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A large-scale coherent signal of canopy status in maximum latewood density of tree rings at arctic treeline in North America

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ABSTRACT

We compared tree-ring width (TRW) and maximum latewood density (MXD) chronologies to remotely sensed indices of productivity (NDVI) and snowmelt since 1981 and to the instrumental temperature record at four arctic treeline sites in North America. Our results show that at these sites, TRW chronologies reflect temperatures less consistently than the MXD chronologies do and that the NDVI does not correlate significantly with TRW at high-frequency, i.e. when comparing yearly values. In contrast, the MXD chronologies correlate positively and significantly with NDVI and temperature during the growing season at all sites. Neither TRW or MXD chronologies appeared consistently influenced by the annual timing of snowmelt. A comparison of tree-ring chronologies and temperatures since 1900 confirms that MXD has tracked growing season temperature at these treeline sites throughout the past century. A spatial evaluation of the correlations further reveals that each of the MXD chronologies investigated here reflects interannual variation in NDVI and growing season temperatures across a large geographic region. As a result, they collectively provide a spatially comprehensive record of historic early-season canopy status as well as growing season temperatures for the high latitudes of North America.

1. Introduction

Higher northern latitudes are experiencing the greatest degree of climate warming on the globe today, and northern ecosystems are projected to undergo substantial change in the coming century (ACIA, 2004). Reconstructions of historic tree distribution suggest that vegetation at high northern latitudes can respond abruptly and non-linearly to climate change (Lloyd et al., 2003; MacDonald et al., 2008) and a northward expansion of forests into present tundra areas is predicted by global vegetation models under future climate scenarios (Lucht et al., 2006; Scholze et al., 2006). If such changes take place over large areas of the Arctic, they will dramatically alter global carbon cycling, land-atmosphere energy exchange, biodiversity patterns, and ecosystem functioning (Bonan, 2008). Therefore, the responses of tundra and boreal ecosystems to current and future climate variability need to be better understood, and in this context, trees growing at the forest–tundra transition, i.e. at arctic treeline, are of particular interest.

Tree-ring data from treeline sites have often been used for climate reconstructions because, in such settings, tree growth is primarily limited by climate, and at arctic treeline specifically by temperature, rather than by biotic factors such as stand dynamics (e.g. Cook and Kairiukstis, 1990). Tree-ring records of annual tree-ring width (TRW) and maximum latewood density (MXD) have proven to be useful proxies of growing season temperatures (Briffa et al., 1995; Jacoby and D'Arrigo, 1995). However, there are reports from a number of sites, mainly at high latitudes, that some metrics of tree growth, and tree-ring widths in particular, have increasingly diverged from temperature in recent decades (Briffa et al., 1998a, 1998b; Wilmking et al., 2004; D'Arrigo et al., 2008, 2009; Andreu-Hayles et al., 2011). Several causes for this loss of temperature sensitivity in tree-ring chronologies have been proposed (Esper and Frank, 2009), most notably a shift from temperature-limitation to moisture-limitation on tree growth (e. g. Jacoby and D'Arrigo, 1995; Barber et al., 2000; D'Arrigo et al., 2004a, 2004b, 2008, 2009; Beck et al., 2011a; Juday and Alix, 2012) and progressively delayed snowmelt reducing the annual period in which tree growth is most sensitive to temperatures (Vaganov et al., 1999).

Meteorological data recorded at weather stations are commonly used to evaluate tree ring records as climate proxies. Remote sensing data from Earth-orbiting satellites now provide a nearly 30-year record of the Normalized Difference Vegetation Index (NDVI), a landscape-level proxy for primary productivity (Myneni et al., 1997; Goetz et al., 2005; Pinzon et al., submitted for publication). This globally mapped vegetation index

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therefore provides the unique opportunity to evaluate the extent to which small-scale records of tree physiology in tree rings reflect not only variations in climate, but also in landscape or regional vegetation productivity. Furthermore, robust links between the satellite and tree-ring data resulting from such an evaluation could inform large-scale spatial extrapolations of historical tree-ring attributes from the dendrochronological record.

In interior Alaska, NDVI data support the growth decline observed over the last decades in spruce tree-ring records (Beck et al., 2011a). Similarly, Lloyd et al. (2010) showed that patterns of increasing and decreasing tree growth along a latitudinal gradient in Siberia match the fraction of the landscape showing positive and negative trends in summer NDVI, respectively. In a tundra area of Western Siberia, Forbes et al. (2009), and more recently Macias-Fauria et al. (2012), reported significantly positive correlations between NDVI in July and growth of shrubs determined from their ring widths. However, comparisons of tree rings to remotely sensed vegetation indices are still not abundant, and close to treeline, reported correlations of annual TRW of trees and NDVI can be low or non-significant (D'Arrigo et al., 2000; Kaufmann et al., 2004; Berner et al., 2011). While growth of mature spruce trees as well as NDVI has increased since 1982 in an ecotonal forest zone in Western Alaska, the high-frequency, i.e. year-to-year, changes in NDVI over this period were not consistently correlated with high-frequency changes in tree-ring widths (Beck et al., 2011a). Furthermore, Berner et al. (2011) documented cases of decreasing tree-ring widths in areas of increasing summer NDVI near treeline in northern Russia. In the latter case, the lack of agreement between the two metrics was attributed to low spatial density of tree cover in the study area. This potentially caused the NDVI data, which represents a spatially integrated measure, to reflect the canopy status of both trees and understory vegetation rather than tree productivity alone (Bunn and Goetz, 2006).

MXD chronologies often reflect current-year environmental conditions better than TRW chronologies do, because MXD appears to be less influenced by temperatures of previous years than TRW is (Frank and Esper, 2005; Andreu-Hayles et al., 2011). As a result, we hypothesized that high-frequency variation in MXD chronologies corresponded better to interannual variation in gross photosynthesis, as observed by NDVI. This hypothesis has not yet been extensively tested: D'Arrigo et al. (2000) found that MXD correlated positively with NDVI-derived net primary productivity over a relatively short period (i.e. <10 years) at three boreal sites, but did not investigate corresponding TRW series. More recently, Andreu-Hayles et al. (2011) demonstrated that NDVI over a 21-year period was correlated to MXD as well as TRW at a treeline site in northeastern Alaska, although during different times of the growing season.

Reconciling satellite observations and tree ring measurements at treeline would improve our understanding of the response of the treeline zone, and high latitude ecosystems in general, to past as well as future climate change. Therefore, we evaluated whether productivity indices extracted from tree rings and NDVI observations coherently describe the response of trees at the arctic treeline to recent climate variability. More precisely, we quantified how TRW and MXD chronologies at four treeline sites at high latitudes of western North America relate to the NDVI, snowmelt, and temperature records over the past three decades. We then extended the comparison between temperature and tree-ring data to most of the 20th century, and mapped the geographic extent of temperature and canopy status signals in the chronologies, in order to assess the temporal and spatial consistency of tree growth responses to climate variables.

2. Material and methods

2.1. Tree rings

Living and relict white spruce wood was sampled during the past decade and tree-ring chronologies (TRW and MXD) were developed for four locations near arctic treeline along a west–east gradient across Alaska and western Canada. The Seward Peninsula chronologies span the years 1389–2001 and were developed from collections made in 2002 at 14 sites at or near elevational treeline sites near the Tubutulik River (53 series, 65.1–65.2°N, 162.2°W, D'Arrigo et al., 2004a, 2005). The Firth River chronologies span 1067–2002 for TRW and 1073–2002 for MXD and were developed from samples collected at northern treeline at the Firth River in northwestern Alaska (232 series, 68.78°N, 142.35°W, Andreu-Hayles et al., 2011; Anchukaitis et al., in press). The Coppermine River chronologies span 1046–2003 for TRW and 1551–2003 for MXD and were developed for sites near the Coppermine River in the Northwest Territories, Canada (427 TRW series, 44 MXD series, 67.23°N, 115.92°W, D'Arrigo et al., 2009). Finally, the Thelon River chronologies span 1309–2004 for TRW and 1492–2004 for MXD and were developed from samples collected at the Thelon River near the border of the Northwest Territories and Nunavut, and is the easternmost of the four sites included here (86 TRW series, 183 MXD series, 64.03°N, 103.87°W, D'Arrigo et al., 2009). None of the sites had visible signs of recent fire or insect disturbance.

Individual raw TRW and MXD series were detrended using the Signal Free method (SF, Melvin and Briffa, 2008). After standardization and detrending, the individual series were combined into site-level chronologies using the biweight robust mean (Cook and Kairiukstis, 1990). The Signal Free method's ability to potentially mitigate 'trend distortion' and end effects that other standardization techniques may introduce motivated its application in this study of recent decades, when satellite and temperature data are available for comparison. Although high-frequency variation in chronologies is generally unaffected by the standardization procedure used, we also performed nine alternative procedures to ensure that the comparisons between tree-ring data and satellite or temperature data were not an artifact of the chosen treatment of the raw series. These alternative detrending and standardization methods included the standardized, and residual (autoregressive-standardized) chronologies produced after negative exponential (NEXP), regional curve standardization (RCS_PT, Cook and Kairiukstis, 1990; Cook and Peters, 1997; Helama et al., 2004), and 120-year 50% spline detrending (Cook and Peters, 1981).

2.2. Satellite data

We used the Global Inventory Modeling and Mapping Studies (GIMMS, version G) which is produced twice-monthly at 0.072° (~64 km^2) spatial resolution (Tucker et al., 2005) from data that the NOAA-Advanced Very High Resolution Radiometers (AVHRRs) have been acquiring since mid-1981. The spatio-temporal changes described by the GIMMS–NDVI since 2000 in the boreal zone of North America are consistent with those described by the more modern Moderate Resolution Imaging Spectroradiometers (Beck and Goetz, 2011). Globally, the GIMMS–NDVI captures vegetation's photosynthetic capacity best among other legacy (i.e. >25 years long) NDVI data sets (Beck et al., 2011b). Nonetheless, to prevent any potential idiosyncrasies in version G of the GIMMS–NDVI data from influencing the results, the analyses were repeated using a forthcoming version of the data set (version 3 g, Pinzon et al., submitted for publication).

Annual dates of snowmelt were mapped from version 3 and the version 3.1 update of Weekly Northern Hemisphere EASE-Grid Snow Cover data (http://nsidc.org/data/nsidc-0046.html, Armstrong and Brodzik, 2005). While these data are mapped on a 25 km grid, their actual spatial resolution is ~200 km. For each grid cell, snowmelt was initially assigned to the first snow-free date of the year. However, if that date was immediately followed by a snow-cover observation the next week, snowmelt was assigned to the next date without snow cover instead. This approach ignores any short snow-free periods in winter and unseasonably late snowfall events which are unlikely to cause a long-lasting snow pack. Instead, it quantifies the timing of the main spring transition from a snow-covered to a snow-free landscape.