Dendrochronologia 67 (2021) 125837

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Arctic aerosols and the ‘Divergence Problem’ in dendroclimatology

Ulf Büntgen [a,b,c,d,*], Alexander V. Kirdyanov [e,f], Paul J. Krusic [a,g], Vladimir V. Shishov [h,i], Jan Esper [b,j]

[a] Department of Geography, University of Cambridge, Cambridge, CB2 3EN, UK
[b] Global Change Research Institute of the Czech Academy of Sciences (CzechGlobe), 603 00, Brno, Czech Republic
[c] Department of Geography, Faculty of Science, Masaryk University, 613 00, Brno, Czech Republic
[d] Swiss Federal Research Institute WSL, 8903, Birmensdorf, Switzerland
[e] V.N. Sukachev Institute of Forest SB RAS, Federal Research Centre, Krasnoyarsk, 660036, Russia
[f] Institute of Ecology and Geography, Siberian Federal University, Krasnoyarsk, 660041, Russia
[g] Department of Physical Geography, Stockholm University, 106 91, Stockholm, Sweden
[h] Mathematical Methods and IT Department, Siberian Federal University, 660075, Krasnoyarsk, Russia
[i] Scientific Laboratory of Forest Health, Reshetnev Siberian State University of Science and Technology, 660037, Krasnoyarsk, Russia
[j] Department of Geography, Johannes Gutenberg University, 55099, Mainz, Germany

ARTICLE INFO

Keywords:
Industrial pollution
Divergence Problem
Boreal forest
Carbon cycle
Arctic Dimming

Considering the importance and complexity of natural (e.g., volcanic eruptions and wildfires) and anthropogenic (e.g., mining, oil and shipping industries) aerosol emissions to Arctic warming is particularly timely given the recent temperature extremes recorded at high-northern latitudes (Cohen et al., 2020; Overland and Wang, 2021). Despite our knowledge about the observed and modelled climatic effects of rising Arctic aerosol concentrations (Schmale et al., 2021), which may exhibit regional and seasonal differences and call for diverse research priorities from local to circumpolar scales, we feel that the ecological consequences of an aerosol-induced reduction in surface irradiance (i.e., Arctic Dimming) justify more thorough tree-ring investigations in the future. We argue that this is particularly true if the goal is to enhance our understanding of all aerosol generating processes that impact terrestrial vegetation and its ability to assimilate carbon dioxide from the atmosphere.

In addition to the exceptional rate of environmental devastation in the vicinity of heavy industrialisation at high-northern latitudes, with Fairbanks and Norilsk just being two extreme cases (Holty, 1973; Bauduin et al., 2014), the large-scale and long-term effects of aerosol emissions on the functioning and productivity of ecosystems are poorly understood and likely underestimated (Kirdyanov et al., 2020a). Moreover, air pollution from lower latitudes is often accumulates in the Arctic atmosphere (Stohl, 2006; Law and Stohl, 2007; Quinn et al., 2007; Arnold et al., 2016), where it can reside for exceptionally long periods of time. Reduced intensity of scattered incoming solar radiation, particularly in the 400–700 nm waveband that is most meaningful to photosynthesis (Urban et al., 2012), has been demonstrated to reduce the functioning and productivity of taiga and tundra biomes (Stine and Huybers, 2014). The boreal forest, however, not only plays a major role in shaping the Earth’s carbon cycle and climate system (Bradshaw and Warkentin, 2015), but also hosts some of the longest tree ring-based climate reconstructions extending back over the Common Era (Büntgen et al., 2020). A better understanding of the possible direct and indirect effects of Arctic aerosols on net primary production and carbon sequestration is particularly important in light of the current geo-political and commercial race to exploit natural resources north of the Arctic circle.

Combined dendrochronological and biogeochemical evidence from Norilsk, the world’s northernmost city with over 100,000 inhabitants, where mining actions and uncontrolled pollutants have expanded

* Corresponding author at: Department of Geography, University of Cambridge, Cambridge, CB2 3EN, UK.
E-mail address: ulf.buentgen@geog.cam.ac.uk (U. Büntgen).

https://doi.org/10.1016/j.dendro.2021.125837
Received 22 March 2021; Received in revised form 21 April 2021; Accepted 21 April 2021
Available online 28 April 2021
1125-7865/

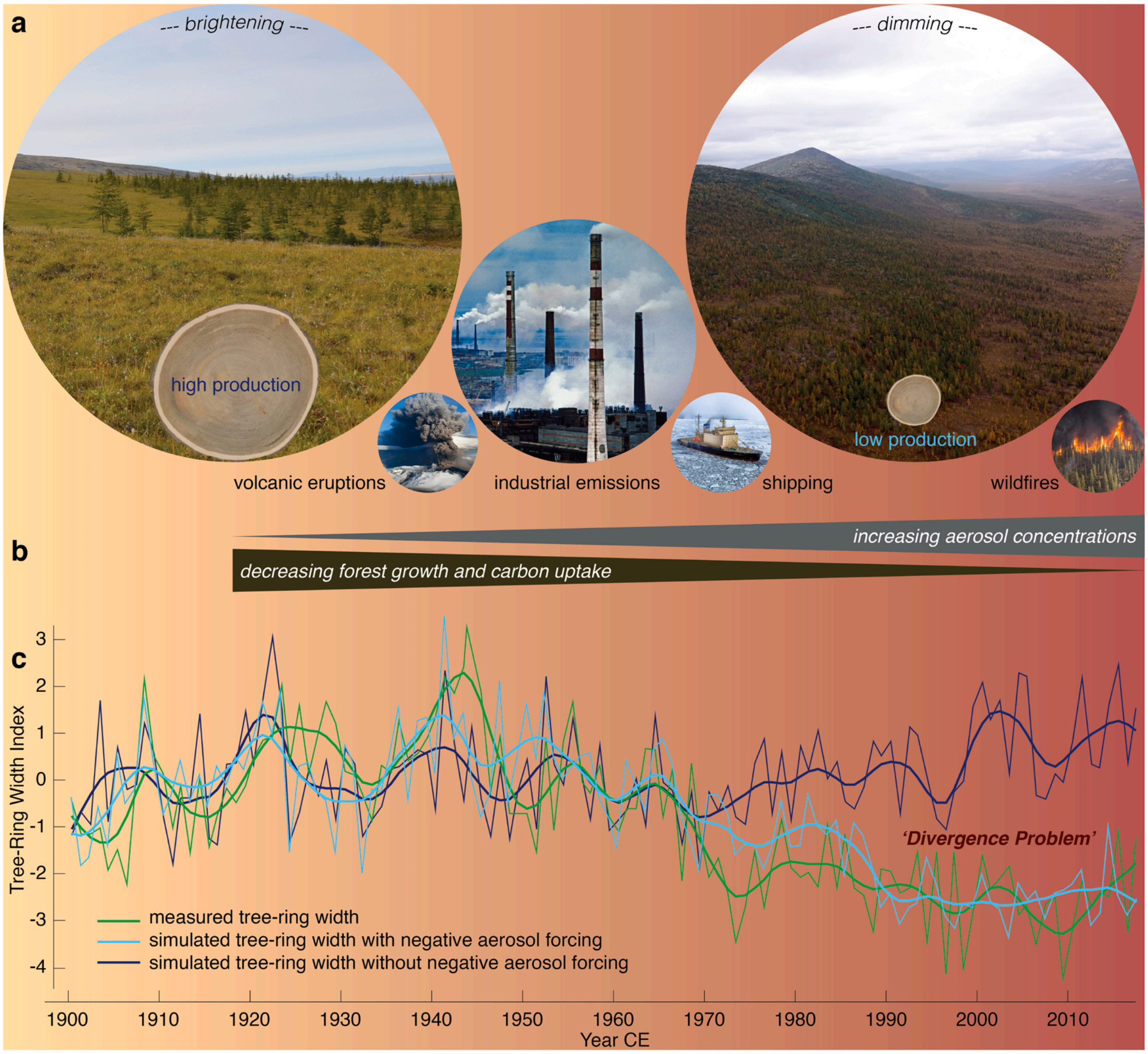

Fig. 1. Arctic aerosols and the 'Divergence Problem'. (**a**) Vegetation growth and carbon uptake of the circumpolar taiga and tundra biomes under pre-industrial (Arctic Brightening; left) and shifting aerosol baseline conditions due to natural and anthropogenic emissions (Arctic Dimming; right). (**b**) Hypothetical long-term trends in high-latitude aerosol concentrations, forest growth and carbon uptake. (**c**) Measured and simulated boreal tree-ring width indices with and without using negative aerosol forcing since the mid-20th century in an updated version of the VS-Light model (data modified from Kirdyanov et al., 2020a), with the thick curves being 10-year cubic smoothing splines. Future studies should expand the process-based forward modelling experiment across the Northern Hemisphere extra-tropical landmass.

rapidly since the 1930s, now suggests that a reduction in surface irradiance during the second half of the 20th century has adversely affected boreal tree growth (Kirdyanov et al., 2020a). When derived from the diurnal temperature range and implemented as negative forcing in a forward model of radial tree growth (Vaganov et al., 2011; Kirdyanov et al., 2020a), Arctic Dimming offers a plausible, large-scale explanation for the 'Divergence Problem' in dendrochronology (see D'Arrigo et al., 2008 for a review): the apparent decoupling between formerly temperature-sensitive tree-ring width and density chronologies at different boreal forest sites in North America and Siberia, and rising instrumental temperature measurements since the 1970s (Briffa et al., 1998). Attributing the 'Divergence Problem' to anthropogenic aerosol emissions, and subsequent reductions in surface solar radiation (Liepert, 2002), is fundamental to our understanding of past climate variability (Büntgen et al., 2020), because it would refer to a relatively modern issue that leaves the Principle of Uniformity in tack as it applies to dendroclimatology (Fritts, 1976; Esper and Frank, 2009), and thus to a substantial portion of high-resolution paleoclimatology. Another concern is that the putative reduction of tree growth in response to increased cloud cover and cloud residence time, as possibly manifest in the 'Divergence Problem', limits the capacity of the boreal forest to assimilate carbon dioxide from the atmosphere (Fig. 1). The contribution of the world's largest terrestrial biome to mitigate the effects of greenhouse gases on global warming will therefore be smaller than expected (Girardin et al., 2016). An anthropogenically induced light deficiency in northern vegetation zones (Nemani et al., 2003), amplified by wildfires and sulphate-rich volcanic eruptions (Stine and Huybers, 2014; Büntgen et al., 2020), will also influence the temperature-sensitivity of treeline and tundra ecotones (Hagedorn et al., 2019). Overall, the alleged changes are likely to slow down the predicted rate of Arctic greening (Fig. 1).

In addition to transported pollutants from lower latitudes, continuous SO_2 emissions from high-latitude mining, oil and shipping activities since the mid-20th century possibly caused a circumpolar negative aerosol forcing capable of countermining the putative effects of Arctic amplification. Reduced surface radiation in high-northern environments can affect evaporation and associated components of the hydrological cycle, including permafrost soils, snow cover and ice melt, as well as plant photosynthesis and productivity, the diurnal and seasonal course of temperatures, and various terrestrial and marine biogeochemical cycles (Kanakidou et al., 2018; Bowen et al., 2020). Our understanding of the direct and indirect implications of Arctic Dimming on the global carbon cycle and climate system is therefore amongst the most important to consider and simultaneously the hardest to grasp. Relevant long-term studies are challenged by the scarcity of spatially explicit measurements of air pollutants, cloudiness, and solar irradiance during the first half of the 20th century in northern North America, Russia and China (see Wild, 2009, 2016 for reviews). In addition to our lack of understanding tree physiological responses to air pollution and forest health as a whole (Cherubini et al., 2021), we are still puzzled by scale-dependent aerosol-cloud interactions and complex processes and feedbacks (Schmale et al., 2021). Further uncertainty emerges from the observed recent increase in the extent and severity of boreal wildfires and their short- to long-term effects on above- and belowground carbon fluxes and stocks (Knorre et al., 2019; Walker et al., 2019; Kirdyanov et al., 2020b), let alone the unpredictable release of large amounts of sulphate and dust particles from volcanic eruptions.

The environmental damage of a shifting Arctic aerosol baseline requires immediate and strict implementation of local to international constraints on pollutants from the ever-growing, and often uncontrolled mining, oil and shipping industries in the high-northern latitudes, as well as from the many emission sources at lower latitudes. In the spirit of cross-disciplinary cooperation, we consider the current momentum *in* and awareness *of* Arctic research and pollution a fresh opportunity to advance scientific projects, coordinate conservation initiatives, advise political decisions, and influence industrial actions, with the overall goal of a long-term net reduction of anthropogenic emissions.

Author contributions

U.B. conceived the study. All authors provided discussion and helped writing the manuscript.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

U.B. and J.E. received support from the SustES project - Adaptation strategies for sustainable ecosystem services and food security under adverse environmental conditions (CZ.02.1.01/0.0/0.0/16_019/0000797) and the ERC Advanced Grant Monostar (AdG 882727). V.S. received support from the project #FEFE-2020-0014. Otmar Urban kindly commented on a previous version of this manuscript.

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