the results.

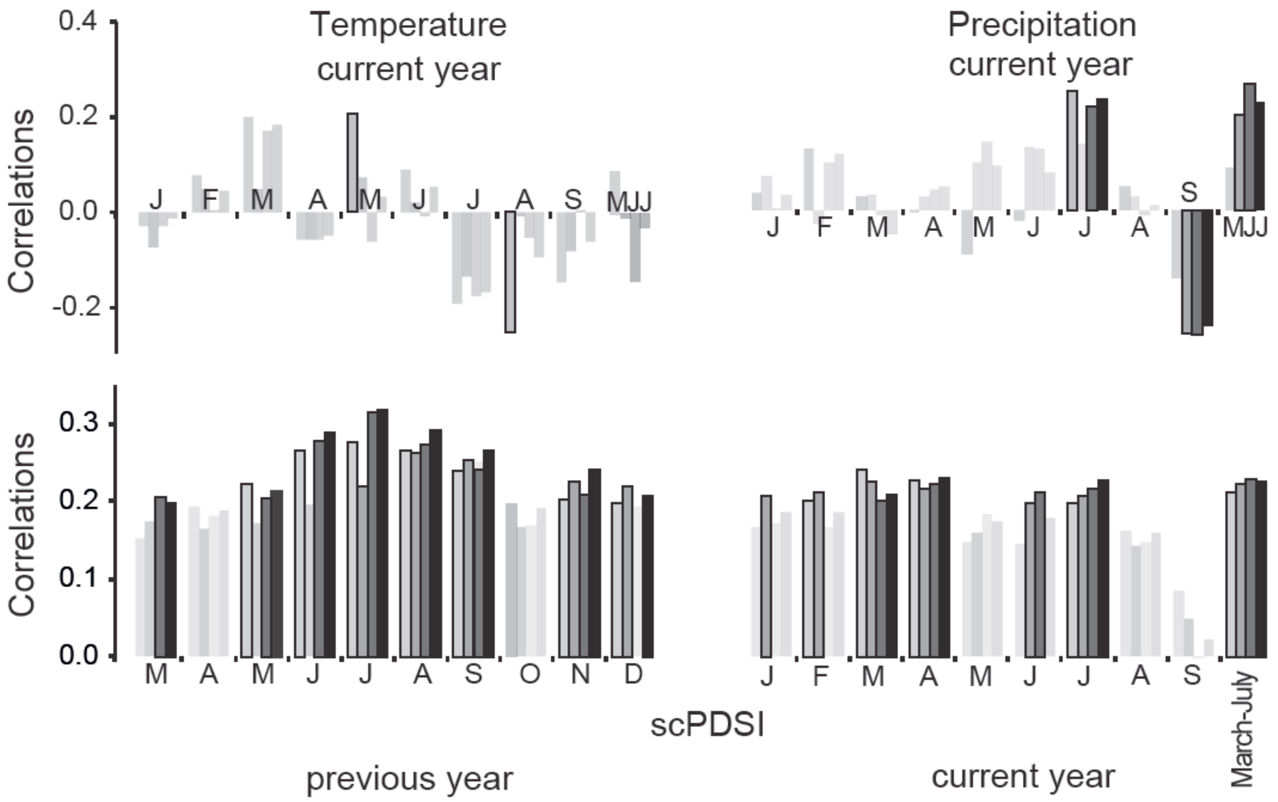

Figure 4: Climate-growth relationships of the low-elevation TRW data. Monthly and seasonal correlations between TRW chronologies (single chronologies in grey scales, combined site-chronology in black) and temperatures (upper left panel; TRW data: negative exponential standardization), precipitation (upper right; TRW data: 30-year cubic smoothing spline standardization), and scPDSI (lower; TRW data: negative exponential standardization). All significant correlations (p<0.05) in bright grey and black framed in black.

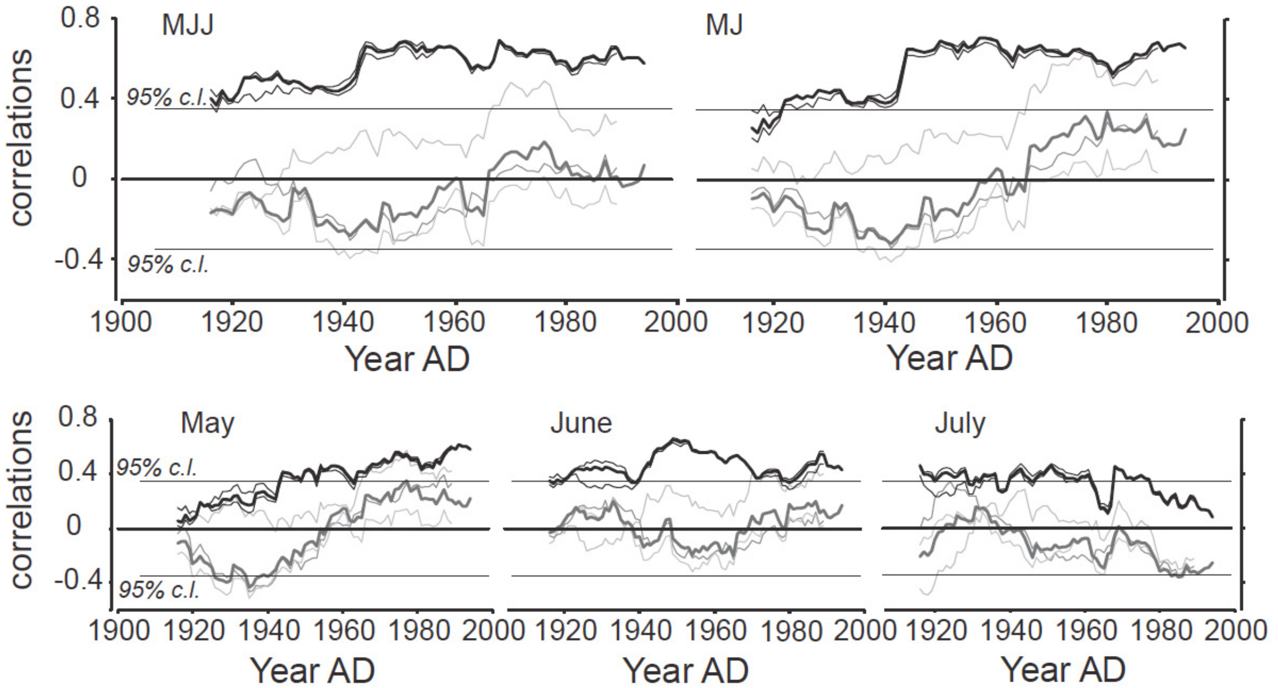

Figure 5: Temporal instability in the monthly temperature sensitivity of TRW chronologies from the Tatra. Black curves refer to the high elevation sites (bold in the combined data), grey curves denote the low elevation sites.

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Focusing on the temporal robustness of the MJJ temperature signal of the high-elevation TRW data, a shift towards earlier summer months excluding July can be observed in the most recent times (Fig. 5). In particular, temperatures in May tend to show increasing relevance for tree growth, since summer months, such as June and especially July, became hotter and simultaneously drier (Büntgen et al. 2010). The trees consequently shift their main growing season to earlier periods of the year, when water availability is guaranteed due to moderate temperatures with simultaneously occurring precipitation events and succeeding snow melt (Fig. 1; upper right panel).
Interestingly, this shift can also be seen in the running correlations of the low-elevation data, in particular for the MJ season and May: although no significant temperature response is traceable due to the overall mixed climate-growth relationship in this altitude, correlations change from negative to positive values in the 20^{th} century (Fig. 5). The increasing importance of early summer temperatures for tree growth in lower elevations could explain the synchronization of long-term trends in the chronologies from both sites within the 20^{th} century ($r_{LP1901\text{-}2012}$=0.45; Fig. 2).

Conclusions

Chronologies comprising historical timber and relict wood with samples from living trees to extend their length back to medieval or Roman times are ideally used in dendroclimatological studies (Büntgen et al. 2008, Büntgen et al. 2011, Esper et al. 2012, Büntgen et al. 2013). Key to this technique is the transfer of calibration results of the most recent period to the period covered by historical wood (Tegel et al. 2010). Separately analyzed, TRW data from high- and low-elevation sites, however, display diverging results in terms of climate-growth relationships. While high elevation tree growth is mainly controlled by summer temperature, tree growth at lower elevations is also affected by water availability, which is somewhat dependent on both, temperature and precipitation.
The transfer of the calibration results from living trees to historical timber remains challenging, since most of the ancient construction wood originate from buildings at lower elevations, thus, indicating a potential provenance from lower elevations. In addition to these spatial climate signal variations, the temporal robustness is subject to slight seasonal shifts from summer to early summer temperature signals in TRW data at both sites in the 20^{th} century. Summer conditions, especially in July, evolved to be characterized by more droughty conditions in the most recent years, particularly at the lower elevation sites.
These spatial and temporal climate signal variations in the Tatra Mountains aggravate the transfer of calibration results within the 20^{th} century to the pre-industrial period. Büntgen et al. (2013) used trees from high- and low-elevations to envelope the boundaries of natural occurrence of *Larix decidua* Mill. in the Slovakian Tatra Mountains for calibration purposes. This technique, however, possibly weaken the accuracy of the millennium-long reconstruction, because the provenance of the historical timber is not fully traceable. The sparseness of historical climatic data in this region though emphasizes the importance of such long-term reconstructions and demands further research to address the questions arising from this analysis.

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A question of time: extension of the Eastern Alpine Conifer Chronology back to 10 071 b2k

K. Nicolussi, G. Weber, G. Patzelt & A. Thurner

Institute of Geography, University of Innsbruck, Innsbruck, Austria
E-mail: kurt.nicolussi@uibk.ac.at

Introduction

The Eastern Alpine Conifer Chronology (EACC) was established from samples originating at treeline or treeline-near sites, i.e. ca. 2000 to 2400 m a.s.l., mainly in the eastern Alps (Nicolussi et al., 2009). The exploited sites are peat bogs, small lakes and glacier forefields where samples of the typical central-Alpine tree species stone pine (*Pinus cembra*), larch (*Larix decidua*) and occasionally also spruce (*Picea abies*) were collected. The EACC continuously spans the last ca. 9100 years up to the present day. The chronology has served as the basis to analyse the Holocene environmental history, i.e. glacier and treeline variability as well as snow avalanche activity in the Alps (e.g. Nicolussi et al. 2005, Nicolussi et al 2007, Joerin et al. 2008, Nicolussi and Schlüchter 2012) but also for dating of archaeological material (e.g. Pichler et al. 2009, Steiner et al. 2009, Stöllner et al. 2012). The tree-ring data itself were utilized for millennial to multi-millennial summer temperature reconstructions for central Europe (Büntgen et al. 2011, Nicolussi et al. 2013).
With a length of some 9000 years the EACC is one of the longest continuous chronologies worldwide. However, additional tree-ring data from sites with the same environmental settings that date from the earliest part of the Holocene have also been obtained. Two multi-centennial but only radiocarbon-dated chronologies that fall into the 10th and 11th millennium b2k were established using these early-Holocene data (Nicolussi et al. 2004).
Recently discovered and analysed samples from the Schlatenkees site in the Austrian Alps now allow closing the chronology gap around 9200 b2k and linking the more recent floating chronology with the calendar-dated EACC.

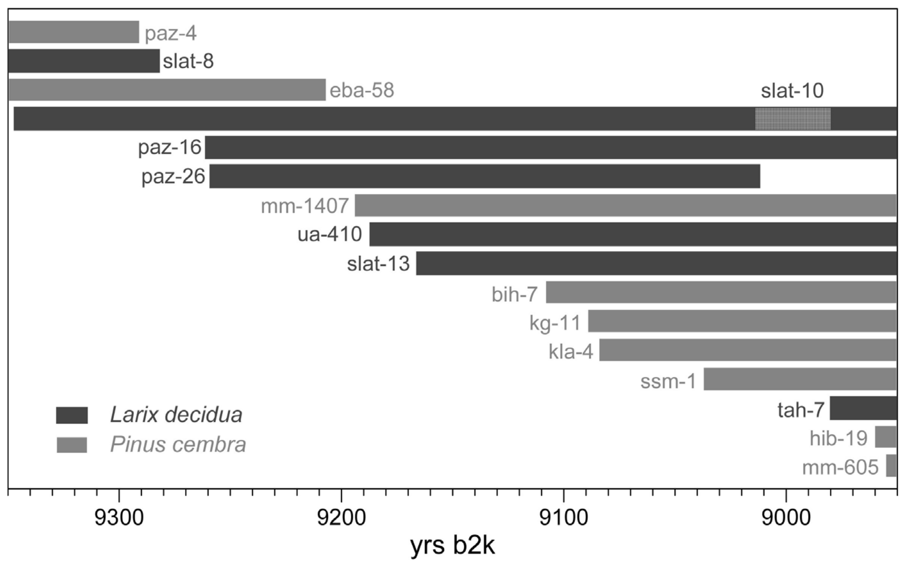

Figure 1. Coverage of tree-ring series around the former end of the EACC (9108 yrs b2k). The extension of the EACC is mainly based on samples from the site Schlatenkees but also on previously not calendar-dated samples.

Site, material and results

The Schlatenkees site (E 12°25'30'' N 47°6'50'') is located in the valley Innergschlöss just south of the main Alpine ridge at an altitude of 2160 m a.s.l. within the local timberline ecotone and near early-Holocene moraines of the Schlatenkees glacier. There are small lakes and peat bogs scattered over a north-facing slope. We collected several sections of logs preserved in these peat bogs.

The most important results were obtained from three larch samples (slat-8, slat-10 and slat-13) for which tree-ring measurement series of 355, 471 and 319 years in length were established. These larch tree-ring series could be crossdated both with the earliest part of the EACC and the end of the floating 10th millennium b2k chronology. Additional crossdating of other, formerly only floating, i.e. radiocarbon-dated, tree-ring series from different sites subsequently improved the sample depth around the chronology gap at ca. 9200 b2k (Fig. 1). However, there are only two tree-ring series that span the period around 9270 b2k. These two samples are from two different sites and of two species.

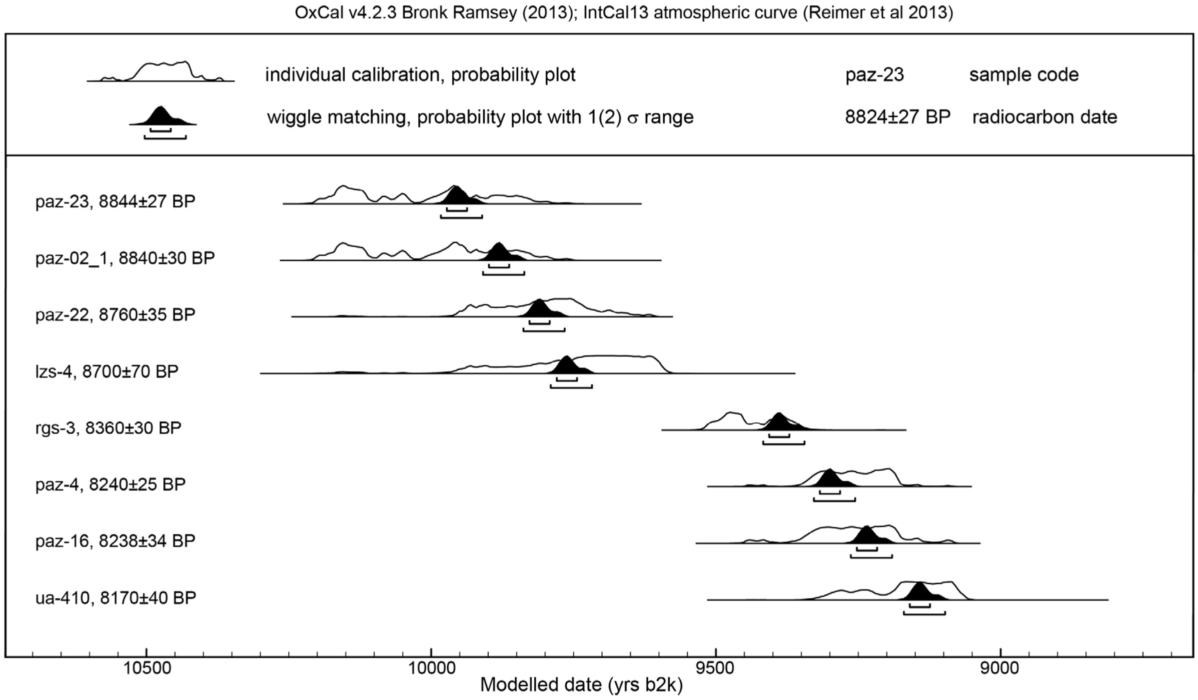

Figure 2. Wiggle matching of ^{14}C-dates from the 10th millennium b2k supports the correct extension of the EACC: the dendro-dates of the radiocarbon-dated samples fall into the 2 sigma wiggle matching range.

The tree-ring crossdating of the EACC is also backed by radiocarbon analysis. Wiggle matching was carried out with eight radiocarbon dates of initially not calendar-dated samples by using the D-Sequence procedure of OxCal 4.2.3 and the IntCal13 calibration curve (Bronk Ramsey 2001, Reimer et al. 2013). The material for radiocarbon dating was always taken with an assigned position at the tree-ring series. The obtained wiggle matching result supports the correct extension of the EACC: i.e., the calendar position of the 16 radiocarbon-dated tree-rings of the sample paz-23 is 9975-9960 b2k and the corresponding wiggle matching result gives 9973-9938 (68.2% probability) and 9984-9911 b2k (95.4% probability) (Fig. 2).

The bridging of the data gap around 9200 b2k enables to establish calendar dates for the tree-ring series of the former floating chronology from the 10th millennium b2k and with that the extension of the continuous EACC back to 10 071 b2k (8072 BC).

Discussion

With the new extension and by adding data from living trees, the EACC covers 10 085 years (8072 BC to AD 2013). The chronology is mainly based on two typical Alpine tree species, stone pine and larch (Fig. 3). Interestingly, the first millennium of the now extended EACC shows a distinct different tree-species composition related to the younger EACC section; it is dominated by larch samples (74%), whereas the following nine millennia are mainly covered by stone pine (81%). Tinner and Kaltenrieder (2005) also found a dominance of larch before 9600 BP at a treeline site in the Swiss Central Alps. These results suggest different (drier) climatic conditions during the Boreal in relation to the following millennia.

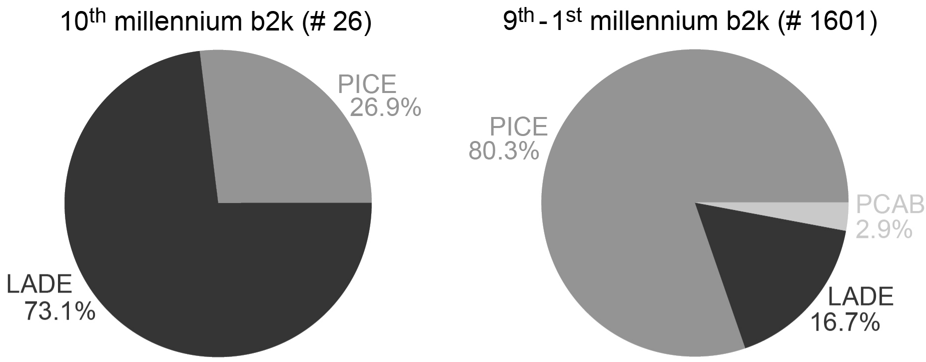

Figure 3. The first ca. 1000 years of the extended EACC show a distinct different tree-species composition related to the remaining EACC section: it is dominated by larch (Larix decidua, LADE) samples whereas the following nine millennia are mainly covered by stone pine (Pinus cembra, PICE).The number of spruce samples (Picea abies, PCAB) is limited, however, this is caused by the selection of the sampling sites.

Even if the EACC covers the last some 10 000 years continuously, the individual species comprising the full chronology still contain a few gaps: the stone-pine data has a small single gap around 9200 b2k, whereas the larch data possess three gaps, around 8150, 6350 and 5350 b2k. These species-related gaps correspond with periods of reduced sample depth of the EACC (Fig. 4) and are, moreover, known, as periods of disturbed and cooler climate. I.e., the larch data gap around 8150 b2k corresponds with the 8.2 ka event. The time periods around 9200 and 10 100 b2k - the latter period overlaps with the actual onset of the EACC - are also proven as periods of cooler climate in the Atlantic sector shown by Greenland ice-core data (Björck et al. 2001, Rasmussen et al. 2007).

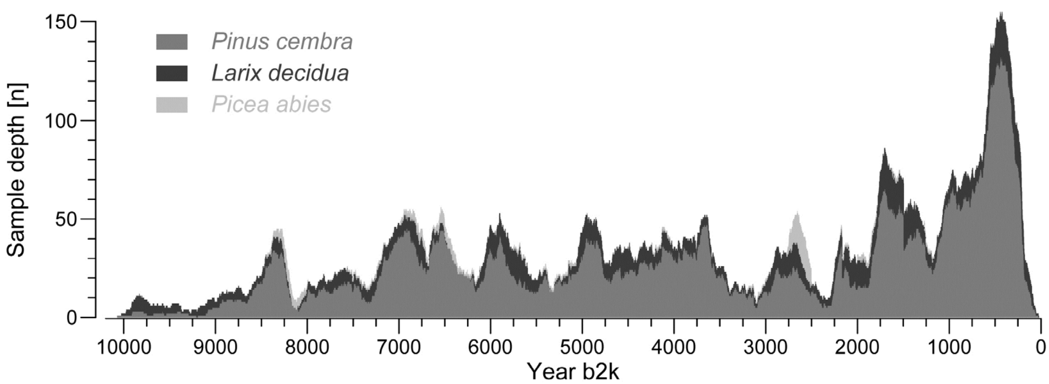

Figure 4. Sample-depth record of the continuous Eastern Alpine Conifer Chronology (EACC). The data (sample) distribution is a consequence of sampling strategy, sample access, climate variability and human impact on high Alpine landscape. The latter factor can be restricted to the last ca. 4000 years.

The synchronicity between sample depth minima / gaps and episodes of cool climate suggests that the ability to find tree remnants preserved at sites in the timberline ecotone of the Alps is related to climate conditions that determined the former tree distribution, i.e the position of the treeline but also the stand density in the timberline ecotone (Nicolussi et al. 2009).

Conclusions

Recently analysed and crossdated samples from the site Schlatenkees allows the closure a former tree-ring chronology gap around 9200 b2k and to extend the continuous Eastern Alpine Conifer Chronology back to 10 071 b2k (8072 BC). This will improve the framework of accurately dated results on past glacier and treeline variability in the Alps as well as enable extended climate reconstructions.

Acknowledgements

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SECTION 3

ECOLOGY

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Juniperus phoenicea growing on cliffs: dendrochronology and wiggle-matching applied to the oldest trees in France

C. Mathaux[1], J.-P. Mandin[2], J.-L. Edouard[3], T. Gauquelin[1] & F. Guibal[1].

[1]*Aix–Marseille Université – IMBE (Institut Méditerranéen de Biodiversité et d'Ecologie marine et terrestre) – UMR 7263 CNRS – 3, place Victor Hugo – 13331 Marseille Cedex 03, France*
[2]*Société botanique de l'Ardèche, Réserve Naturelle Nationale des Gorges de l'Ardèche, 2649 Route de St Paulet 30760 St Julien-de-Peyrolas*
[3]*Aix–Marseille Université – Centre Camille Jullian - UMR 6573 CNRS – 5, rue du château de l'Horloge – 13094 Aix-en-Provence Cedex 2, France*
E-mail: coralie.mathaux@imbe.fr

Introduction

Juniperus phoenicea L. (family *Cupressaceae*) is an arborescent shrub or small tree up to twelve meters tall and evergreen (Farjon 2005). Its geographic range extends from the Canary Islands and the Atlas mountains in Africa in the West, to Jordan and Saudi Arabia in the East (Dzialuk et al. 2011). It develops under Mediterranean climate and it is a heliophilous, xerophilous and thermophilous species (Rameau et al. 2008). It is a saxicline plant that it is found on rocky or skeletal soils in Mediterranean region (Garraud 2003). Two subspecies are identified, *Juniperus phoenicea* subsp. *turbinata* in populations of the coastal areas and *Juniperus phoenicea* subsp. *phoenicea* in all the other populations growing in hinterland landscapes up to 2500 m as on the slopes of the Atlas Mountains. It is a light-demanding tree resistant to dry climates and characterized by pioneer properties (Quézel & Pesson 1980, Quézel & Médail 2003).
In the French Mediterranean region, populations of this *Juniper* tree can also grow on vertical and exposed limestone cliffs. Larson et al. (1999, 2000) assigned to cliffs the property of supporting ancient, primary or virgin woodland. In such habitats, disturbances from humans are absent, due to inaccessibility. Trees also benefit of absence of fires, grazing and competition by more aggressive level-ground vegetation. On these cliffs, in the southeast of France, *Juniperus phoenicea* is adapted to extreme growing conditions where the main constraints are verticality and compact hard limestone constituting a strong mechanical stress on roots. Indeed it limits their growth and both nutrients and water supply in dry and warm conditions under Mediterranean climate. In addition to that, trees face sporadic rockfall.
Junipers which colonize these very harsh sites, respond to these constraints by a very low growth rate, partial cambium mortality and hydraulic sectoriality, and they can achieve exceptional lifespans. The longevity of these trees in such habitats offers tree-ring series which can be very long but, like many other species of *Cupressaceae*, uncertainty remains about the representativeness of a ring (Lemoine 1966, Couralet et al. 2005). *Junipers* are especially remarkable by their longevity and their abundance in the cliffs of the Ardèche valley (Fig. 1) where this study has been performed.

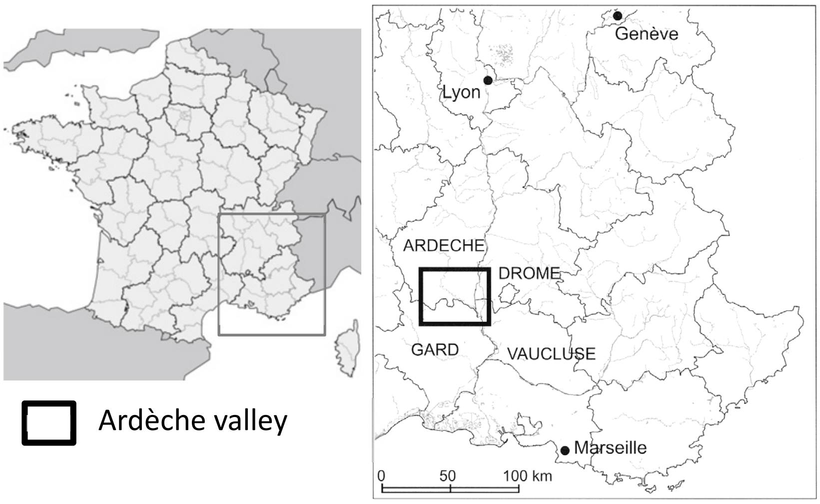

Figure 1: Location of the Ardèche valley (France). Courtesy by Christophe Gauchon

Materials and methods

Study site

We sampled about 150 dead juniper trees located on vertical cliffs in the protected nature reserve of the gorges of Ardèche (Southeast France). There, the river has carved a canyon 200 meters deep in a vast plateau of Urgonian limestone covered by coppices and garrigues dominated by holm oak (*Quercus ilex* L.).

Sampling material and analyses

On the cliffs, sampling of dead branches and dead trunks were made by using specific rock climbing equipment. Stem disks were collected using a hand-saw and sanded using a belt sander up to a 1200 grit band. Attempts to crossdate different radii of a single stem and different stems were carried out under a binocular microscope in order to provide an accurate determination of the age of the trees (Stokes & Smiley 1968, Fritts 1976). Then, radiocarbon dating was applied in two different ways. First, the pith area of six trees was dated. Second, the wiggle matching technique was applied on four disks having enough rings. Six to seven twelve-year segments of tree-rings were sampled on each of these disks; the relative position of these segments to one another on each slice was known from exact ring counts. Twelve-year segments were selected for wiggle-matching, because most of the samples include periods of extremely narrow rings with a limited amount of material to sample. We obtained a series of closely sequentially spaced ^{14}C dates. Calibration of the ^{14}C dates was done by means of the wiggle-matching technique which uses the non-linear relationship between the ^{14}C age and calendar age to match the shape of the ^{14}C calibration curve. The sequences of AMS dates for each sample were wiggle-matched using OxCal 4.2 (Bronk Ramsey et al. 2001, Bronk Ramsey 2009) and compared against the IntCal09 radiocarbon calibration curve (Reimer et al. 2009).

Results and discussion

Longevity and anatomical anomalies

As regards secondary growth, in spite of these harsh growing conditions, some trees can get very old*. Juniperus phoenicea* can reach ages exceeding 1500 years thus providing the longest tree-ring series for the Mediterranean area (Fig. 2). At such sites, trees are probably the oldest ones of the French Mediterranean region. The age is only known by counting growth layers. The accurate age remains unknown because we ignore the seasonality of a growth layer. Indeed, there are many anatomical anomalies. Both false and partially missing rings (=wedging rings) are visible under the microscope (Fig. 3a) to such an extent that uncertainty remains about the periodicity of ring formation thus making crossdating very difficult. In addition to that, as regards anatomical features, annual radial growth is very low (Mathaux et al. in prep), some areas are darkened by the presence of secondary metabolites in the wood tissue (Fig. 3b) and intra-annual density fluctuations are frequent (Fig. 4). All these anatomical anomalies hinder the fundamental stage of crossdating, prerequisite for the determination of an accurate age. This problem is already known in Mediterranean area (Cherubini et al. 2003).

Radiocarbon dating

Considering the crossdating failure, we decided to test the hypothesis that observed rings are annual by doing radiocarbon dating in the pith area of 6 trees. The radiocarbon dates cover the time period 2520 BP to 295 BP (Tab. 1). Radiocarbon results evidence ages much different from those assessed by counting rings. Difference between the number of counted rings and the most recent calibrated date is between 1797 years (tree 03TEM6) and at least 20 years (tree 03AUT5). For example, tree 03TEM6 was sampled in 2008, the difference between the counting of rings and calibrated age is calculated as follows: [(year of tree sampling (2008) – (number of counted rings (735)) + (youngest calibrated age (-524))] = 1797 years. We can conclude that counting rings underestimates the age. These differences can be explained by 3 reasons: (i) the alteration of the external part of the trunk by erosion (wind, water), (ii) the visual counting of rings underestimates the actual age of the tree due to a high number of completely missing rings subsequent to the cessation of cambium functioning in some years and, (iii) the tree staying in place over many centuries after its death (snags). In *Cupressaceae*, wood is very durable and resistant; the molecules responsible for the durability of wood are tropolones (Haluk & Roussel 2000) and in *Juniperus phoenicea* are especially beta-Thuyaplicines and Nootkatines (Runeberg 1960).

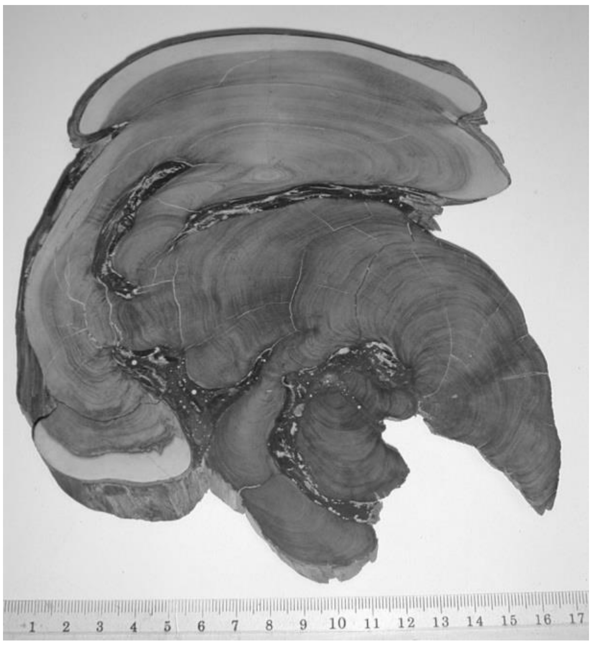

Figure 2: Disk of Juniperus phoenicea (1491 rings were counted). Courtesy by Jean-Paul Mandin

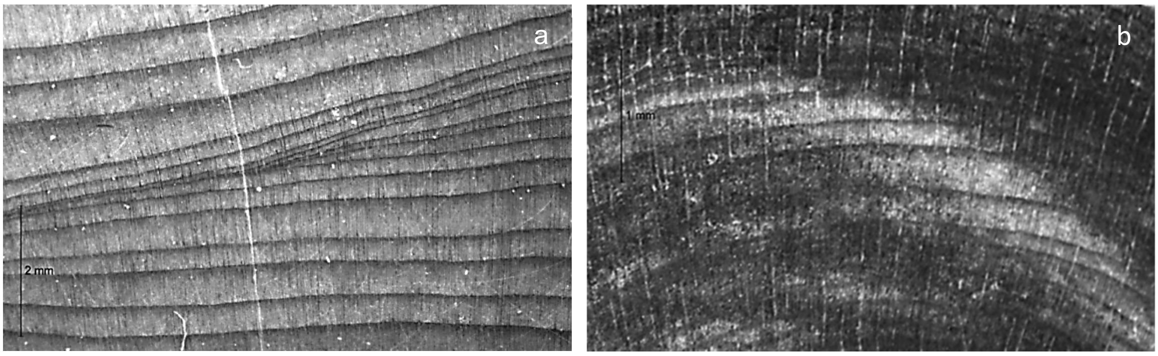

Figure 3: Anatomical anomalies of Juniperus phoenicea wood; a: Partially missing rings, b: Areas darkened by the presence of secondary metabolites.

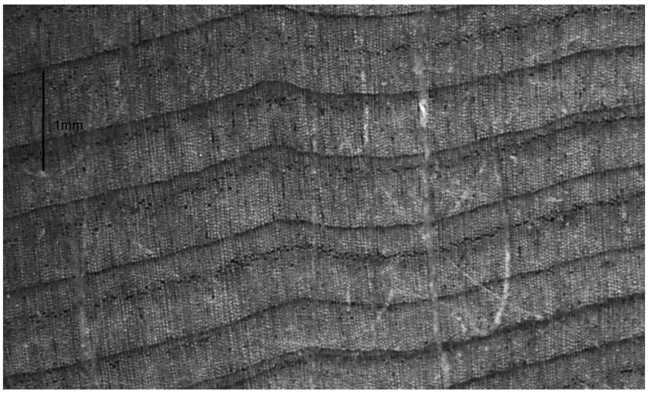

Figure 4: Intra-annual density fluctuation of Juniperus phoenicea.

Table 1: Radiocarbon dates done in the pith of 6 Juniperus phoenicea.

Tree	Number of rings	Reference	^{14}C years BP	Calibrated date
03TEM6	735	Ly-4105	2520 ± 35	792 - 524 cal BC
PTT1	652	Ly-4103	835 ± 30	1159 - 1262 cal AD
PTT2	506	Ly-4104	685 ± 30	1273 - 1385 cal AD
03 AUT 4a	1225	Ly-4102	1770 ± 35	136 - 376 cal AD
03 AUT 5	1052	Ly-4101	1190 ± 30	730 - 936 cal AD
01 GOU 1a	-	Ly-4106	295 ± 40	1475 - 1794 cal AD

Wiggle-match dating technique

It was decided to apply the «wiggle-match dating» technique to check whether dendrochronological detection of tree-rings coincides with the age provided by ^{14}C dating. The technique was applied on four trees from cliffs of the Ardèche valley on which 652 up to 1225 rings were counted. Results of 03AUT5 are shown (Tab. 2). It appears that the difference between the number of counted tree-rings and ^{14}C dates is small for the first six dates. The seventh date shows a higher difference between the number of counted rings and ^{14}C dates (Mathaux et al. in prep.). Accordingly, the uncertainty of our counting appears limited. The gap seems triggered by totally missing rings but their frequency seems rather low. Considering this and the high number of old trees in different cliff populations (Mathaux et al. in prep.); it seems feasible in a near future to cross-date juniper trees growing on cliffs and build up a long chronology from this long-lived species. That agrees with Grissino-Mayer (1993) who states that *Juniperus phoenicea* is a species known to crossdate between cores from the same tree as well as between trees from the same site.

Table 2: Wiggle-match dating techinique done on 03AUT5 tree.

	Rings sequence			Unmodelled (BC/AD)		Modelled (BC/AD)		
Data sequence	^{14}C	±	Gap after	from	to	from	to	A
Date AUT5	1190	30	47	722	945	847	878	114.2
Date AUT51	1155	30	185	775	969	894	925	66.3
Date AUT52	960	30	41	1020	1155	1079	1110	106
Date AUT53	950	30	144	1024	1155	1120	1151	99.2
Date AUT54	740	30	78	1224	1291	1264	1295	103.9
Date AUT55	605	30	107	1297	1406	1342	1373	108.8
Date AUT56	320	30		1483	1646	1449	1480	13.9

Conclusion and perspectives

In old trees growing on vertical cliffs, the key-question is whether rings are annual or not. We showed that there is a low difference between the radiocarbon dates and the number of counted rings, showing that missing rings occur but not in a large amount. That means that accurate annual dating of tree rings is theoretically possible by crossdating and leads to further dendrochronological investigations.

In the Mediterranean region, such old trees are uncommon. They are of high interest in terms of their functioning, past and present cliff ecosystem change and climatic reconstruction. Cross-dating of ring-width series is probably a complicated challenge but that could be achieved by using other parameters such as wood micro-density (Schweingruber et al. 1978, De Micco et al. 2007) or content in stable isotopes of wood cellulose (Leavitt & Long 1982, Battipaglia et al. 2010).

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Effects of climate on the radial growth of *Thuja occidentalis* northern marginal populations in Québec

J. Housset[1,2,3], M. Girardin[2,4], M. Baconnet[1], C. Carcaillet[3] & Y. Bergeron[1,2]

[1]Forest Research Institute, Université du Québec en Abitibi-Témiscamingue, 445 boulevard de l'Université, Rouyn-Noranda, QC, J9X 5E4, Canada
[2]Centre d'étude de la forêt, Université du Québec à Montréal, C.P. 8888, Montréal, QC, H3C 3P8, Canada
[3]École Pratique des Hautes Etudes (UMR5059, CNRS), Institut de Botanique, F-34090, Montpellier, France
[4]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S, PO Box 10380, Stn. Sainte-Foy, Quebec, QC, G1V 4C7, Canada
E-mail: housset.johann@courrier.uqam.ca

Introduction

Current evidence indicate that boreal forest and tundra are exposed to warming. One of the expected results of projected climatic change on trees is a northward shift of biogeographic ranges. In boreal ecosystems, the effects of climate change are expected to be most visible at the species northern margin. Global warming should allow a relaxation of the cold related climatic constraints, as suggested by studies conducted at high latitude tree-lines. Housset et al. (submitted.) assessed the interannual and interdecadal climate variability response of the boreal gymnosperm eastern white cedar *Thuja occidentalis* L. (hereafter "cedar") over a latitudinal gradient encompassing its northern marginal, discontinuous and continuous distribution areas. This study analysed a network of annually-resolved tree growth increment multi-century data combined with meteorological data covering 1953 to 2010. Cedar is an evergreen long-lived and shade-tolerant species of the eastern side of North America. The following hypothesis was tested: growth variability of cedar is positively correlated with variations of temperature and growth increases over time in link to the recent climate warming. This increase would be expected to be the greatest in the northern marginal area.

Materials and methods

The study area is located in the western regions of Quebec. A latitudinal transect was established from 47.3ºN to 50ºN and divided into three zones based on cedar abundance: the continuous zone (CZ) where cedars are common, the discontinuous zone (DZ) that marks the northern edge of the continuous distribution and where cedars become less common in the forest matrix, and the marginal zone (MZ) where only a few isolated patches of cedars are found (Fig. 1a.). Sampling was concentrated on poorly drained lowland sites as it is the most representative edaphic conditions of the species northern margin in Québec.

In 2010, up to 30 dominant and co-dominant cedar trees were randomly sampled in 27 sites across the study area (Fig.1). Two cores per tree were collected at 1.3 m above ground, sanded and tree-ring widths were measured. Crossdating was verified visually and statistically with the software COFECHA. The ring-width measurement series were normalized and averaged for each biogeographic zone using power transformations and exponential detrending to eliminate noise caused by site- and biological-related effects. This procedure preserves the variance in low frequencies necessary for the study of long-term growth trajectories (Cook & Peters 1997). These low-frequency cedar Tree Growth Index (hereafter called TGI) chronologies were used for the study of low-frequency growth variations in the recent past. Each raw ring-width series was also detrended using 60-year splines with a 50% frequency response using the R package dplR (Bunn 2008) and a residual chronology was computed for each site using a biweight robust mean for the dendroclimatic analysis (Cook & Kairiūkštis 1990).

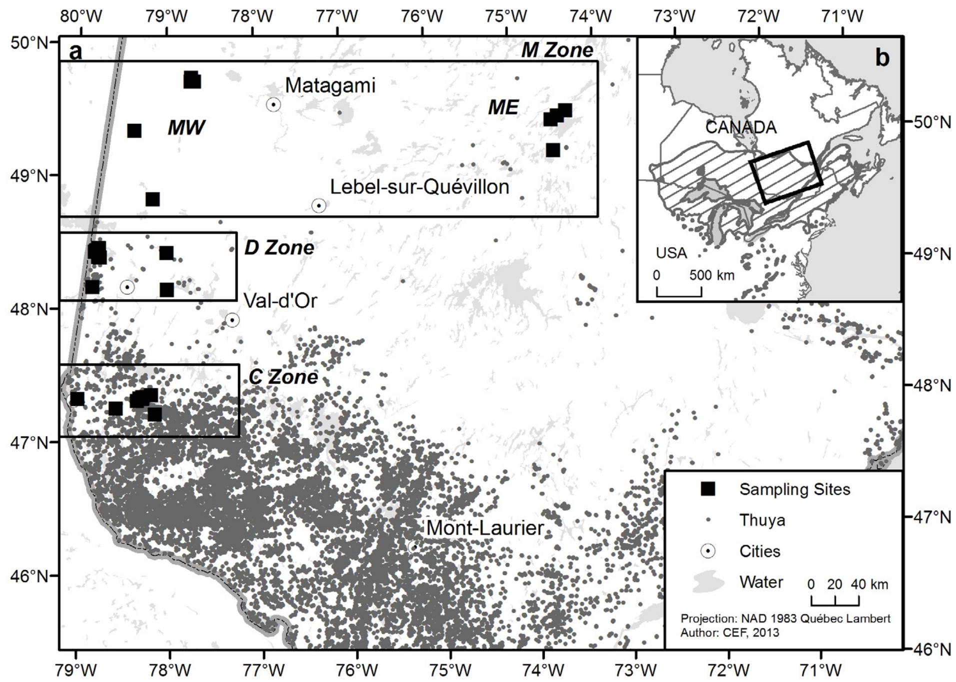

Figure 1: (a) Location of Thuja occidentalis sample sites (black squares). Background represents the known occurrences of Thuja occidentalis from the forest inventories of the province of Québec. Sampling was stratified between the continuous zone of distribution (C Zone), the discontinuous zone (D Zone) and the marginal zone (M Zone). (b) Location of the study area (black box) in the northern part of the species range (hatched area).

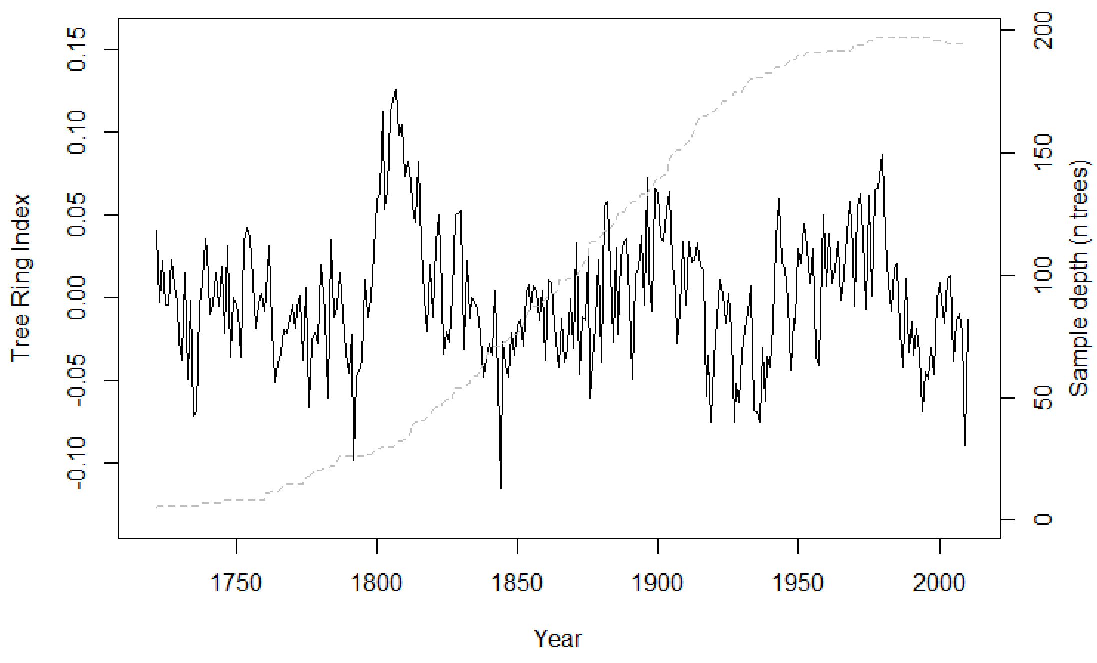

Figure 2: Low-frequency growth variations for Thuja occidentalis marginal populations. Tree growth index (TGI) chronology is compiled from the mean of all single tree detrended tree-ring width measurement series (black line). The gray dashed lines represent the sample depth, corresponding to the tree numbers.

Monthly mean temperatures and total monthly precipitation were interpolated for 1953–2010 at each sampling sites using the BioSIM software (Régnière & Bolstad 1994). Long-term trends in climatic series were linearly detrended using the period 1953-2010 to obtain unbiased data of interannual climatic variations. The relationship between climatic variability and residual chronologies of cedar was examined using bootstrapped correlation analyses over the period covered by observations. Analyses were conducted from May of the year preceding ring formation to October of the year current to ring formation using the R package bootRes (Zang & Biondi 2009).

Results

The recent warming did not result in a growth increase in the marginal zone (Fig. 2). On the contrary, a growth decline was observed with an onset starting ca. 1980. In more southern areas, the recent growth is not markedly different from past variations.
Interannual variations of cedar growth between 1953 and 2010 were positively correlated with spring temperature (March, April, mostly May). In contrast, growth was negatively correlated with warm summer (July and August) temperatures of the year preceding ring formation. A negative correlation was also observed for most sites, with June temperature of the year current to ring formation. While high temperatures are favourable to cedars at the beginning of the growing season, they become a limiting factor as the season progresses towards the end. Radial growth was positively correlated with precipitation in June of the year preceding ring formation, especially in the DZ. Radial growth was also positively correlated with precipitation in August of the current year in both the CZ and DZ but not in the MZ. Besides, excesses of precipitation during October of the year preceding ring formation had negative impacts on growth in the CZ. A negative effect of precipitation was also observed in the MZ during May of the current year.

Discussion

Contrary to the working hypothesis, Housset et al. (submitted) found that the warming has not caused a growth rise at cedar cold margins. Results suggest that the cold climate was not limiting growth at the northern edge of the cedar distribution. Surprisingly, a radial growth reduction was observed between 1980 and 2010. This slowing of cedar growth rates in the northern boreal forest during the last 30 years is consistent with reported evidences of productivity declines in these regions detected through remote sensing (Hicke et al., 2002; de Jong et al., 2012) or tree-ring analyses (Girardin et al. 2014). Drought stress may limit productivity despite the relatively wet environment in which cedar is growing at its northern margin.
Dendroclimatic analysis allowed to better identify the impact of drought stress on cedar growth over the gradient. Growth appeared to be positively influenced by May temperatures during the year of ring formation all over the gradient. However, summer temperatures have a negative consequence on radial growth, primarily indicated by the negative correlation with July and August temperatures of the year previous to ring formation. The drought stress constraint on radial growth is also suggested by a positive correlation with precipitation of August during the year of ring formation and June of the previous year. The negative effect of June temperature could be explained by the higher loss of carbohydrates due to maintenance respiration during warm episodes (Lavigne & Ryan 1997).
The negative effects of current May and previous October precipitation on radial growth is most likely linked to the soil hydrology. An increase in spring rain during the snow melting could cause a rise of the water table in swamps or a flooding event in lakes and rivers resulting in tree roots asphyxia. A wet soil in fall likely delays the soil warming up in the next spring, that could indirectly cause a growth delay. The paradoxal transition from spring water excess to summer drought is probably due to the shallow roots system developed by the cedars in hydric soils (Musselman et al. 1975). During summer's lowering of the water table, the upper layer of organic soils becomes dry and cedar shallow roots cannot supply water. Cedar growth is thus dependent on the precipitation seasonality and on local soil hydrology.

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Dendroecological studies in the Nepal Himalaya - review and outlook in the context of a new research initiative (TREELINE)

N. Schwab, U. Schickhoff, B. Bürzle, J. Hellmold & M. Stellmach

Physical Geography, Center for Earth System Research and Sustainability (CEN)
University of Hamburg, Bundesstr. 55, 20146 Hamburg, Germany
E-mail: niels.schwab@uni-hamburg.de

Dendroecological studies in the Nepal Himalaya with regard to treeline elevations

Himalayan treeline ecotones show considerable differences in altitudinal position as well as in physiognomy and species composition (Schickhoff 2005). In Nepal, treeline ecotones from closed subalpine forests to the upper limit of crippled and stunted tree individuals correspond approximately to the altitudinal range between 3600 and 4300 m (north-facing slopes), with slightly increasing elevations in an eastward and in a northward direction. This paper reviews the history of dendroecological work in Nepal with special consideration of studies in treeline environments, introduces a new research initiative (TREELINE) focusing on the detection of climate change signals in the treeline ecotone of Rolwaling Himal, Nepal, and presents first results.

According to our knowledge, first tree-ring samples in Nepal were collected by Rudolf Zuber in 1979/80 (under the direction of Fritz Schweingruber) with the objective to develop ring width chronologies, respective results were published by Bhattacharyya et al. (1992; see also Gaire et al. 2013). Some of the presented chronologies are based on sampling at near-treeline locations (3620-3720 m) using increment cores from *Abies spectabilis* and *Larix potanini*. The results were considered promising with respect to dendroclimatological correlations, which have been and still are, however, constrained by the lack of sufficient meteorological data (cf. Bhattacharyya et al. 1992).

Prior to this publication, Suzuki (1990) presented a first dendroecological study focusing on the correlation of *Abies spectabilis*, *Pinus wallichiana* and *Picea smithiana* tree-ring widths with climatic variables, based on sampling in montane/subalpine forest stands (c. 3100 m) in West Nepal. He also addressed the influence of changing canopy cover on tree-ring widths and resulting chronologies. In the aftermath of these pioneer studies, dendroecology in Nepal witnessed a significant upturn in the number of publications, giving attention to the establishment of chronologies and/or following dendroclimatological, dendroarchaeological, and modelling approaches (e.g., Schmidt 1992; Gutschow 1994; Romagnoli & Lo Monaco 1995; Schmidt et al. 1999, 2001; Zech et al. 2003; Bräuning 2004; Udas 2009; Tenca & Carrer 2010; Sano et al. 2010; Bräuning et al. 2011; Scharf et al. 2013; Dawadi et al. 2013; Shrestha 2013). Detailed dendroclimatological reconstructions were provided by Cook et al. (2003) and Sano et al. (2005) for seasonal temperature, and by Sano et al. (2012) for precipitation. Recently, an increasing number of tree-ring research studies has been initiated at Nepalese universities, the results of which are documented in hardly accessible M.Sc. or Ph.D. theses (e.g., Suwal 2010) and to some extent also in published papers (Chhetri 2008; Chhetri & Thapa 2010; Gaire et al. 2011; see Gaire et al. 2013 for further unpublished theses and conference papers). These studies indicate an increasing dissemination of tree-ring research expertise in Nepal, also reflected in the percentage of nationalities of involved researchers conducting dendrochronological/-ecological studies. 50 % of the studies were carried out by only Nepalese and 29 % by only foreign scientists, while joint projects account for 21 % (Gaire et al. 2013).

The majority of the above cited studies (see Tab. 1 in the appendix for a complete overview) is based on material sampled well below treeline elevations, and scarcely any of these studies is embedded in an integrated approach to detect climate change effects at treeline elevations with regard to treeline dynamics. In the following, we highlight hitherto available studies that used dendroecological approaches to detect the response of Himalayan treelines in Nepal or of upper subalpine forest trees to climate change. In general, there is increasing evidence suggesting that growth response of Himalayan treeline trees to climate change and variability is spatio-temporally differentiated, species-specific and not unidirectional (Schickhoff et al. 2014). A positive relationship of ring widths to increasing winter temperatures was ascertained in several studies. E.g., Bräuning (2004) reported a strong positive relationship between high elevation *Abies spectabilis* ring width and November-January temperature in Dolpo. Gaire et al. (2014) found tree growth of *Abies spectabilis* in Manaslu Conservation Area to be positively correlated with higher winter temperatures prior to growing season, and stressed the positive effects of earlier snow melt and increased melt water supply for growth.

Recently, an increasing number of studies in western and central Himalaya have revealed a strong sensitivity of tree growth to pre-monsoon temperature and humidity conditions (cf. Schickhoff et al. 2014). Increased evapotranspiration and soil moisture deficits induced by higher temperatures during the relatively dry spring months obviously impedes tree growth in particular on sites which are prone to drought stress. In Nepal, significantly negative correlations with long-term pre-monsoon temperature series were detected in *Abies spectabilis* tree-ring data from near-treeline sampling locations in Humla District (Sano et al. 2005) and in Langtang National Park (Gaire et al. 2011; Shrestha 2013). The pre-monsoon period has been shown to be also critical for broad-leaved treeline trees. Dawadi et al. (2013) assessed for the growth of birch trees at treeline sampling sites in Langtang Valley a positive correlation with March-May precipitation and an inverse relationship with pre-monsoon temperatures. Reduced pre-monsoon moisture availability being a primary growth-limiting factor for *Betula utilis* at treeline and the coincidence of years with high percentage of missing rings or narrow rings with dry and warm pre-monsoon seasons was confirmed by Liang et al. (2014) for study sites in Sagarmatha National Park, Langtang National Park, and Manaslu Conservation Area (Nepal) (for Manaslu see also Gaire et al., 2014). Results from current research of the present authors based on a ring-width chronology of *Betula utilis* from treeline sites in Langtang Valley dating back to AD 1657 confirmed a negative correlation of tree-ring width with pre-monsoon temperature and a positive correlation with pre-monsoon precipitation (in review).

Other studies in treeline environments of Nepal incorporated dendroecological techniques to infer more general information on stand characteristics, recruitment of tree species, and treeline dynamics. Bhuju et al. (2010) provided baseline information on structural parameters, recruitment and growth patterns of *Abies spectabilis* and *Betula utilis* assessed at two permanent plots in the treeline ecotone in Sagarmatha National Park. Gaire et al. (2011) addressed dynamics of *A. spectabilis* based on tree-ring and stand structural data from a treeline ecotone in Langtang National Park. By analysing the altitudinal distribution of tree, sapling and seedling densities and comparing total tree age distribution with elevation wise distribution the authors found an upward shift of *A. spectabilis* during recent decades. Recruitment patterns of *A. spectabilis*, derived from dendrochronological data, were assessed by Lv & Zhang (2012) from a study site in Mt. Everest Nature Reserve (across the border between Nepal and Tibet), showing a positive correlation with mean summer temperature. Shrestha (2013) ascertained significant but inconsistent growth responses to growing season and non-growing season climate factors of *Abies spectabilis* on a mesic north-facing slope in Langtang National Park and of *Pinus wallichiana* on a dry south-facing slope in Manang. The study did not reveal any significant variation in *A. spectabilis* and *P. wallichiana* treeline elevation over the past six decades and in the timing of the current treeline establishment. Another recent study (Gaire et al. 2014) investigated tree-rings of *Abies spectabilis* and *Betula utilis* from the treeline ecotone of Manaslu Conservation Area. *A. spectabilis* showed a high percentage of individuals younger than 50 years, indicating a high recruitment rate. Population structure along the elevational gradient indicated a distinct upward shift of *A. spectabilis*. In contrast, the upper limit of *B. utilis* occurrences did not change in the past decades. In general, the stand density increased. More recruits of *A. spectabilis* compared to *B. utilis* were found, pointing to a change in dominance patterns. Gaire et al. (2014) also established a negative correlation of the increment of *A. spectabilis* with monthly mean and minimum temperatures from June to September of the current and of the previous year. Regeneration of the same species was favoured positively by precipitation and maximum temperature of current year's August. Moisture stress during the pre-monsoon season was found to limit the growth of *B. utilis*. Regeneration of *A. spectabilis* correlated positively with the above-average monthly maximum temperature during most of the months and with above-average precipitation during dry warm summer months.

In conclusion, the use of dendrochronological/-ecological methods contributes to a better understanding of age structures, regeneration patterns, and dynamics of treeline ecotones. Most of the cited studies point to distinct growth responses of treeline trees to climate change with *A. spectabilis* showing mainly positive correlations with climate warming, and *B. utilis* showing negative response in particular to pre-monsoon warming. The low number of hitherto published studies restrict the drawing of wider conclusions regarding the correlations of climatic and other environmental factors with upper species limits, changing treeline ecotone species compositions and altitudinal shifts of species for the Nepal Himalaya. Comprehensive respective research programmes are badly needed.

The project TREELINE

State of the art and TREELINE objectives

While at global scale plant growth limitation by low-temperature determines the position of natural alpine treelines (e.g., Troll 1973; Stevens & Fox 1991; Holtmeier 2009; Körner 2012), factors and mechanisms influencing treeline position and dynamics at smaller scales are not well understood. Recent studies on the world's alpine treelines give evidence of both advancing treelines and rather insignificant treeline responses to climate warming (e.g., Baker & Moseley 2007; Hofgaard et al. 2009; Wieser et al. 2009; Lv & Zhang 2012). The inconsistency of findings on changing treeline spatial patterns points to considerable research deficits concerning the sensitivity to climate changes. It is widely accepted that climate exerts a top-down control on local ecological processes at the treeline (e.g., Batllori & Gutiérrez 2008). It is not well understood, however, how landscape scale and local scale abiotic and biotic factors and processes interact and influence the treeline and its response to climate. Moreover, effects of climate warming often mix up with impacts of land use (Malanson et al. 2007; Batllori et al. 2009). In consequence, complex research approaches at local and landscape scales at natural treelines are needed (e.g., Malanson et al. 2011).

The new research scheme "Sensitivity and Response of the Treeline Ecotone in Rolwaling Himal, Nepal, to Climate Warming" (TREELINE) aims at investigating treeline sensitivity and response using a landscape approach. The project focuses on spatially differentiated patterns and processes by correlating varied treeline responses to landscape- and local-scale site conditions and mechanisms (geomorphic controls, soil physical and chemical conditions, plant interactions associated with facilitation, competition, feedback systems). This approach will allow inferences on how the region-wide climate warming input and finer-scale modulators interact to govern non-uniform treeline response patterns.

The near-natural treeline ecotone in Rolwaling extends from the closed subalpine forest via timber- and treeline to the lower alpine vegetation belt. The near-natural status of the treeline can be attributed to the remote location without connection to the road network (3 days walking distance), to the small human population and to the fact that plants and animals in Rolwaling are protected to a certain extend by the recurring Buddhist theme of a sacred hidden valley (Sacherer 1979). The study slopes show no signs of fire or of grazing by cattle. The Rolwaling River separates the uninhabited north facing study site slope from the very sparsely populated south facing slope where human activities take place, albeit to a limited extent.

Vegetation analyses include the sampling of tree individuals along elevational transects across the treeline ecotone with regard to growth rates, age structures, tree physiognomy, stand densities, and tree recruitment. Moreover, we measure/analyse standard soil physical and chemical parameters, altitude, slope, exposition and microrelief (percentage and size of rocks, stones and soil covering the ground), composition of ground vegetation, leaf area index, air temperature, solar radiation, soil moisture, and soil temperature. We also sample naturally established seedlings of the treeline tree species, and correlate recruitment patterns with microhabitat conditions (vegetation and substrate cover, species composition, shelter elements, edaphic conditions) to analyse requirements for successful recruitment. To assess the impacts of ongoing temperature enhancement on seedling establishment, we install open top chambers at and above the treeline ecotone and replant seedlings of *A. spectabilis* to sites of experimental warming. Scenarios of treeline dynamics under climate warming will be based on the assessed interactions. Amongst others, we will apply statistical and forest growth models including data gained by dendrochronological methods (cf. Schickhoff et al. 2014).

The objective of the dendroecological approach in TREELINE is to detect changes in age structures and recruitment of treeline stands and in radial increment of trees in order to evaluate whether the Rolwaling treeline advances or remains stable under the influence of climate warming. We collect and analyse tree-ring cores of treeline tree species with a focus on the dominant species *Abies spectabilis* and *Betula utilis*, and correlate tree-ring parameters with modelled climate variables (Gerlitz et al. 2014; Gerlitz 2014). Our sampling design stratifies each altitudinal transect (2 NE-exposed, 1 NW-exposed) in four belts of distinct vegetation patterns (named A to D). The lowest belts (A, B) contain mixed forest stands with the upper limits of tall, upright growing individuals of *Acer caudatum* in A and of *Abies spectabilis* and *Betula utilis* in B. The third belt (C) represents the krummholz belt with dense and largely impenetrable *Rhododendron campanulatum* thickets and the species limit of *B. utilis*, while the uppermost belt (D) contains alpine vegetation with only small (DBH < 7 cm) and stunted individuals of *A. spectabilis*, *Sorbus microphylla* and *Rh. campanulatum* (Fig. 1).

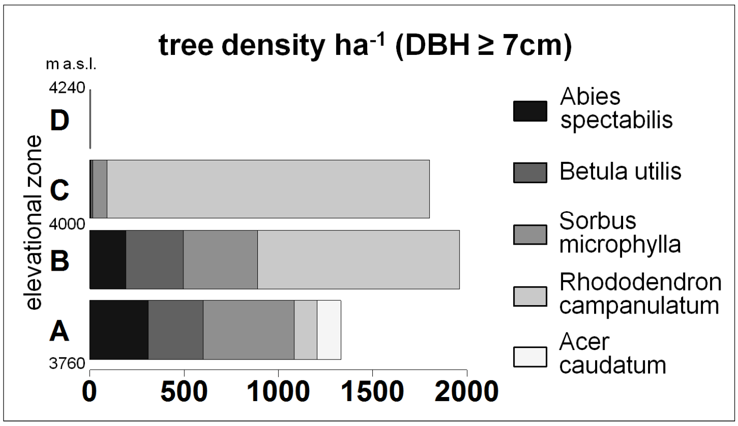

Figure 1: Tree species density in four altitudinal vegetation zones (A, B, C, D), forming the treeline ecotone in Rolwaling valley.

Intensive tree-ring sampling, accompanied by comprehensive recording of tree growth parameters and spatial patterns, started in 2013 and was completed in September 2014. We sampled a total of c. 280 individuals of *Abies* and *Betula* each, c. 160 *Sorbus* trees and c. 40 trees of *Acer* and *Rhododendron* of all diameter classes. We extracted two increment cores from each tree. We analyse all increment cores and test in particular the suitability of *A. caudatum*, *S. microphylla* and *Rh. campanulatum* for dendrochronological analyses since these species have hardly been sampled to date. Tree-ring cores are prepared according to standard dendrochronological procedures (Pilcher 1990; Stokes & Smiley 1996). Annual rings are counted, measured and cross-dated in the recently initialised dendro-laboratory at the Institute of Geography, University of Hamburg using a LINTAB 6 measuring system and TSAP-Win software (Rinntech, Heidelberg). We apply standard methods for cross-dating, detrending and correlating of annual radial increment with climatic variables (Fritts 1976; Cook 1985; Cook & Briffa 1990; Fang et al. 2014). Measured raw series of *A. spectabilis* cores point to the potential of establishing a 50 year long chronology covering the period of 2012 – 1962. The longest series from our sample measured so far dates back 200 years, but many trees are affected by heart rot causing substantial loss of the number of cores in the chronology already after about 50 years. An initial crossdating attempt of all measured raw series resulted in a mean Gleichlaeufigkeit value (GLK%, Eckstein & Bauch 1969) of about 50 % (max: 67 %, min: 39 %) indicating the need for checking for missing and double rings. We will continue with exact cross-dating, accuracy checking, discarding of poorly correlated samples, detrending and standardisation of the ring-width series, and identification of pointer years. We found promising results for the crossdating suitability of *Rh. campanulatum*: The longest measured series comprises 136 years and 20 of the collected cores date at least 50 years back. Mean initial GLK calculated within the sites accounts for about 55 % (min: 36 %, max: 72 %) which is possible to improve by checking for missing and double rings and discarding of poorly correlated series. The wood is little infested by heart rot but the rings are difficult to measure precisely due to low visibility and small ring widths.

More detailed results from dendrochronological/-ecological studies in TREELINE will be included in forthcoming publications. Preliminary findings point to complex growth and spatial patterns dominated by the altitudinal gradient but influenced by environmental factors, e.g. soil properties and microclimate, at the small scale.

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Appendix

Overview of published and/or online available dendrochronological studies from Nepal. There are few studies with an explicit dendroecological background. RW: ring width, MLD: maximum latewood density, n.s.: not specified.

authors + year published	study area	altitude [m] sampling site	tree-ring research domain	studied species	studied parameters
Suzuki 1990	Jumla District	3060 / 3100	chronology + climate response	*Abies spectabilis, Picea smithiana , Pinus wallichiana*	RW
Bhattacharyya et al. 1992	25 sites across Nepal	1320 – 3720	chronology building	*Pinus roxburghii, Tsuga dumosa, Abies spectabilis, Cedrus deodara, Picea smithiana, Larix potanini, Juniperus recurva, Pinus wallichiana*	RW
Schmidt 1992	South Mustang	n.s.	chronol. building with dendroarchaeol ogical background	*Pinus sp.*	RW
Gutschow 1994	Kagbeni / South Mustang	n.s.	dendroarchaeol ogy	*Pinus sp.*	RW
Romagnoli & Lo Monaco 1995	Western Nepal	n.s.	chronology building	*Betula utilis, Abies spectabilis , Juniperus sp., Picea smithiana, Pinus wallichiana*	RW

authors + year published	study area	altitude [m] sampling site	tree-ring research domain	studied species	studied parameters
Schmidt et al. 1999	Mustang, Manang, Khumbu	n.s.	chronol. building with dendroarchaeological background	*Abies spectabilis , Pinus wallichiana, Picea smithiana*	RW
Schmidt et al. 2001	Kagbeni / South Mustang	n.s.	dendroarchaeology	*Pinus wallichiana, Cupressus torulosa*	RW
Cook et al. 2003	25 sites across Nepal	1830 – 3630	climate reconstruction (temperature)	*Abies spectabilis, Tsuga dumosa, Pinus wallichiana, Juniperus recurva, Picea smithiana, Ulmus wallichiana*	RW
Zech et al. 2003	Gorkha Himal	n.s.	climate reconstruction, glacial history	*Abies spectabilis*	RW
Bräuning 2004	Mugu and Dolpo	3500 / 3850 / 4020	chronol. building + climate response	*Abies spectabilis, Betula utilis, Pinus wallichiana*	RW, MLD
Sano et al. 2005	Humla District	3850	climate reconstruction (temperature)	*Abies spectabilis*	RW, densities
Chhetri 2008	Langtang National Park	n.s.	chronol. building + climate response	*Abies spectabilis*	RW
Udas 2009	Mustang District	3415 – 3242 3220 – 3092	chronol. building + climate response	*Abies spectabilis*	RW
Bhuju et al. 2010	Sagarmatha National Park	3850 / 4050	dendroecology	*Abies spectabils, Betula utilis*	RW
Chhetri & Thapa 2010	Langtang National Park	3309 / 3444	chronol. building + climate response	*Abies spectabilis*	RW
Sano et al. 2010	Humla District	3850	chronol. building + climate response	*Abies spectabilis*	RW, $\delta^{18}O$
Suwal 2010	Manaslu Conservation Area	3624 - 3841	dendroecology	*Abies spectabils*	RW
Tenca & Carrer 2010	Khumbu	3800 - 4100	chronol. building + climate response	*Abies spectabils, Betula utilis*	RW
Bräuning et al. 2011	upper Dolpo	n.s.	chronol. building with dendroarchaeological background	*Pinus wallichiana*	RW, ^{14}C dating
Gaire et al. 2011	Langtang National Park	3730 - 3950	climate response, dendroecology	*Abies spectabilis*	RW
Sano et al. 2012	Humla District	3850	climate reconstruction (precipitation)	*Abies spectabilis*	RW, densities, $\delta^{18}O$

authors + year published	study area	altitude [m] sampling site	tree-ring research domain	studied species	studied parameters
Dawadi et al. 2013	Langtang National Park	3780 / 3950	chronol. building + climate response	*Betula utilis*	RW
Scharf et al. 2013	Dolpo	n.s.	chronol. building with dendroarchaeological background	*Pinus wallichiana*	RW, ^{14}C dating
Shrestha 2013	Manang, Langtang National Park	3770 - 4180	climate response, dendroecology	*Abies spectabils, Pinus wallichiana*	RW
Shrestha et al. 2013	Dolakha District	900 - 1750	construction of allometric model	*Pinus roxburghii*	RW
Gaire et al. 2014	Manaslu Conservation Area	3690 - 3996	climate response, dendroecology	*Abies spectabilis, Betula utilis*	RW
Liang et al. 2014	Sagarmatha NP, Langtang NP, Manaslu CA	3900 - 4150	climate response, dendroecology	*Betula utilis*	RW

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The tree ring study of Downy birch in Northern Europe

R.J. Kaczka[1] K. Janecka[1], B. Czajka[1] & O. Eggertsson[2]

[1]Faculty of Earth Science, University of Silesia, Poland
[2]Icelandic Forest Research, Iceland
E-mail: ryszard.kaczka@us.edu.pl

Introduction

Downy birch (*Betula pubescens* Ehrh.) is one of the main native tree species in Northern Europe. It grows from Greenland and Iceland to Scandinavia and further east, across the Northern Eurasia. Although various birch species are common on both continents, Downy birch is more associated with exposed habitats such as mountains and high latitudes. In Iceland the growth of Downy birch is driven by summer temperatures (Levanic and Eggertsson 2008; Mook and Vornen 1996; Odland 1996). At the same time, little is known about these relationships for populations from the rest of the North Europe and Asia.
The aim of the study was: i) to define the climate influence on birch growth in different locations (Fig. 1), ii) to test the teleconnection between selected regions of Europe.

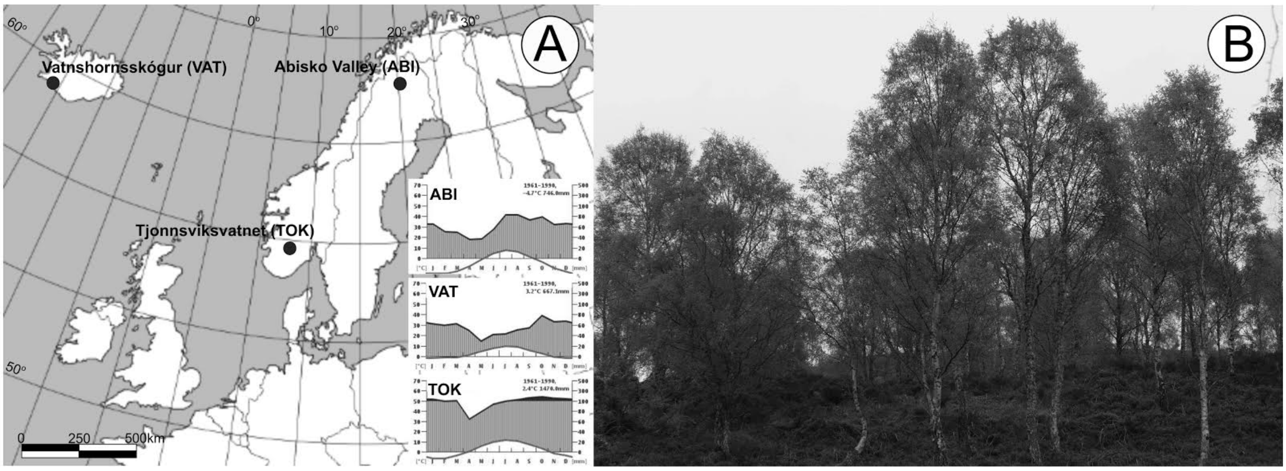

Figure 1: (A) The location and climatic characteristics of investigated sites: VAT – Vatnshornsskógur (260 m a.s.l.), Iceland; TOK – Tjonnsviksvatnet (820 m a.s.l.), Telemark Region, Norway; ABI - Abisko Valley (470 m a.s.l.), Sweden. (B) The typical Downy birch forest in Norway. The climate diagrams assembled with gridded (0.5° resolution) temperatures and precipitation calculated over the 1901-2006 period (CRU TS 3.1; Harris at al. 2013).

Material and methods

Three sites from distant locations were selected and compared: Iceland, Norway and Sweden (Fig. 1). The data from the Swedish site were obtained from ITRDB, uploaded there by Jan Hoogesteger (Eckstein et al. 1991). Between 44 (ABI) up to 100 trees (TOK) were sampled per site; two cores per tree, parallel to slope were taken. The character of the wood, frequent occurrence of growth irregularities and abundance of missing rings create challenges related to the preparation, measuring and analysis. Standard dendrochronological methods were used to produce and test time series of tree-ring width (TRW). To obtain clearly-visible borders of rings and other features of wood cores required careful sanding and polishing with use of fine, up to 1000 grit sandpaper. The width of annual rings was measured using a Velmex, Inc. TA UniSlide measurement system (resolution 0.001 mm) combined with MeasureJ2X software. The statistical parameters of series were examined (by implementation) of both CDendro (Cybis Elektronik & Data AB, Larsson 2003a, 2003b) and Cofecha (Grissino-Mayer 2001) software. Nonetheless visual cross-dating was essential to assemble the coherent sets of tree-ring width series. Following these criteria the selected measurement series were used to develop three chronologies. The Arstan (Cook, Holmes 1986) software was employed to compute the chronologies and their main statistics. Different methods of detrending were tested. Based on the main statistics and response to climate drivers 120-year cubic smoothing splines were used. Growth–climate relationship analysis were calculated between the residual site chronologies and the monthly as well as seasonal averages of gridded (0.50 × 0.50) data of several (temperature, precipitation, PDSI, see level pressure) parameters covering period 1901-2009 (CRU TS 3.1; Harris at al. 2013). The pointer years (7 years time window and 80% of response) were calculated using Weiser software (Gonzales 2001).

Results

Trees from Iceland were relatively young (23 – 123 years, mean length of series: 67). Approximately half of the examined samples were included in site chronology (38 trees). The birches from Norway are characterized by similar values (31 – 128 years, mean length of series: 74), also similar percentage of samples (74 series) were used to compute the chronology. The data obtained from the ITRDB set of 44 series show higher ages (41 – 162 years, mean length of series: 89). The wood of the birches from Iceland and Norway exhibits a lot of anatomical anomalies: frost rings, micro scars related to the cambium injuries caused by insects, light rings typical for insect defoliation. These features are not discussed here due to the lack of such data from the third site (Abisko Valley). The basic analysis of TRW series reveals the substantial irregularities of the growth (Tab. 1).

Table 1. Characteristics of the 3 Downy birch TRW chronologies, sorted by altitude (North-South). Statistics refer to chronologies after 120-year spline detrending, and truncation <5 series. Columnes named: Period - full length/after truncation; MSL - mean segment length (years); AGR average growth rate (mm); Rbar and EPS - calculated over 30 years lagged by 50% along the full chronology length.

Site	Lat/Long	Altitude (m a.s.l.)	Series	Period	AGR	Rbar	EPS	No of missing rings
Abisko Valley (Sweden)	68.2/18.4	470	44	1820-1983	0.49	0.76	0.94	0
Vatnshornsskógur (Iceland)	64.2/-21.3	260	39	1890-2012	0.90	0.62	0.92	74
Tjonnsviksvatnet (Norway)	59.2/7.4	820	51	1886-2013	0.86	0.36	0.91	56

The considerable number of missing rings (respectively 2.84% and 1.158%) was detected during crossdating of samples from VAT and TOK, whereas no missing ring data information is included in data set from the North of Sweden. This particular result could be contradicted by the results reported from similar location (Abisko Valley) by J. Hoogesteger (2006) who noticed up to 2.3% of missing rings. The compression of the two radiuses obtained from one tree reveals asymmetric growth. The proportion of radius A and B changes from 0.32 to 0.96 for VAT site and from 0.35 to 0.99 for TOK site (Fig. 2).

The developed chronologies differ in length and covered period. The most North located, based on ITRDB data chronology (ABI) spans (after truncation < 5 series) from 1840 to 1983. Two others cover similar period. The chronology from South of Norway (TOK) spans the period 1890 - 2013, and from Iceland (VAT) 1902 – 2012. Therefore all the comparisons of the chronologies consider common period 1902 – 1983.

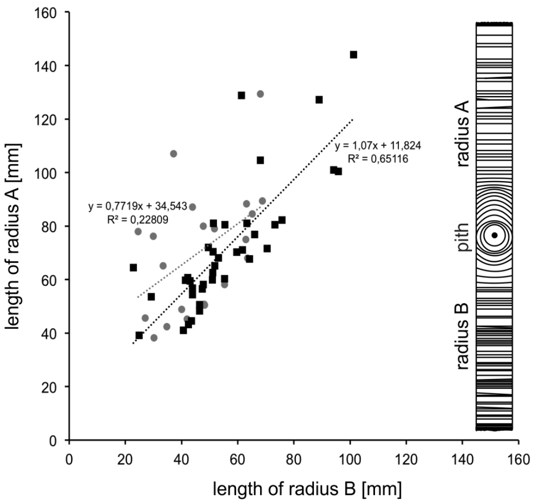

Figure. 2: The proportion of the A and B radii as indicator of the irregular growth of the Downy birch trees. The comparison of TRW measurements from VAT (grey) and TOK (black) sites.

The standard TRW chronologies exhibit somewhat independent behaviour and insignificant correlation (Fig. 3). This results from the dominants of the local influences rather than regional ones. The regional factor such as climate is not unified in terms of entire Scandinavia (Tømmervik et al. 2004; Hynynen et al. 2010). The occurrence of both positive and negative pointer years also shows lack of the synchronicity between three sites (Fig. 3), except 1928 when all three chronologies show negative pointer year. There is no indication of any positive pointer years derived from all studies sites. Outside common period, the TOK and VAT chronologies reveal two additional negative pointer years: 2005 and 2011 respectively.

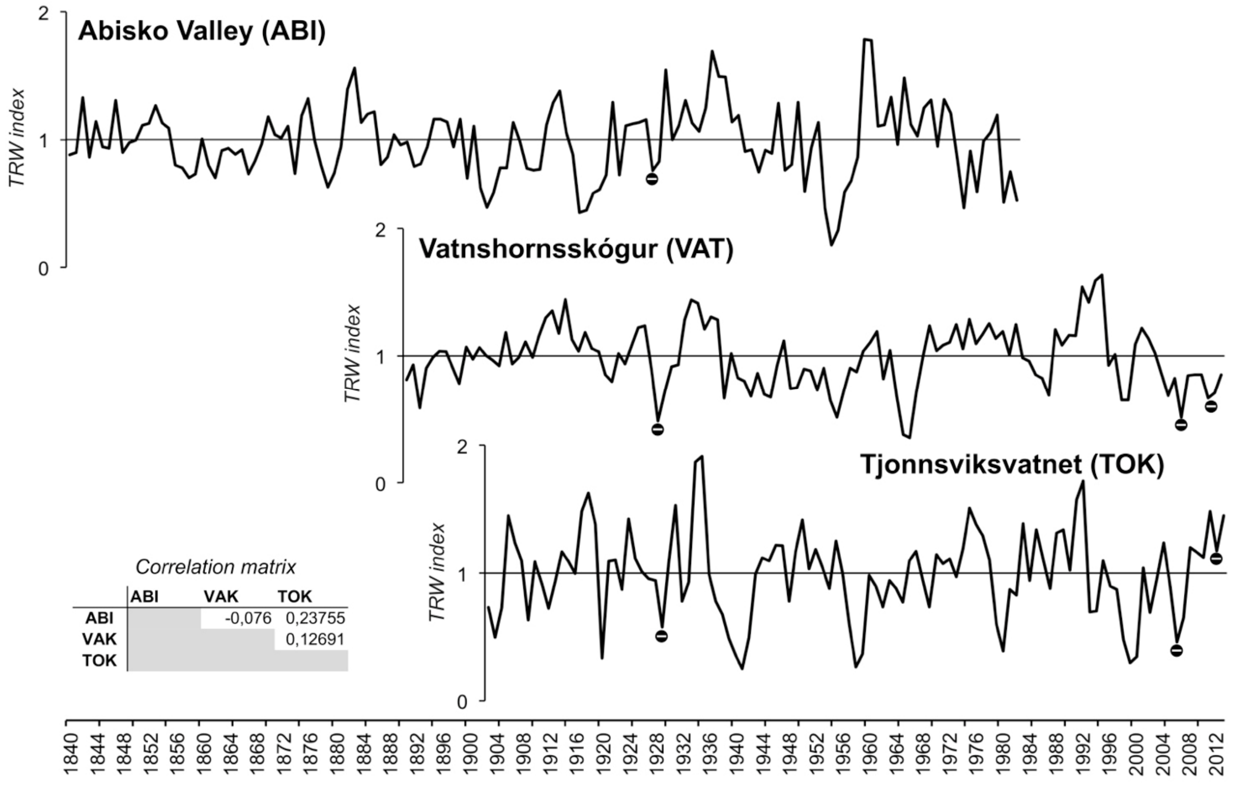

Figure. 3: TRW standard chronologies of three Downy birch sites. Correlation matrix calculated for common period of 1902 – 1983. The "minus" signature indicates the years of negative pointer years registered for three (1928) or two (2005 and 2011) chronologies.

The results of growth – climate correlation analyses show coherent response of chronologies to climatic factors. All three chronologies reveal positive response to current year spring - summer temperature (Fig. 4). The growth of birches at VAT site is the most influenced by mean monthly temperature of June (CC=0.29).

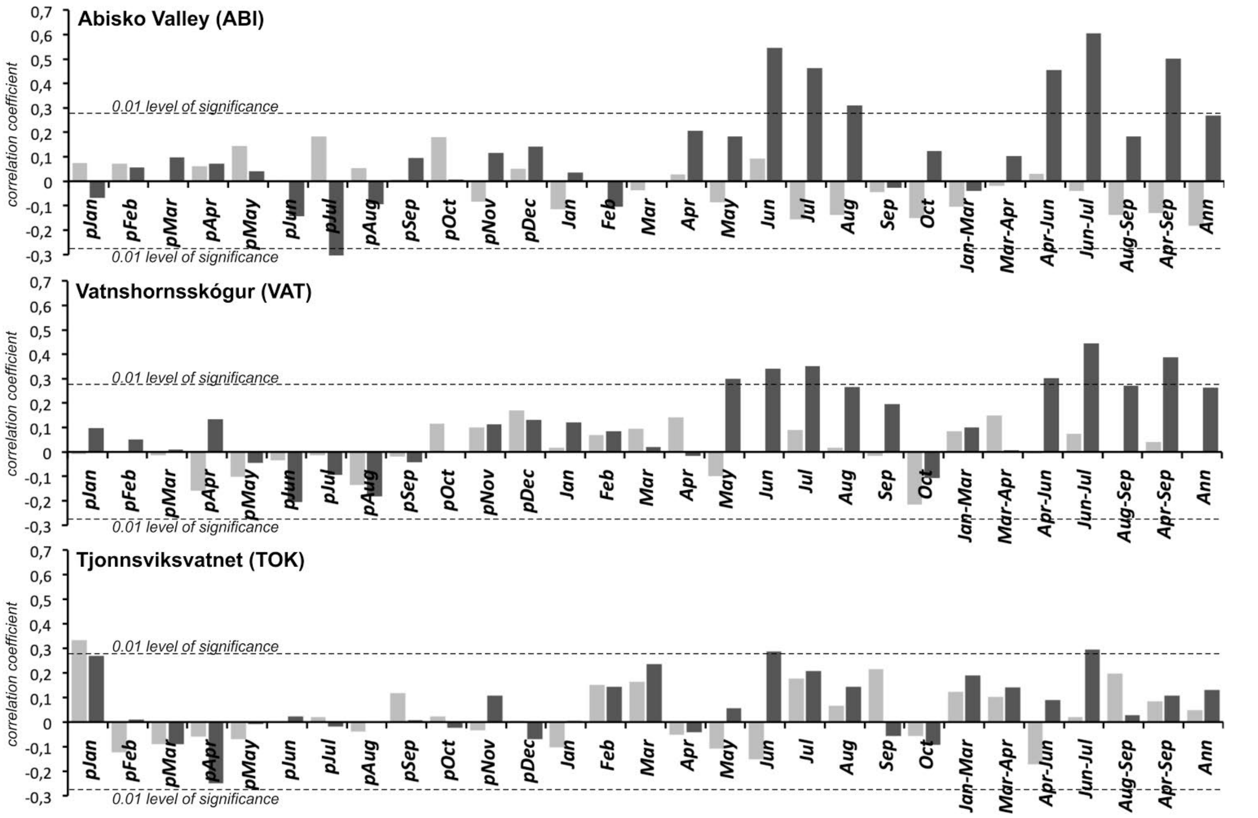

Figure 4: Correlation between residual chronologies with gridded (0.5° resolution) monthly resolved temperature (dark bars) and precipitation (light bars) computed throughout the common 1902–1983. (CRU TS 3.1; Harris at al. 2013).

Trees from the TOK site reveal the highest correlation with mean and minimum temperature of July (respectively CC=0.35 and 0.36). The site located at Abisko Valley shows the highest response to June mean temperature (CC=0.55). The TOK and ABI chronologies reveal slightly higher correlations to mean temperature of longer period: June-August (respectively CC=0.43 and 0. 61). The studied chronologies correlate with precipitation in less consistent manner and the results are insignificant in the most of cases (Fig. 4). The spatial correlation of the three chronologies to temperature reveals connection to rather restricted field (Fig. 5). Only ABI chronology shows relationship with wider pattern of air circulation including Scandinavia and Atlantic Ocean.

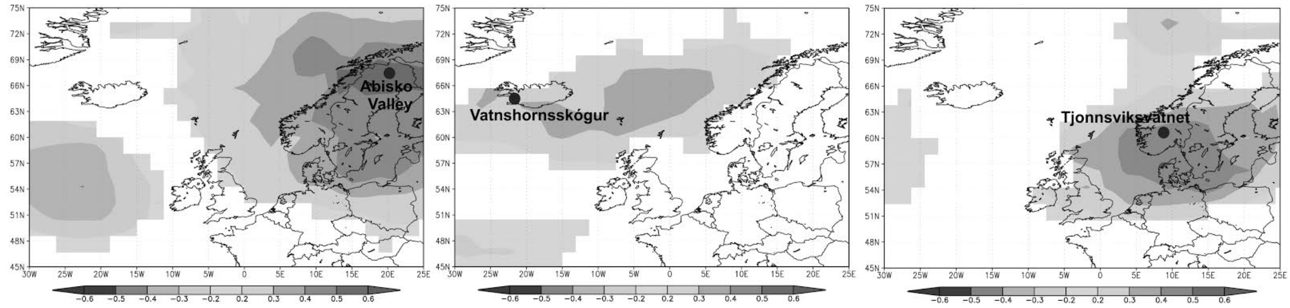

Figure 5: Spatial field correlations of the TRW chronologies (VAT, TOK, ABI) computed against gridded JJ temperature of the common period 1902-1983 (20th Century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA).

Summary

1. The studied trees exhibited significant irregularities of growth including both anatomical features and characteristics of TRW. Anomalies are related to the climatic factors (e.g. commonly occurrence of frost during growing season) and biological factors (reindeer and sheep grazing, insects outbreaks - mainly *Epinotia solandriana*).
2. Strong influence of these local and short-lasting factors does not diminish the sensitivity of Downy Birch to one common climatic factor. All three chronologies reveal significant correlation to summer: June and June-July temperature.
3. The spatial correlation of the TRW chronologies and climatic factors reveals wider spatial window for trees from North rather than South of Scandinavia or Iceland.
4. The shortage of detailed metadata for the chronology obtained from ITRDB limits the study to the basic analyses. The lack of the information of the missing rings in TRW series from the coldest location is very contrasting to the high amount of these growth anomalies detected in two other, bigger sets of TRW data.

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SECTION 4

GEOMORPHOLOGY

Longitudinal and cross-sectional wood anatomy variability of vertical fir roots (*Abies alba* Mill.) as a record of landslide processes – an example from the Carpathian foothills

D. Wrońska-Wałach, A. Zielonka, M. Sobucki & B. Oleszko

Institute of Geography and Spatial Management, Jagiellonian University, ul. Gronostajowa 7, 30-387 Kraków, Poland
E-mail: dominika.wronska-walach@uj.edu.pl

Introduction

Changes of wood anatomy within a tree root occur when environmental conditions such as temperature, aeration, moisture, soil compaction as well as mechanical stress along the root change (Rowe, 1964; Fayle, 1968, 1975a, 1975b; Shea, 1973). The most significant anatomical changes occur when soil is removed off the root due to exposure to external conditions (Fayle, 1968; Gärtner, 2003, 2006). Analyses of changes in the structure of annual rings in tree roots are considered to be a useful tool in geomorphology and are taken into account in the context of a range of morphogenetic processes (Gärtner et al., 2001; Gärtner, 2003, 2006, 2007; Malik & Matyja, 2008; Stoffel & Bollschweiller, 2008; Corona et al., 2011). Gärtner et al. (2001), as well as Malik (2006, 2008), stressed that by analysing changes in the wood anatomy of roots exposed to external factors the intensity of past morphogenetic processes can be retraced. One of the processes which cause the exposure of roots is landsliding.

In 2010 a significant amount of rainfall occurred in Central and Eastern Europe. Activation of rainfall-induced landslides in mountain and foothill areas was the consequence of these meteorological conditions (Bartholy & Pongracz 2012). Following field investigations, one of these landslides in the Wiśnickie Foothills (Polish flysch Carpathians) was recorded and analysed in detail. The activation of the study landslide caused the exposure of roots and bending of trees. Three vegetation cycles later root samples were collected in the field and anatomical changes within the roots were analysed by referring to 2010 (when the activation of the landslide occurred). Exposed roots tend to form annual rings with a higher amount of latewood including compression wood (Alestalo, 1971; Carrara & Carroll, 1979; Gärtner, 2003, 2007; Rubiales et al., 2008; Wrońska-Wałach, 2009, 2014). Furthermore, after exposure the mechanical function of the roots starts to perform an important role as a consequence of which the entire structure of the roots' wood anatomy changes and wide wedging rings are formed (Fayle, 1968; Gärtner, 2003; Pérez-Rodríguez et al., 2007; Zielonka et al., 2014). Such assumptions were mainly based on the analysis of exposed horizontal roots. Fayle (1968) emphasised that, in the analysis of the growth pattern of roots, the location and orientation of the root within the root system is of high relevance. The growth pattern of horizontal roots differs significantly from the one which is typical for vertical roots (Fayle 1975a, b). Therefore, the main aim of the research was to detect the activity of landslide processes by means of wood anatomy analysis of exposed vertical fir (*Abies alba* Mill.) roots; the above-mentioned were rarely investigated before. This raises the question whether the record of the exposure of vertical roots by landslide processes is the same in the longitudinal and cross sectional profile of the root.

Study area

The research was carried out on a small landslide (0.14 ha) in southern Poland which was activated after spells of heavy rainfall which occurred in the Carpathian Foothills in 2010. The study area is located in the Wiśnickie Foothills (N: 49°56'47.95'' E: 20°30'21.3''). The study site was located in the headwater area of the Stara Rzeka stream where landslides are common features. The bedrock of the Wiśnickie Foothills is made of flysch which is covered by loess. The study site belongs to the lower mountain vegetation belt in which there are deciduous beech forests with common European silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.). The study landslide is composed of a single niche and tongue (Figure 1) and located at 280-288 m a.s.l. The scarp of the landslide is 68 m long and 8 m high. The average annual precipitation totals in the study area for the period 1954-2012 are between 400 and 600 mm during the vegetation season. In 2010 total precipitation in May and June was about 500 mm, which was the main reason for the activation of the study landslide.

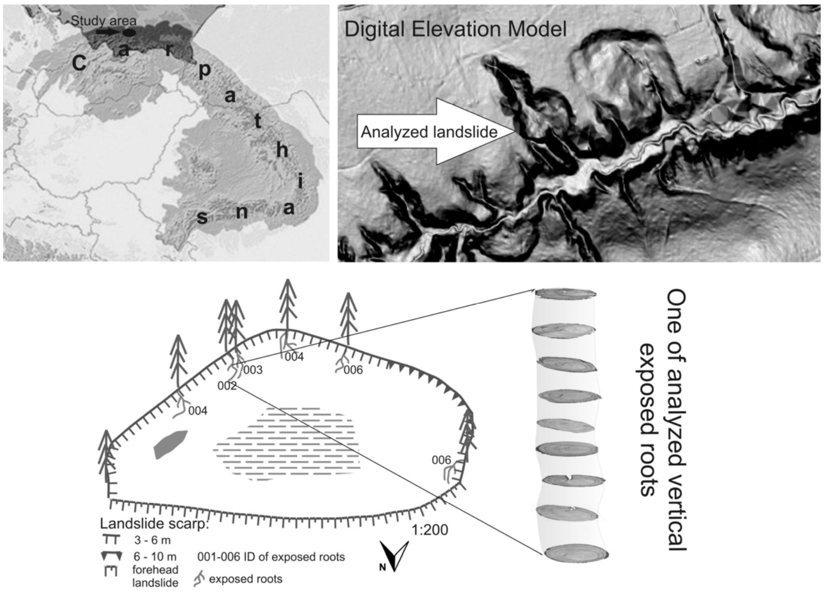

Figure 1. Study area: A – location of site in the Carpathians; B – study site – digital elevation model; C – outline of the landslide together with an example of one of the roots analysed (001-006 – roots ID)

Methods

Detailed geomorphological mapping was conducted in the study area. The activity of the landslide was investigated by exposed vertical fir roots, one of which was analysed in detail. The root was sampled 1 m from the trunk to reduce errors resulting from anatomical changes induced by stem sway, such as compression wood and false rings (Fayle 1968, 1975, LaMarche 1968). Eight samples were prepared from the root and used for further analysis. All samples were taken about 5 to 7 cm from each other to examine the anatomy of tree rings in different parts of the root. Root parts were polished and cut into 15-20 µm slides by the use of a GSL 1 Microtome (Gärtner et al. 2014). Microanalysis of root cross-sections was performed according to the procedure developed by F. Schweingruber (1990) and Gärtner et al. (2001). After laboratory preparation, images of the micro-sections were made using a polarising microscope (Nikon 50iPOL). The anatomical indicators on the basis of which the identification of the year of root exposure was established were the size of earlywood cells (EW) (Gärtner et al., 2001; Gärtner, 2003, 2006), the percentage of latewood (LW), the presence of compression wood (CW) and ring width (RW) (Bodoque et al., 2005, 2011; Corona et al., 2011; Wrońska-Wałach, 2014). Measurements of EW, LW and RW were performed using the WinCELL Pro software (Regent 2010) on each cross-section obtained from serial sectioning of the root. Visual detection of the first indication of exposure was carried out on the whole cross-section. Measurements were made on at least 30 tracheids and in four radii per cross-section (including the longest and the shortest radii) to check the differences between the anatomical indicators of tree rings (Figure 2). In addition cross-dating was carried out on the samples analysed.

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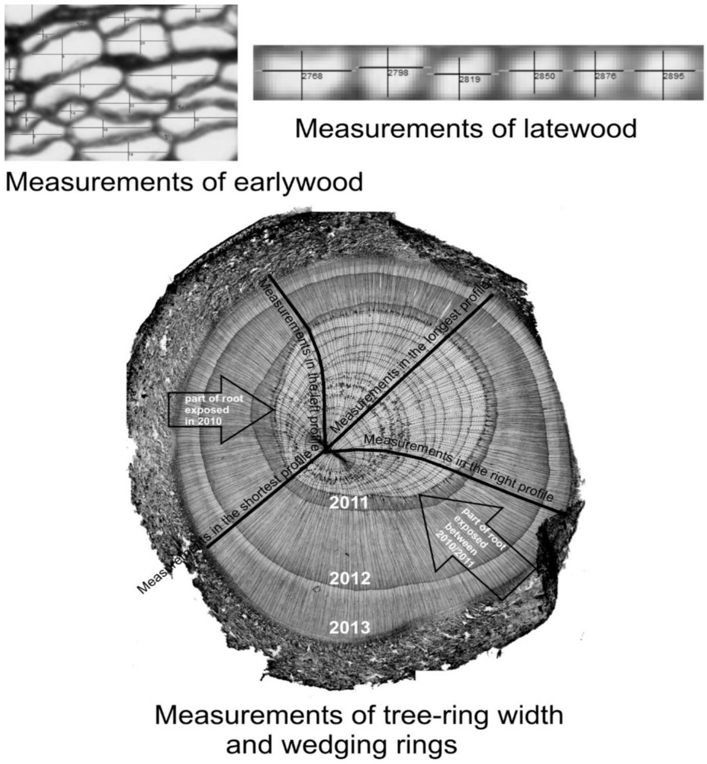

Figure 2. Root cross-section with four radii marked and an example of the anatomical indicators analysed in WinCELL.

Analyses of eccentricity and circularity were performed for every annual ring between 2008 and 2013. Within each cross-section each of these annual rings was vectorised in QGIS, creating a polygon having the shape and size of a whole root cross-section in the corresponding year. Geometric centres were calculated for each annual ring analysed in every cross-section; the actual centre of the root within each cross-section was marked as well. Distances between the actual centre of the root and the corresponding geometric centres were measured in every cross-section. These distances were presented as a percentage of the corresponding average root radii (calculated from the cross-sectional areas). The above steps allowed the dominating root-growth direction before and after exposure to be traced. The circularity of each annual ring was calculated by dividing its surface area by the surface area of a circle having the same perimeter.

Results

The analysis conducted proved that the anatomical changes along the longitudinal and cross-sectional profile of root wood are varied and occurred from 2009 to 2012 depending on the location within the root. The majority of the anatomical changes in tree rings in the roots appeared in 2010 (41%); many fewer were recognized in 2011 (30%). A relatively significant number of changes occurred in 2012 (24%) – about two years after activation of the landslide. Changes in EW were mainly recognized to have happened in 2010 (61%) and 2011 (21%). Nevertheless, in three of the cross-sections these changes did not emerge until 2012 (Figure 3). If we take into account the changes in LW, most (64%) took place in 2010, but some also occurred in 2011. In most cases (56%) increase in RW appeared two years after activation of the study landslide.
The first anatomical changes which indicate exposure were recognized in 2010, and are varied in the longitudinal profile. Maximal RW, developed in 2010, is from 436 μm in the upper part of root to 964 μm in the lower part. The analysis revealed diverse changes of EW in longitudinal profile (from 690 μm to 1119 μm) and increase of the LW content from 21% to 98%. The maximum width of the 2010 tree-rings increases suddenly in the lower part of the study root. Moreover, this ring tends to

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wedge in cross-section and longitudinal profile. In the longest radius, the 2010 ring is either reduced to one or two rows of tracheids with no signs in LW connected with exposure or has completely disappeared. Changes of anatomical indicators for the 2011 ring are less variable in longitudinal profile with no evidence of wedging.

In most of the cross-sections in the longest of the radii analysed, the increase in the percentage of LW in tree-rings appeared in 2010. However, the stem-like RW and CW did not emerge until 2011. In the shortest radius the same amount of anatomical change was recognized for rings from 2010 and 2011. In the left and right radii of cross-sections most EW changes occurred in 2010 (Figure 3). No regularity in the longitudinal profile was observed for the above-mentioned indicators.

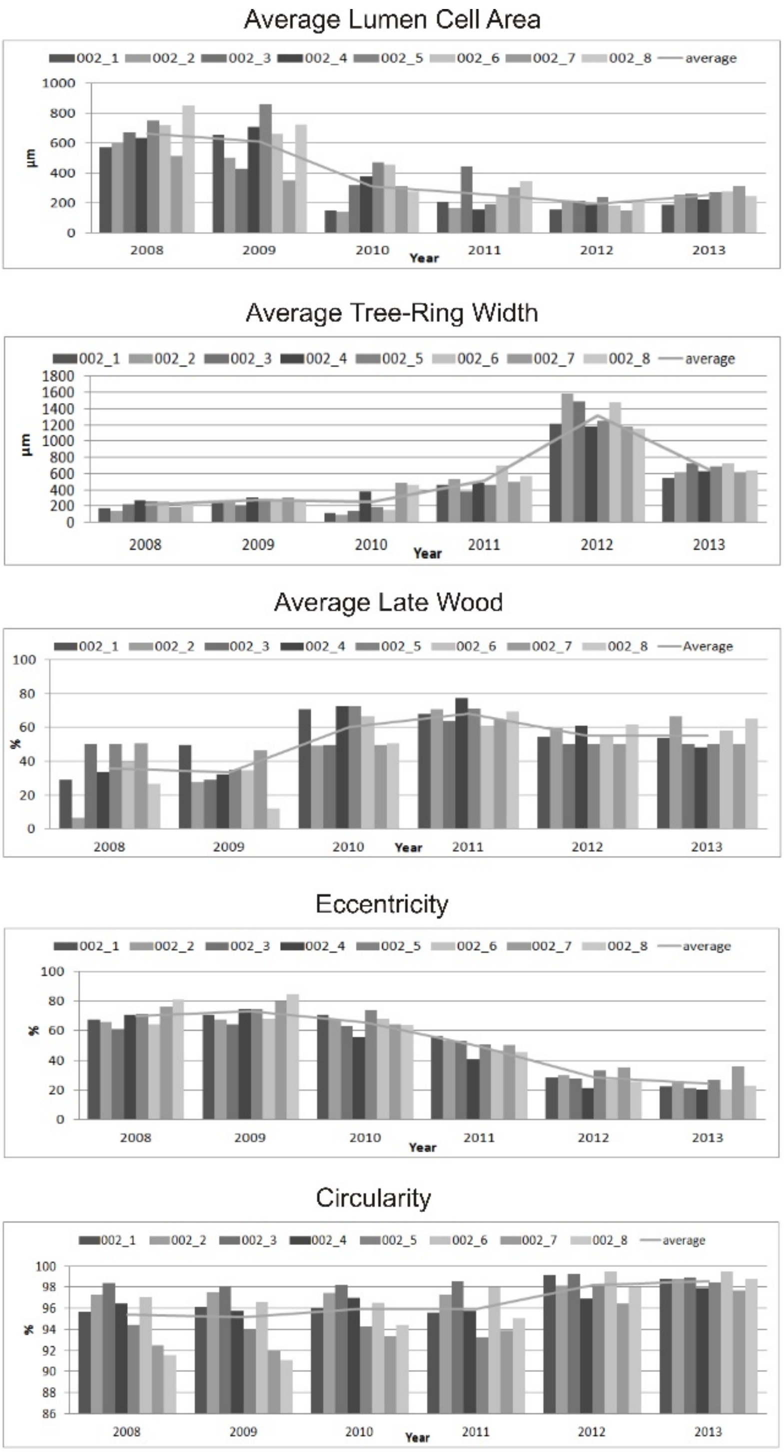

Figure 3: Variation in tree-ring wood anatomy parameters in eight cross-sections of exposed vertical fir root (002_1 – 002_8) in the period 2008-2013.

After root exposure the eccentricity decreased from an average 72.6% in 2009 to an average 24.5% in 2013, while circularity increased from an average 95.2% to an average 98.4%. The study root was clearly increasing its eccentricity until 2009 with 9-10 wedging rings recognised. In 2010 the root eccentricity decreased in most cross-sections, mainly in the lower part of the root. The first year when eccentricity substantially decreased in the whole root was 2011 (Figure 3). In 2010 a noticeable increase in circularity was noted in the cross-sections having the highest RW which influenced average increase. After nearly no change in 2011, a substantial increase in circularity occurred in the whole root apart from one cross-section in 2012, an increase continuing in 2013.

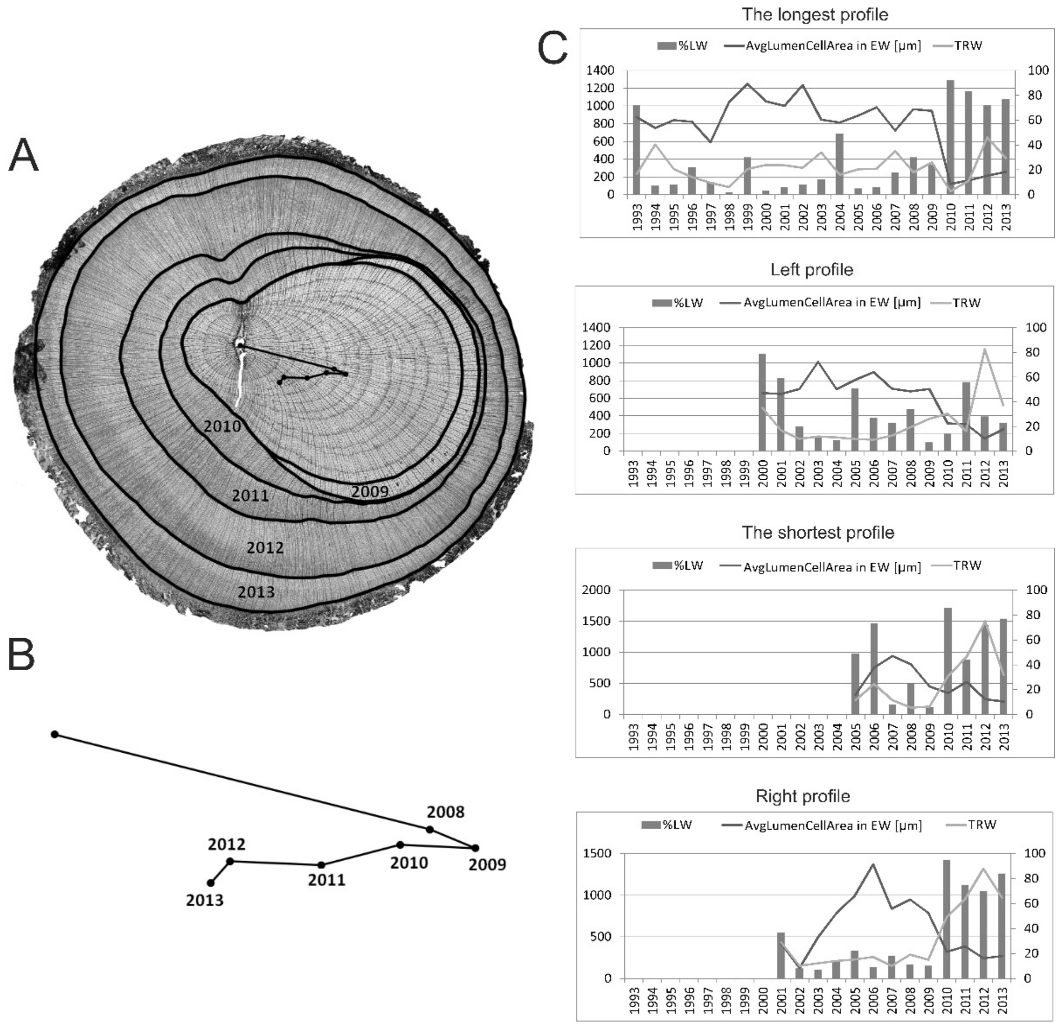

Figure 4. Characteristics of a typical root cross-section (002_8): A – growth pattern, B – geometric centre path (upper left point indicates the actual centre of the root), C – annual tree-ring parameters in four radii

Discussion

Exposed vertical fir roots have a similar tendency in overall structural change in wood anatomy to that found in horizontal roots analysed previously by different researchers (Alestalo, 1971; Carrara & Carroll, 1979; Gärtner, 2003, 2007; Rubiales et al., 2008; Wrońska-Wałach, 2009, 2014). Fayle (1968) as well as Gärtner (2003) emphasised that after exposure the mechanical function of roots starts to perform an important role, as a consequence of which the entire structure of root's wood anatomy changes. An increase in root eccentricity is usually observed after exposure. The shape of the study root as well as of other roots observed in our study area does not follow general rules. In these cases the roots are eccentric with wedging rings before exposure and are becoming concentric after exposure.

As we consider the root exposure by landslide processes directly observed in the field, we know that the root was exposed in 2010. Therefore, we referred all wood anatomy parameters analysed to that year. In 61% of cases the changes of EW occurred in 2010 and the analysis confirmed that EW changes are the most important indicators for recognising the year of exposure (Gärtner et al., 2001; Gärtner 2003, 2007). Nevertheless, selection of a suitable root sampling location is very important. Our results showed that in some parts of the root the EW anatomical changes are shifted by about one to two years. It is also indisputable that it is necessary to analyse the whole cross-section when dealing with exposed roots as we found a clear differentiation in the EW changes in the four measured radii.

According to Malik (2006, 2008), when the changes in EW occur at the beginning of the ring, the exposure occurred in the previous year or during the dormant season. In our analysis we know that the root was exposed abruptly at the beginning of the vegetation growth period in 2010 and that the first changes in both EW and LW were already visible in 2010. The ring from 2010 is not completely formed and wedges in both cross-sections and longitudinal profile. An increase in RW and percentage of LW, which are considered as indicating upcoming root exposure (Fayle 1968; Gärtner 2003; Rubiales et al., 2008) were not observed in rings developed in 2008 and 2009, which confirms abrupt exposure in 2010. In subsequent years, the mechanical function of the root became more important, therefore the root produced CW. As secondary growth of the root, normally affected by climatic conditions, was enhanced by the production of CW (Timell, 1986; Schweingruber 1991), an increase in RW and amount of LW occurred (Figure 2, 4).

Variability in longitudinal and cross-sectional wood anatomy of vertical fir roots exposed by landslide processes may be a result of either stepwise exposure or the different response of different parts of roots to a single event. Within each part of the root the first changes of EW and LW occurred in 2010, but the signal is variable in the cross-section of the root. As it is a vertical root, when EW tracheids decrease and the average lumen size area is only varied in the cross-section of the root, the exposure of the root is more likely to be a result of a single event as a result of which variation in stress occurred along the root. The consequence of single event exposure could also be observed in terms of longitudinal changes in the 2010 tree-ring resulting in a decrease in eccentricity and an increase in circularity.

Conclusions

1. The main direction of radial growth within the root tends to change with time, especially after events which modify the distribution of mechanical stress and cause the production of compression wood. The above-mentioned seems to apply to vertical roots in general and was observed in all the roots examined originating from the study site.
2. In vertical fir roots concentricity and circularity increase after exposure. The response within the root is varied in longitudinal profile as a result of different mechanical stresses. The first ring after root exposure tends to wedge in longitudinal and cross-sectional profile and may be very narrow or missing in some places within the root.
3. In addition to the horizontal roots, the vertical roots in root systems could also be taken into account in the analysis of landslide processes. However, the analysis of a vertical fir root in one location on the root does not incorporate sufficient data on root exposure. Selection of sampling is of great importance and serial sectioning of a root seems to be the best solution.

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Dendrogeomorphological study on snow avalanches in the Tatra Mountains (Southern Poland)

M. Lempa[1], **R. Kaczka**[1], **K. Janecka**[1] **& Z. Rączkowska**[2]

[1]Faculty of Earth Science, University of Silesia, Sosnowiec
[2]Institute of Geography and Spatial Organization, Polish Academy of Sciences, Cracow
E-mail: michciosam@interia.pl

Introduction

Snow avalanches are the major natural hazard influencing the natural environment, tourist infrastructure and also endangering human life in the Tatras. The activity of snow avalanches affects forests by controlling the course of the timberline. Avalanches are the main factor limiting the warming-related upslope advance of the subalpine forest. Snow avalanches in Poland occur only in the Tatra Mountains, the Babia Góra massif (the Polish Flysch Carpathians) and the Karkonosze Mountains (the Sudetes).

The research of avalanches in Poland started in the 19th century but was conducted in an irregular and unsystematic way. Methodical records of snow avalanches have been kept only since the beginning of the 21th century. No studies involving spatial reconstruction of snow avalanches by applying the dendrochronological methods and GIS techniques have been conducted in Poland so far. The aim of this study was to identify and analyze the main areas influenced by avalanches and reconstruct the spatiotemporal dynamics of the process in the Biały Żleb chute as a case study.

Study area

The study area is located in the Polish High Tatras (Western Carpathians) in the Rybi Potok Valley (Fig.1). The Biały Żleb chute is situated on the south-eastern slope of the Opalony Wierch range (2115 m a.s.l.). The chute is over 1 km long and about 300 meters wide. The altitude difference amounts to over 700 m (Cywiński 2005) from 1310 m a.s.l. to 2060 m a.s.l. The elevation of timberline in the part of the Biały Żleb is about 335 m lower than the average in the valley. The tourist trail running from the Morskie Oko Lake to the Pięć Statwów Polskich Valley crosses the Biały Żleb chute at a distance of over 450 m. Moreover, the chute crosses one of the most popular Polish tourist trails leading from Palenica Białczańska to Morskie Oko and is visited by more than 600 000 people per year. Thus, due to the avalanche during winter the road is often closed and an alternative trail is used.

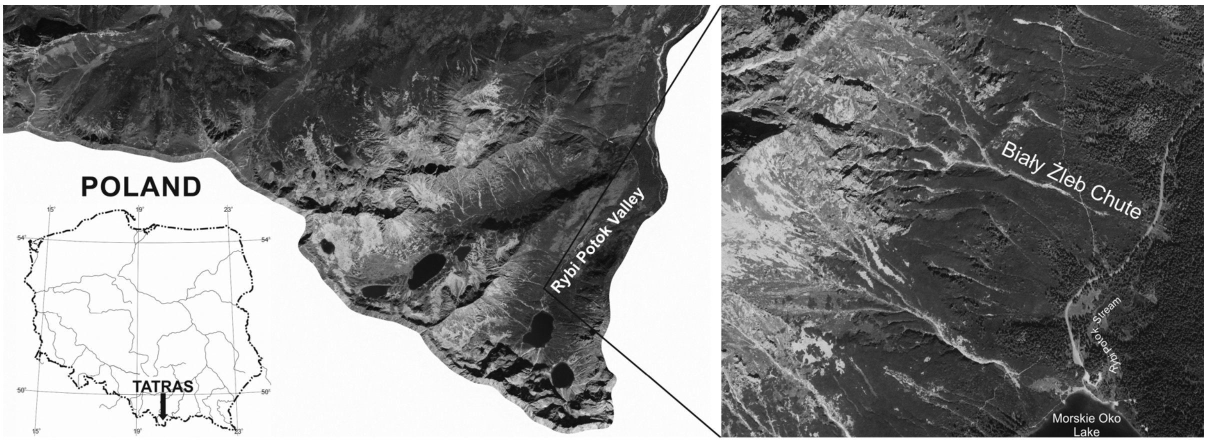

Figure 1: Location of the study site.

Methods

The research was conducted using standard dendrochronological methods. A total of 1225 samples were taken from 537 trees growing at the bottom and sides of the avalanche path (Fig. 3A). Trees with recognizable crown and stem damage were selected for sampling. Samples were taken from the following tree species: *Picea abies* L Karst. (97% of the sampled trees), *Pinus cembra* L., *Sorbus aucuparia* L. and *Betula pubescens* Ehrh subsp. carpatica. Samples from trees with partly damaged stems (Fig. 2A) were collected from 3 places: directly from the scar (X), from above the damage in order to obtain a sample with resin ducts (Y) and from an undamaged part of the stem to obtain a complete sequence of growth-rings (Fig. 2B).

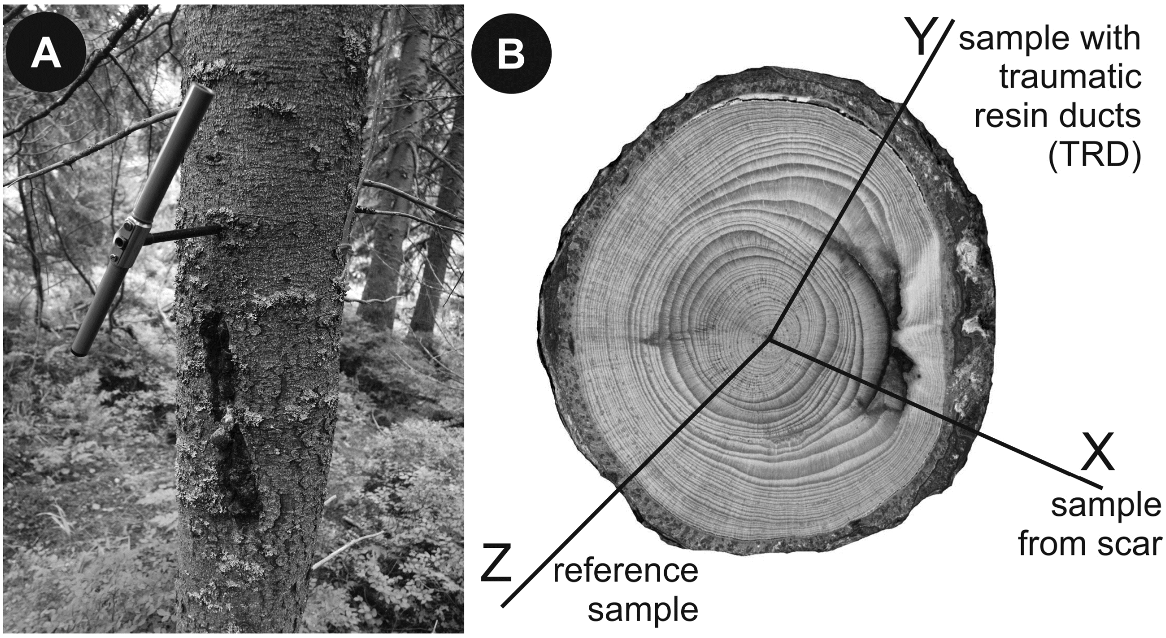

*Figure 2: A-Tree with damaged stem;*B-*The strategy of an injured tree sampling*

Each collected sample was provided with an individual code and the location of every tree was registered with GPS. Moreover, the circumference of a trunk, the height of the injury on the trunk and the size (length and width) of the damage were measured. The samples were glued into wooden laths, sanded and scanned in 2400 DPI resolution. The rings width measurements were made with CooRecorder 7.7 software provided by Cybis Elektronik & Data AB company (www.cybis.se). The obtained data were compared with the local chronologies from the Rybi Potok Valley. In case of decapitated trees or those with a partly damaged crown, determining the time of the avalanche event consisted in finding adequately long and clear growth reduction. In order to identify the year of decapitation, samples were taken from below the damage. Usually one Z sample was collected from a decapitated tree. However, in case of a tree with more than one decapitation, an adequate number of samples, respectively to the amount of injuries, was obtained – always from below the damage in order to find each single growth reduction signal. Altogether 192 samples from 172 trees bearing decapitation marks were analyzed.

For trees with scars from partly damaged stems the determination of the time of the avalanche event was based on specifying the difference in the number of growth-rings between the Z and X samples. The Y sample was used to analyze the occurrence of traumatic resin ducts (TRD). Only such Y samples in which TRD appeared in the early wood were considered an avalanche event (Bollschweiler et al. 2008). A total of 1033 samples from 365 trees bearing marks of partly damaged trunks were examined.

In order to specify the frequency of the events for particular years the avalanche activity index(Decaulne et al. 2012), which is the quotient of the number of trees in which the signal appeared in a particular year and the number of trees growing that year, was applied (Schroder 1978).The index is expressed as a percentage.

$$AAI = ((\sum_{i=1}^{n} Rt) \div (\sum_{i=t}^{n} At)) \times 100$$

The spatial analyses were done with the use of ArcGis10 software provided by ESRI company (www.esri.com). The numerical elevation model was created on the basis of the LIDAR data and employed to study the details of the relief of the lower part of the avalanche runout sector. 9 zones which corresponded to the relief were defined (Fig. 3B). In order to indicate the major avalanche events for the entire avalanche runout sector, a threshold of 5% was employed. The determined value is lower than the values referred to the subject in literature (Dubé et al. 2004; Butler et al. 2010), whereas a threshold of 10% was employed for each of the 9 zones.

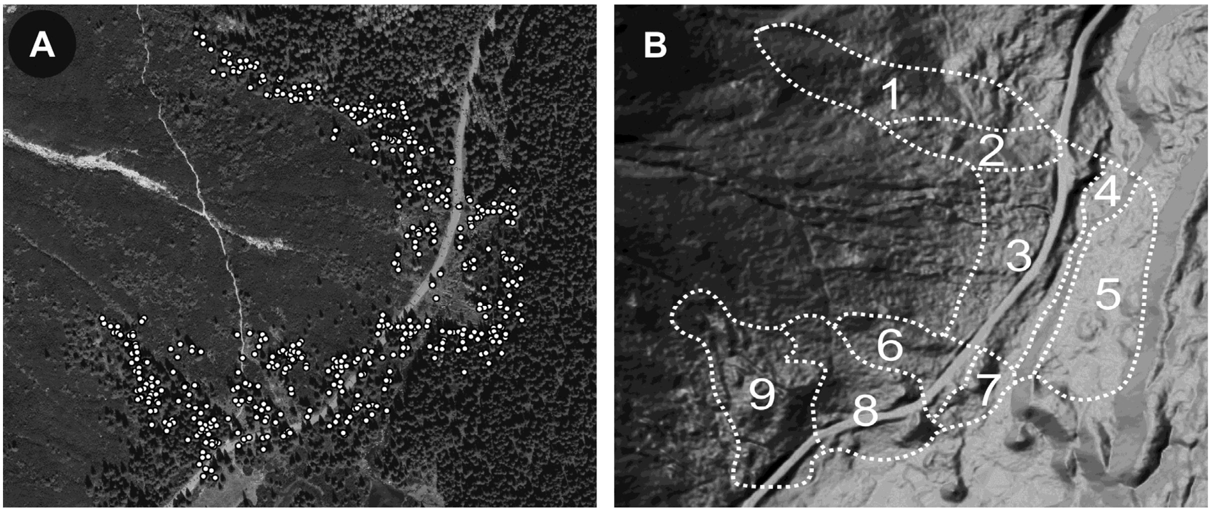

Figure 3: A-distribution of studied trees; B-*9 zones of avalanche runout sector determined on the basisof relief analyses*

Results and discussion

The conducted dating of scars and decapitations allowed to establish an over 100-year chronology of avalanche events for the Biały Żleb chute. Five main avalanche events were detected: 1912/1913, 1923/1924, 1954/1955, 1961/1962 and 2008/2009 (Fig. 4).

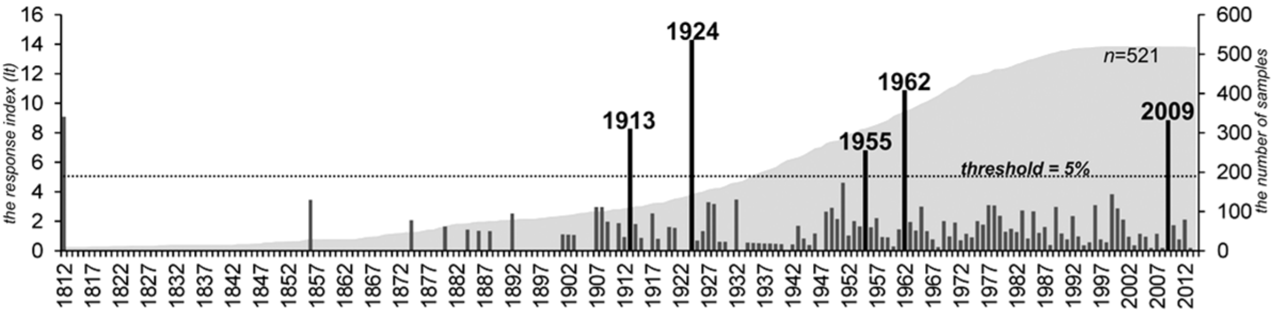

Figure 4: Chronology of avalanche events for the Biały Żleb chute.

GIS comparison of historical and recent cartographic data (aerial photos from 1955 and 2012) shows that the timberline in the studied avalanche path is stable and none of the reconstructed avalanches has changed it significantly. Furthermore, the five tree-ring reconstructed major events reveal a similar spatial range (Fig. 5). The avalanches during the winters:1912/1913, 1923/1924, 1954/1955, 2008/2009 crossed the road to the Morskie Oko Lake and the Rybi Potok Stream, encroaching on the opposite slope. Only during the winter 1961/1962 the main body of the avalanche stopped immediately behind the road.

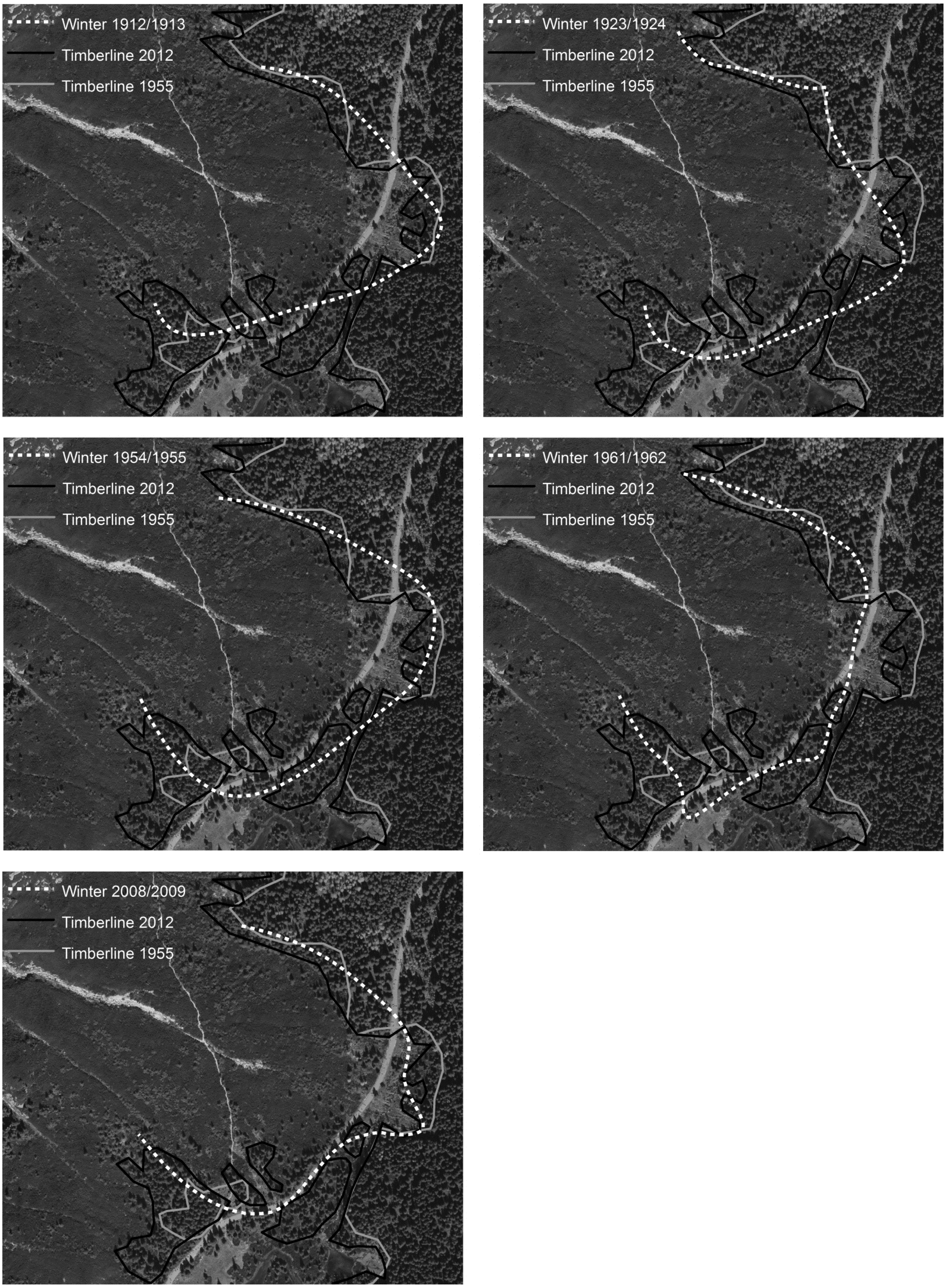

Figure 5: Spatial reconstruction of 5 main avalanche events (white dashed line) confronted with the timberline course in 1955 (grey line) and 2012(black line).

The reconstruction of the avalanches shows that in the winters of 1912/1913, 1923/1924, 1954/1955, 1961/1962 and 2008/2009 the nature of the avalanches which came along the entire length of the chute, was similar. It may indicate similar snow conditions due to which the avalanches descended. The division of the runout zone allows to identify the local minor avalanche events.
The analysis of each of the 9 zones (Fig. 3B) shows that avalanches in the Biały Żleb chute did not always cover the entire chute. Although at least one of the main events is always presented in the reconstruction which was done for separate zones. Based on the study, several new events were detected (Fig. 6), the number of which increased up to 13. In the sectors 2, 6 and 9 located in the lower lateral part of the chute respectively 6, 5 and 5 events were registered.

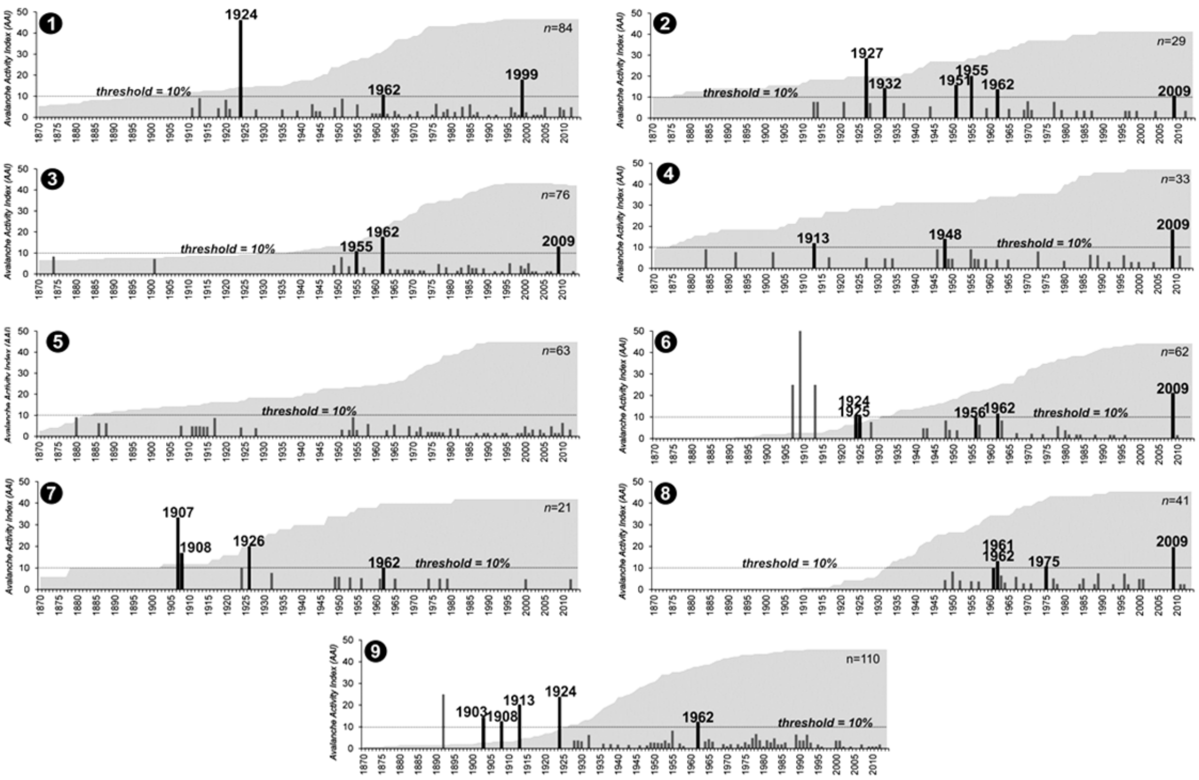

Figure 6: Local avalanche chronologies for the 9 mapped out zones

Conclusions

- A 100-year-long avalanche chronology was established and 5 main avalanche events were reconstructed: 1913, 1924, 1955, 1962, 2009.
- The 5 main identified events had similar magnitude at the point of entering into the forest.
- The detailed analyses conducted in the 9 zones of the runout sector revealed uneven activity of avalanches in different parts of the path. As a result, 8 new events were identified.
- The results of the tree-ring reconstruction couple well with the GIS analyses of historical cartographic data. The changes of the timberline course of the runout sector correspond to the reconstructed range of avalanches.

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Tree-ring dating of lateral and terminal Little Ice Age moraines of four glaciers in southeast Tibet

P. Hochreuther[1], D. Loibl[2], J. Wernicke[1], J. Grießinger[1], H. Zhu[3] & A. Bräuning[1]

[1]Institute of Geography, University of Erlangen-Nuremberg, Am Wetterkreuz 15, 91058 Erlangen, Germany
[2]Department of Geography, RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany
[3]Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China
E-mail: philipp.hochreuther@fau.de

Introduction

The eastern Nyainqêntanglha Range contains more than 10,000 km^2 of monsoonal temperate-type glaciers that are highly sensitive to climate change (Fujita and Ageta 2000, Su and Shi 2002). Recent studies have shown that glacier mass loss in this area significantly exceeds the average in High Asia (Bolch et al. 2012, Gardelle et al. 2013, Neckel et al. 2014, Yao et al. 2012). However, the coverage of the heavily glaciated southeastern Tibetan Plateau (TP) is comparatively low and remote sensing-derived time series are too short for a recognition of long-term trends. The maximum of the LIA glaciation, just like phases of glacier advances and retreats, varies distinctly between and within different parts of the Tibetan Plateau (Xu and Yi 2014; Yi et al. 2008). It has been stated by numerous authors that topographic factors and local conditions play an important role for mass balance and equilibrium line altitude (ELA) calculations (Benn and Lehmkuhl 2000; Owen and Benn 2005), and also on the succession dynamics of trees in glacier forefields (Sigafoos and Hendricks 1969; Villalba et al. 1990). Regardless, a comprehensive analysis of the impact of these factors on moraine ages has not been done for the eastern Nyainqêntanglha Range.

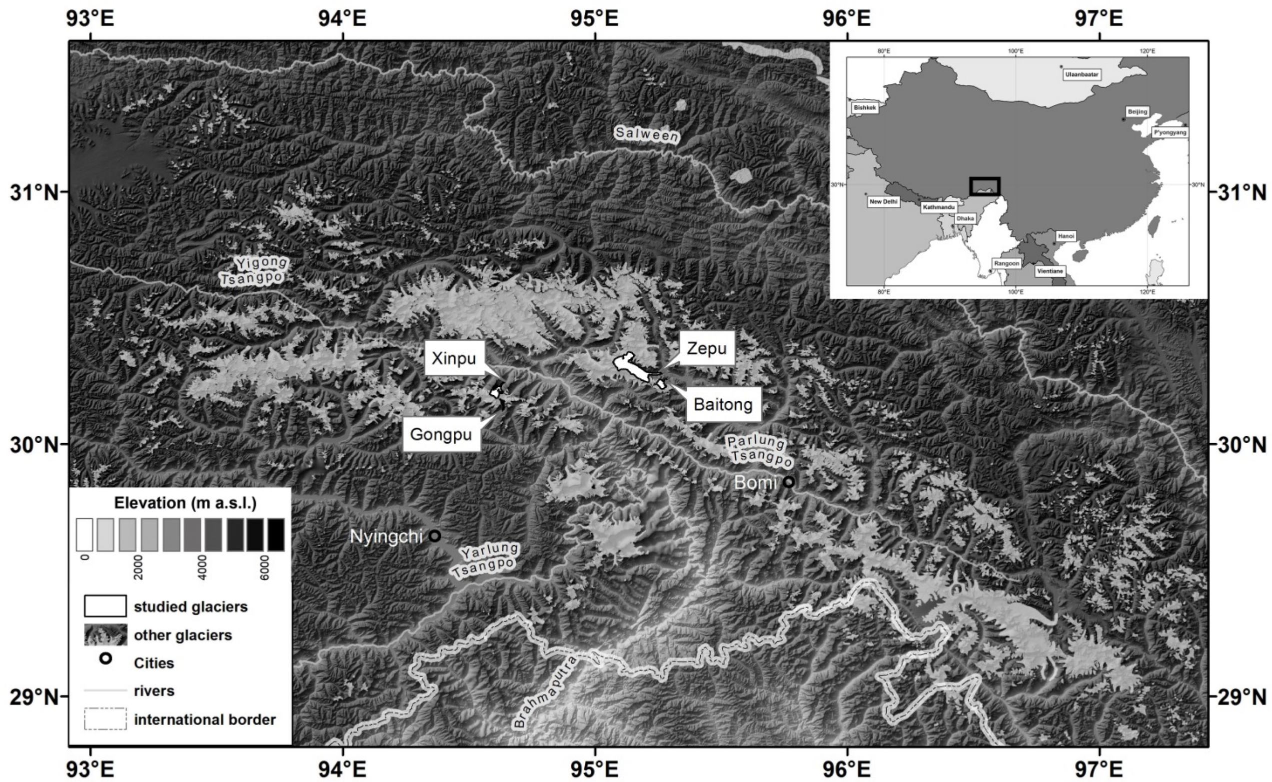

Figure 1: Topography of the eastern Nyainqêntanglha Mountain Range with locations presented in this study.

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To provide precise age estimates of glacier moraines, we used the ages of trees growing on glacier deposits as estimates for minimum moraine ages. In a next step, these dates were related to geomorphological features in the respective glacier forefields.

Materials and methods

Site characteristics

The study area is located on the southeastern TP, Xizang autonomous region, China (Fig. 1). Though still being strongly glaciated, the ice masses of the region show a rapid decline in the last decades (Ding et al. 2006, Yang et al. 2008). The retreating glaciers leave prominent deposits and recently deglaciated forefields located at elevations below 4000 m a.s.l. This is far below the upper forest limit located at around 4500 m a.s.l. in the region, leading to a quick primary vegetation succession (Bräuning 2006). The regional climate is dominated by the Indian Summer Monsoon system during the vegetation period (May – September). Valley bottoms receive 700-900 mm precipitation/year, while mountains, glaciers and their adjacent valleys are expected to receive a multiple of that (e.g. Böhner 2006, Su and Shi 2002).

Sikkim Larch (*Larix griffithii* J.Hooker) is a shade intolerant deciduous pioneer conifer tree species. Larch forests in SE Tibet usually occur at morphologically active and well drained slopes at 3000–4100 m a.s.l. (Wu and Raven 1999). It is the pioneer species colonizing Little Ice Age (LIA) moraines and former subglacial till in tributary valleys of the Yigong- and Parlung Tsangpo valleys (Fig. 1). *Picea balfouriana* (syn. *P. likiangensis var. rubescens*), is the dominant species of late-successional tree stands in undisturbed forests. Thus, these individuals are of similar or lower age at sites that underwent a vegetation succession within the past centuries. *Hippophae* is a pioneer shrub species colonizing the bare forefields, while various *Rhododendron* species dominate the understory of the conifer forests. No evidence of fire and insects disturbances was found at the respective sites.

Increment cores were collected during three field trips in 2011-2013. Where possible, trees growing on the crests were sampled on both the lateral (LM) and terminal (TM) moraines. In those cases where terminal moraines were sampled, we included trees from the outer slope to gain knowledge about the advancing succession.

Data treatment

In a first step, all cores were air-dried and sanded. Ring-width was measured using a LINTAB 6 linear table with TSAPWin software (Rinntech, Heidelberg, Germany).The resulting series were cross-dated statistically and visually, and site chronologies were built to ensure correct dating. All calculations, except direct ring width measurement, were performed using the R environment for statistical computing (http://www.r-project.org) in combination with the dplR package (Bunn 2008). In cases when the pith of a tree was missed, curvature and width of the innermost rings were used to estimate the pith offset. This number was added to the tree-ring record.

Coring at breast height requires the addition of a growth correction to account for the distance to the root crown. We followed the estimate of Bräuning (2006), who used 10 years as a minimum estimate for the same species at Gyalaperi less than 50 km away. Morphological glacier properties were inferred from optical (Landsat ETM+, ASTER) and radar (SRTM) satellite data (see Loibl and Lehmkuhl (2014) for details).

Results and discussion

Moraine ages in the context of local morphology

Maximum ages of trees for the respective glacier sites, as well as important morphological parameters, are given in Table 1. Each of the two largest glaciers (Zepu and Xinpu, Table 1) form

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two lobes, indicating two isolated major advances during the LIA. At Xinpu, the beginning of the following retreats could be dated to 1663 and 1746 (Fig. 2a); at Zepu, the shorter one to 1785 (Fig. 2c). The dating of Baitong is based on one very old individual which exceeds all other sampled trees by 270 years. This indicates that the LIA maximum extent was reached before 1544 at this glacier, as it was possible for the tree to survive several readvances. Nonetheless, growth conditions between the16th and beginning of the 19th century were probably harsh enough to prevent germination and growth of further individuals.

*Table 1: Sampling sites visited in 2011-2013. Altitude T: altitude of glacier terminus in m a.s.l., Altitude S: altitude of mountain summit in m a.s.l. Aspect T: Orientation of the glacier terminus. Aspect A: Orientation of the accumulation area (above ELA). *LIA Maximum at Gongpu could not be determined due to heart rot of the sampled trees.*

Glacier name	Lat/Lon	Altitude T	Altitude S	Area (km^2)	Aspec t T	Aspect A	LIA maximum moraine age
Xinpu	N 30,245°/ E 94,636°	3310	6310	16.8	N	N	1746
Gongpu	N 30,134°/ E 94,631°	3900	6310	7.7	S	SE	*
Zepu	N 30,281°/ E 95,254°	3550	6364	72.4	E	E	1785
Baitong	N 30,263°/ E 95,292°	3580	5660	9.2	NE	N	1545

A common characteristic of all sampled glaciers is that trees on TM are of much younger age than those on the respective LM. The higher stability of the latter is a regular phenomenon and usually attributed to stronger fluvial erosion and mass movement at the glacier terminus (Fu and Yi 2009). Additionally, the source of the seeds is likely a compromising factor: while LM receive their seedlings from higher altitude slopes, the succession advances from below, i.e. lower altitudes, at the TM. This is indicated by a) a mean difference of 150 years in tree age between LM and TM, b) increasing age of trees downslope the TM at Gongpu, and c) species composition, as *Larix* is progressively replaced by *Picea* at the outer slope of the TM.

Furthermore, our analyses reveal that aspect is another important factor for glacier advance and retreat as well as for tree growth. This is best demonstrated by Xinpu and Gongpu glaciers, both descending from Mount Pulongu in opposite directions. Though the LM could not be dated as all sampled trees showed heart rot, the terminus of Xinpu still rests 600 m lower than the one of Gongpu, which can be directly attributed to its northern exposition and associated shading effects as well as reduced radiation angle. Likewise, recolonization of the TM crest occurred 15 years earlier at Gongpu (Fig. 2a, b). The recent ice bodies of Baitong and Gongpu glaciers are of comparative size, however, Baitong is able to prevail at much lower altitudes due to its northern exposition.

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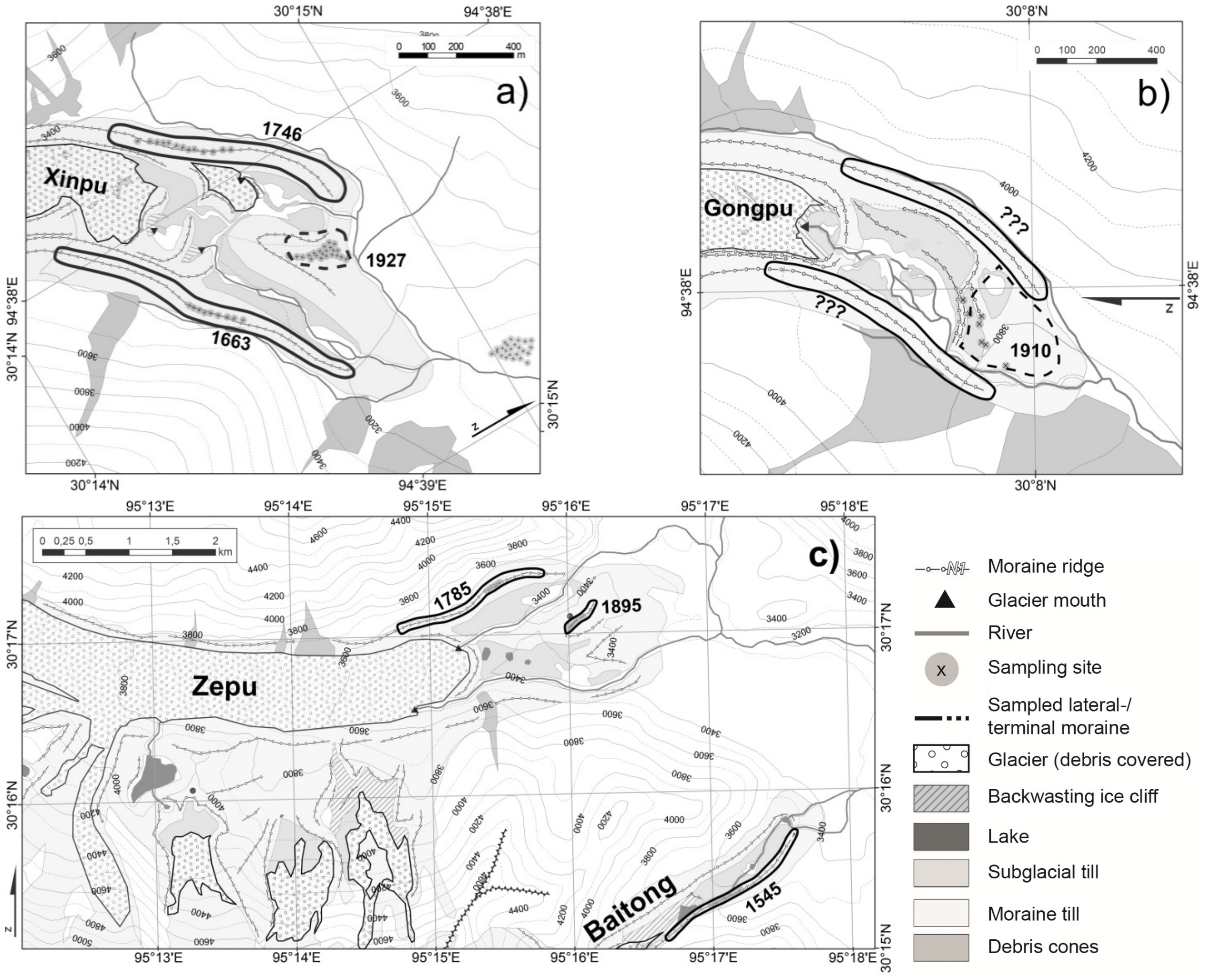

Figure 2: Glacial geomorphologic maps of (a) Xinpu-, (b) Gongpu-, (c) Zepu- (upper glacier) and Baitong glacier. Indicated moraine dates are maximum tree ages and thus represent minimum ages for glacier retreat phases.

Macroclimatic implications

Taking the similar two-lobate structure of the recent glacier forefields of Zepu and Xinpu into account, the dates of the two shorter lobes can be parallelized, indicating a regional glacier retreat between 1740 and 1790. Transferring this principle to the longer lobe would indicate a further retreat phase around 1660. Assuming that the germination of the Baitong tree marks the end of a first LIA advance, we may distinguish three major phases of glacial advances prior to 1540, 1660 and 1730. As a consequence, the preceding phases of glacial advances are expected to be either a reaction to lower temperatures, increased precipitation, or a combination of both. According to Grießinger et al. (2011), the LIA period between the 15th and 19th century was constantly moist, with major fluctuations occurring before 1500 and after 1800. Therefore, glacier fluctuations during the LIA are likely to be related to temperature, as suggested by several studies (Fujita and Ageta 2000, Fujita 2008, Bolch *et al.* 2010). This assumption is supported by northern hemispheric temperature reconstructions (Fig. 3).

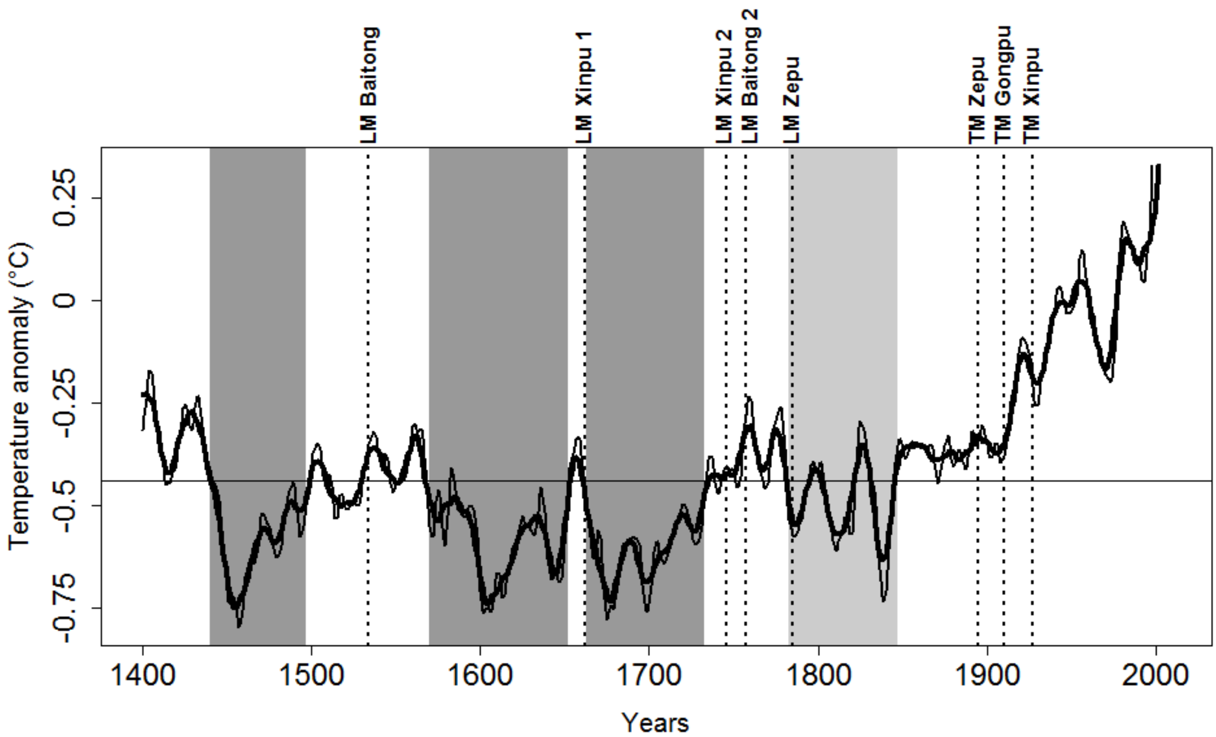

Figure 3: Northern Hemisphere land temperature anomalies (with respect to AD 1961 to 1990; Shi et al., 2013). Shaded areas represent cold phases where the 10-year running mean (thick line) falls below the median (horizontal line). Dotted lines show moraine dates.

The end of the 19th century marks the stabilization of the terminal LIA moraines. Assuming fluvial processes as a main factor for moraine instability, this may be evidence of reduced monsoonal precipitation or moisture during the summer months after 1850, as indicated by several studies (Grießinger et al. 2011, Sano et al. 2013, Wernicke et al. *in press*).

Conclusions

Our study underlines the importance of topographical and glaciomorphological factors, which have to be considered while a) choosing a suitable site and b) comparing the resulting time series to sites with different characteristics. The glacier response time to temperature changes is directly affected by glacier size (which is dependent on the morphology and steepness of the accumulation area) and aspect (and thus thermal energy, depending on insolation angle, shading effects and more). Lagged retreat from LIA high stands due to these factors can be up to 50 years in southeast Tibet and depends mostly on glacier size. Nonetheless, the number of confidently dated LIA moraines is still considerably low. Since especially larger-sized glaciers seem to express different phases of advances through forming prominent and datable moraine sets, we recommend those as preferable study objects.

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Rob Wilson

Rob Wilson has been a dendrochronologist for over 20 years and his main passion is the reconstruction of past climate over the last millennium. He has been based at the University of St Andrews since 2007 and is often seen "frolicking" through the Scottish mountains looking for sub-fossil pines.

Gerhard Helle

Dr. Gerhard Helle is senior scientist and head of dendrochronology laboratory of Section 5.2 at the German Centre for Geosciences GFZ in Potsdam. He is specialist for stable isotope dendroclimatology. His current interest is the invention and optimization of techniques for ultra high-resolution intra-annual isotope studies in tree-rings. These techniques shall help studying the climate and isotope signal transfer from atmosphere into tree-rings. Another objective of his reasearch is the natural climate variability since the last Late Glacial as reflected in tree-ring stable isotopes. Dr. Helle is teaching Dendrochronology at the FU Berlin.

Holger Gärtner

Dr. Holger Gärtner (1965) studied Geography and Geology at the University of Heidelberg, Germany. In 2001 he finished his PhD on variations in annual growth rings of roots caused by exposure due to various geomorphic processes. Since 2002 he is working as a research scientist specialized on wood anatomy at the Swiss Federal Research Institute WSL, Birmensdorf, Switzerland. His current research interests in focus on environmental changes and the resulting effect on the anatomical structures of various tree and shrub species. H. Gärtner has teaching assignments for Dendroecology at the University of Zürich (Geography) and for wood anatomy at the University of Basel (Botany). Once a year he is also teaching an international course on wood anatomy.

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