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A novel stochastic method for reconstructing daily precipitation times-series using tree-ring data from the western Canadian Boreal Forest

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ABSTRACT

Tree ring data provide proxy records of historical hydroclimatic conditions that are widely used for reconstructing precipitation time series. Most previous applications are limited to annual time scales, though information about daily precipitation would enable a range of additional analyses of environmental processes to be investigated and modelled. We used statistical downscaling to simulate stochastic daily precipitation ensembles using dendrochronological data from the western Canadian boreal forest. The simulated precipitation series were generally consistent with observed precipitation data, though reconstructions were poorly constrained during short periods of forest pest outbreaks. The proposed multiple temporal scale precipitation reconstruction can generate annual daily maxima and persistent monthly wet and dry episodes, so that the observed and simulated ensembles have similar precipitation characteristics (i.e. magnitude, peak, and duration)—an improvement on previous modelling studies. We discuss how ecological disturbances may limit reconstructions by inducing non-linear responses in tree growth, and conclude with suggestions of possible applications and further development of downscaling methods for dendrochronological data.

1. Introduction

Precipitation is a fundamental driver for both ecological and anthropogenic systems. Yet our understanding of historical precipitation patterns is typically limited to annual time scales and many records of daily precipitation are spatial heterogeneous and temporally discontinuous (Razavi et al., 2015). Tree rings provide information about low frequency (i.e., decadal) climate oscillations and drought severity, and have facilitated reconstruction of historical precipitation across North America (Cook et al., 2015). Precipitation reconstructions are commonly developed using correlation analysis in the time domain (Touchan et al., 1999) and spectral analysis in the frequency domain (Meko et al., 1985). Advanced time series approaches, such as wavelet techniques, have also become common for analysing tree ring and precipitation data in both the time and frequency domains simultaneously (Gray et al., 2003). However, shorter time periods, e.g., 30 years, can be truly misleading in calculating the statistical properties of precipitation time series, due to extensive non-stationarities observed in this time frame, highlighting the difficulty in reconstructions that employ short instrumental climate records (Razavi et al., 2015). Moreover, and in spite of the success in using dendrochronological records for annual reconstructions (e.g. Biondi, 2014), daily precipitation reconstructions are non-existent to our knowledge. Therefore, in order to generate accurate, high-resolution precipitation time series, reconstruction techniques must be able to simulate both the underlying stochastic process in the time series and incorporate non-stationarities in the first-order (e.g., mean) and second-order (e.g., variance and autocorrelation) statistical properties (Elshorbagy et al., 2016; Razavi et al., 2015, 2016).

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Statistical downscaling is used to generate fine-scale time series from coarse numerical model outputs (Maraun et al., 2010). Downscaling uses historical data to establish relationships among different time scales and employs these empirical associations to generate fine scale time series using coarse-scale data as proxies (Chun, 2010). For example, we can generate daily precipitation time series using coarse climate model outputs and/or low frequency climate oscillations (Chandler and Wheater, 2002; Chun et al., 2013). These daily time series may help to understand environmental hazards such as flooding (Chun, 2010; Yang et al., 2006), and provide important information for placing climate variability in a historical context (Bradley, 2015). Here we propose a novel method that incorporates ring-width time series to reconstruct daily precipitation using downscaling (Chandler and Wheater, 2002). We analysed the simulated daily precipitation properties, including persistence characteristics (Biondi et al., 2002) and annual daily extremes (Chun, 2010) at multiple temporal scales, in order to simulate daily precipitation sequences using tree rings.

Dendroclimatological studies typically analyse growth at frequencies of several months to years, thereby integrating over consecutive episodes of cambial cell division and radial growth. This is a time horizon that may cover distinct changes in soil moisture as caused by fluctuating precipitation intensities (Au and Tardif, 2012; Chen et al., 2017; Köcher et al., 2012). Periods of rainfall followed by infiltration into the soil may take hours to reach the absorbing roots and physiologically significant increases in soil moisture may only occur after larger events and with a delay, if soil hydraulic conductivity is low. Tree rings do not incorporate a resolvable daily precipitation signal (Köcher et al., 2012). However, tree ring data do incorporate coarse scale (i.e., monthly and seasonal) precipitation information (Girardin and Tardif, 2005; Hofgaard et al., 1999; Huang et al., 2010) that may be used in simulations of underlying stochastic processes and non-stationarities in statistical properties into finer scale reconstructions of hydrological variables (Razavi et al., 2015, 2016). As a case study for our empirical downscaling approach, we used tree rings from the three most widespread boreal tree species across western Canada: trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), and black spruce (*Picea mariana* [Mill.] B.S.P. Our goal was not paleoclimate reconstruction *sensu stricto*, but to provide a methodology for obtaining the necessary parameters to reconstruct daily precipitation ensembles. Here we used coarse-scale tree-ring data from these species to generate fine-scale daily precipitation ensembles, and provide the details of the data, downscaling methods, and their evaluation approaches.

2. Material and methods

2.1. Site description

The study was undertaken at the Boreal Ecosystem Research and Monitoring Sites (BERMS; Griffis et al., 2003) located near the southern edge of the Boreal Plains Ecozone (Fig. 1). Three sites were sampled: Old Aspen (OA), Old Black Spruce (OBS), and Old Jack Pine (OJP). More details of the three BERM sites can be found in Barr et al. (2012). The mean annual temperature of the area is around 3–4 °C with high seasonal and inter-annual variation (Ireson et al., 2015). Moisture stress is expected to increase (i.e., declining P-PET, precipitation minus potential evapotranspiration) under a warming climate (Ireson et al., 2015). Three main regional tree species (aspen, jack pine, and black spruce) represent the dominant land cover types of western Canadian boreal forests (Hall et al., 1997).

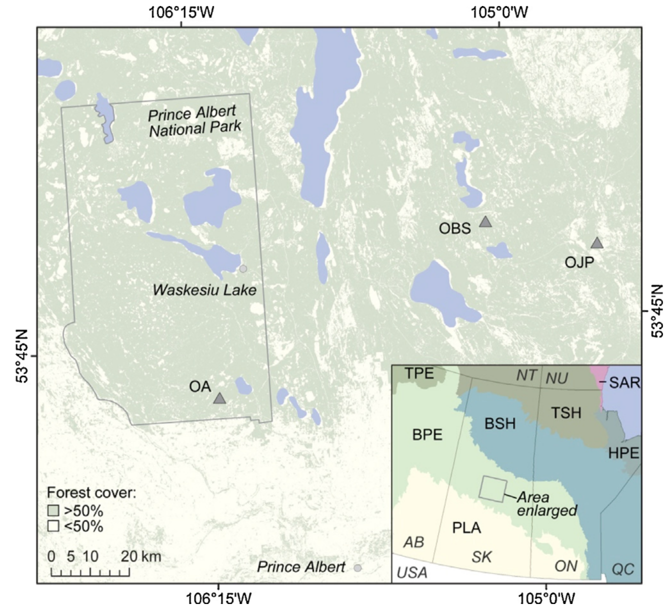

Fig. 1. The location of the Old Aspen (OA), Old Black Spruce (OBS), and Old Jack Pine (OJP) flux towers (triangles) in the Boreal Plains Ecozone (BPE) of central Saskatchewan. Adjusted and Homogenized Canadian Climate Data (AHCCD; Vincent et al., 2012) were obtained from Waskesiu Lake in Prince Albert National Park (outlined) and Prince Albert. The green area represents >50% forest cover compared to beige (<50% forest cover) as determined by Hansen et al. (2013). Inset map shows location of the study area in relation to ecozones: TPE = Taiga Plains, PLA = Plains, BSH = Boreal Shield, TSH = Taiga Shield, HPE = Hudson Plains, SAR = Southern Arctic, and provincial boundaries: Alberta (AB), Saskatchewan (SK), Ontario (ON), Québec (QC), Northwest Territories (NT) and Nunavut (NU). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1.1. Target tree species

The dendroclimatic response of aspen has been intensively studied in Canada (e.g., Chhin and Wang, 2016; Hogg et al., 2005; Huang et al., 2010; Huang et al., 2013; Lapointe-Garant et al., 2010; Leonelli et al., 2008), and drought, insects and pathogens may contribute to widespread decline in aspen growth. Defoliation and drought events also leave aspen more susceptible to secondary attack by the wood-boring large aspen tortix (*Choristoneura conflictana* [Wlk.]), the poplar peniophora fungus (*Peniophora polygonia* [Pers.:Fr.]) Boud., and *Armillaria* root disease (Hogg et al., 2005). Widespread mortality is predicted for aspen across its southern range due to a combination of climate change, and biotic and abiotic influences (Rehfeldt et al., 2009).

Jack pine is the most widely distributed pine species in Canada (Burns and Honkala, 1990), but in spite of its apparent climatic sensitivity, it has not received widespread attention in boreal forest precipitation reconstructions (one exception is Pisaric et al., 2009). While jack pine is a drought-tolerant species due to deep tap roots, it has shown sensitivity to drought (Mamet et al., 2015), a signal that is evident in spite of periodic defoliation by jack pine budworm (*Choristoneura pinus pinus* Free.) (Volney, 1998) and *Armillaria infection* (Mallett and Volney, 1990). Thus jack pine offers considerable promise for precipitation reconstruction, which is particularly useful in light of the drought-induced growth decline predicted for most of Canada (Peng et al., 2011).

Black spruce is a wide-ranging, abundant conifer in the northern parts of North America (Viereck and Johnston, 1990). Though black spruce typically grows in wet environments, evidence suggests that drought impacts on black spruce may be more widespread than previously thought (e.g. Girardin et al., 2016; Walker and Johnstone, 2014). Drought stress in black spruce is likely related to