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The origin of driftwood on eastern and south-western Svalbard

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ABSTRACT

The Arctic is one of the regions where the effect of global change is most evident. Associated with warming are changes in snow, sea ice and hydroclimate, all which have significant impacts on environments and society. However, due to short observational records, it is difficult to set the current climate in a long-term context. Arctic driftwood (DW), available throughout the Holocene, is a paleoclimate resource that may shed information on past sea-ice, ocean current and atmospheric conditions because it is transported by sea ice across the Arctic. Moreover, DW tree-ring data can be used to interpret climate in the boreal forests where the trees grew. Here we present a study of 380 DW samples collected on eastern and south-western Svalbard. Combining species identification and dendrochronology, it was found that the DW mainly consisted of *Pinus sylvestris*, *Picea* sp. and *Larix* sp. (87% of all samples), mainly originating from northern Russia. In total, 60% of the DW could be dated and their provenance determined, and four tree-ring width chronologies representing Yenisei and Dvina-Pechora were constructed, facilitating extension and improvement of the existing chronologies representing those regions. Moreover, DW from relict beaches that can be subjected to dendrochronological analyses, provides possibilities to extend pan-Arctic tree-ring data even further back in time. Because there are several processes governing the temporal patterns of wood deposition in the Arctic, using DW as an indicator of sea-ice variations needs further investigation.

1. Introduction

The Arctic is warming faster than most of the world, and the current pace of change is unprecedented in recorded history. Rates of warming, sea ice loss, glacier and permafrost melt are higher than humans have ever observed, and some of these changes are likely irreversible (Lenton et al., 2019). The regional impacts of what is called Arctic amplification (AA, Serreze and Francis, 2006) are severe. Additionally, AA may lead to an increase in the frequency and intensity of mid-latitude weather extremes through changes in atmospheric circulation patterns (Serreze and Barry 2011; Cohen et al., 2014), partly caused by a reduced equator-pole temperature gradient (Francis et al., 2017). Consequently, AA will have economic and societal impacts across much of the Northern Hemisphere. However, there is still uncertainty about the nature of the influence of AA on lower latitudes (Cohen et al., 2020), because of a lack of detailed data on long-term Arctic climate and environmental change (Bekryaev et al., 2010; Pisaric et al., 2011).

Tree rings, ice cores and laminated sediments, can extend our knowledge of climate back in time, and have played important roles in the understanding of regional to hemispheric climate variability in the past two millennia (PAGES 2k Consortium 2019; Neukom et al., 2019). Despite the emergence of several proxy-based reconstructions of Arctic temperature and hydroclimate (Overpeck et al., 1997; Kaufman et al., 2009; McKay and Kaufman 2014; Nicolle et al., 2018), and sea ice changes (Kinnard et al., 2011), over the past centuries to millennia, the distribution of proxies is heterogeneous, with many regions severely underrepresented (Büntgen et al., 2014; Linderholm et al., 2018).

Rivers in northern North America and Eurasia draining into the Arctic Ocean not only carry huge quantities of depleted organic matter (Opsahl et al., 1999), but also wood from the boreal forests (e.g. Eggertsson 1994; Hellmann et al., 2017). Driftwood (DW) originates from the boreal zone and is released into the Arctic Ocean, either through river bank erosion, mainly in spring during river breakup (Dyke et al., 1997), or from logs lost during river drives (e.g. Hellman et al.,

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2015; 2016a, 2017), and is frequently washed up and deposited on Arctic shores. Trees entering the Arctic Ocean cannot stay afloat long; it has been estimated that conifers can stay afloat for about 10–17 months (6–10 months for deciduous trees), where the buoyancy depends mainly on size and degree of desiccation (Häggblom 1982). Because the passage across the Arctic Ocean takes several years, DW needs to be incorporated in sea ice in order to reach deep into the Arctic (e.g. Dyke et al., 1997).

Morphological features and microscopic wood anatomy analyses are used to determine which genus, or even species, a DW sample belongs to (Hellman et al., 2013). This information enables a rough (e.g. continental scale) identification of where a tree originally grew. By adding dendrochronological techniques, it is possible to reconstruct when, as well as where, it grew with quite high geographical precision, often at catchment level (see Hellman et al., 2017). Moreover, a firmly dated DW sample with known origin indicates that sea ice was present to transport it sometime after its death, but it can also provide some information of the currents transporting it (Bennike 2004; Hole and Macias-Fauria 2017). Changes in driftwood, origin and/or abundance, may therefore offer unique insights into past changes in Arctic Ocean sea ice and current dynamics (Dyke et al., 1997). Additionally, tree-ring data derived from Arctic DW contain high-resolution climate information representing the location where the trees grew (St George 2014; Hellmann et al., 2016b), and since large parts of the northern boreal region in Eurasia and North America lack long paleoclimate records (PAGES 2k Consortium 2017), increasing the number of datasets is of high importance.

Most DW found at or close to the present Arctic shorelines, dates to the late nineteenth and twentieth centuries, and in most cases shows signs of logging (e.g. Hellmann et al., 2013). Older DW can be found on raised beeches, or buried in sediments above the present sea level (Häggblom 1982; Bennike 2004; Funder et al., 2011; Hole and Macias-Fauria 2017). Previously. ^{14}C-dated DW has been used to infer past sea-ice conditions (Bennike 2004; Moros et al., 2006; Polyak et al., 2010; Funder), changes in Arctic Ocean currents (Giddings 1952; Eggertsson 1994; Dyke et al., 1997; Dyke and Savelle 2000), and post-glacial rebound (Salvigsen 1981; Salvigsen and Mangerud 1991; Bondevik et al., 1995). However, few studies have explored the potential of employing dendrochronological methods on DW tree-ring data.

DW from Svalbard has been described and studied for more than a century. In 1869, the Swedish botanist Jacob Georg Agardh, wrote about DW collected during Swedish expeditions to Svalbard (Agardh 1869). He concluded that DW consisted of conifers, mainly larch and spruce, and that it came from northern Siberia (based partly on the general widths of the rings in the DW). Analysing DW material collected on the Swedish polar expeditions in the late 1890s, Ingvarson (1903) divided the DW into two categories, those transported with the "Polar current" from northern Siberia, and those transported with the Gulf stream (consisting of both American and Norwegian material). The most common DW from Svalbard was *Larix sibirica*, but some *Larix americana* was found on the northernmost parts of Svalbard. Salvigsen (1981) investigated raised beaches on Svenskøya and Kongsøya in the eastern Svalbard archipelago, and found DW on different elevations up to 100 m a.s.l., where the oldest samples dated to the early Holocene (ca. 9–10 000 years BP). In addition to the old DW, consisting mainly of *Larix* sp. and *Picea* sp., where a few of the latter were identified as *Picea mariana*, consequently having originated from North America. Investigating shoreline displacement on Agardhbukta, eastern Spitsbergen, Salvigsen and Mangerud (1991) found a "log-level", comprising *Larix* sp. and *Picea* sp., corresponding to ca. 6500 BP. One *Pinus sylvestris* sample was found closer to sea level, dated to ca. 800 BP. Combining DW samples from Isfjorden, western Spitsbergen, collected by Bartholin and Hjort (1987), and Widefjorden, northern Svalbard, Eggertsson (1984) presented a detailed dendrochronological study. The DW were collected from present shores, and *Pinus* sp. was most abundant at both sites, followed by *Picea* sp., while *Larix* was in principle only found at the northern site. Moreover, based on the ring-with patterns of the trees, which all had their end dates in the twentieth century, the provenances of the DW were inferred; *Pinus* came from the While Sea region and central Siberia, *Picea* from the While Sea region and *Larix* likely from eastern Siberia. Data from northwestern Svalbard were later included in a study where almost 1500 DW samples from the North Atlantic/Arctic Ocean sector were analysed in detail (Hellman et al. 2013, 2015, 2016a, 2017), again mainly focusing on material from present-day beaches.

The aim of the present study was to explore the potential of using DW from hitherto unexplored locations on Svalbard, to extend existing pan-Arctic tree-ring chronologies back in time, and thus further our knowledge of regional climate variations in the past. To achieve this, DW was sampled from Kongsøya in the easternmost part of the Svalbard archipelago and the southwestern coast of Spitsbergen. Using dendrochronological methods, we attempted to date and the provenance the collected material. Based on our results, we discussed the major sources of DW on Svalbard, issues related to its dating, as well as the potential of DW as a proxy for Arctic sea-ice variations.

2. Material and methods

2.1. Driftwood

The *Icebound* expedition sailed around Svalbard in 2014 with the aim to collect information about Arctic climate in a historical perspective. Sampling sites included Kongsøya, in the easternmost part of the Svalbard islands, and the southwestern coast of Spitsbergen (Fig. 1). Kongsøya is the main island in the Kong Karls Land group of islands. This uninhabited island belongs to the Nordaust-Svalbard nature reserve, and since 1985 landing on the island without permission is forbidden. For the dendrochronological part of the project, 380 driftwood samples were collected from seven locations along the expedition route. Samples of DW were mainly collected from material found on the present beaches, where it was most abundant, but additional material was also sampled further inland, often partially buried, and at higher elevations, such as raised beaches (Fig. 2). The strategy was to sample all DW found in the investigated areas, but severely decayed DW or very small tree remains with few visible annual rings was avoided, because of the difficulties when processing the annual rings. Using a chainsaw, discs were taken from each DW sample. The positions (latitude-longitude, elevation) and special characteristics (e.g. cutting marks) of each DW were noted, the discs labelled and put in plastic bags. The DW found lying on the ground are often dry and light due to long aerial exposure, and easy to handle. The DW found embedded in sediments were wet and more fragile, having to be handled with care. Details of the samples from each site are given in Table 1.

2.2. Species identification

First, macroscopic classification of the key characteristics of the wood was made to identify if the individual samples belonged to hardwoods (deciduous) or softwoods (conifers). The surfaces of cross sections of all samples were prepared, where the dry wood (majority) was sanded and the wet (buried) wood cut with a scalpel. Contrary to conifers, large pores (vessels) and faint/diffuse transitions between early- and latewood characterises deciduous wood. Thus, it was possible to divide the two types of wood. Given that the vast majority of the samples were conifers, macroscopic features were used to subdivide these into genera: *Pinus*, *Picea*, *Larix* and *Abies*. A detailed identification, where in some cases also the species could be determined, was then made microscopically, using the identification keys described by Hellmann et al. (2013). Radial sections were cut for all samples using a microtone and unstained thin sections were investigated under a microscope. The identification of the respective genera and species is related to some uncertainty, but with a careful combination of macro- and microscopic techniques, most samples were successfully determined.

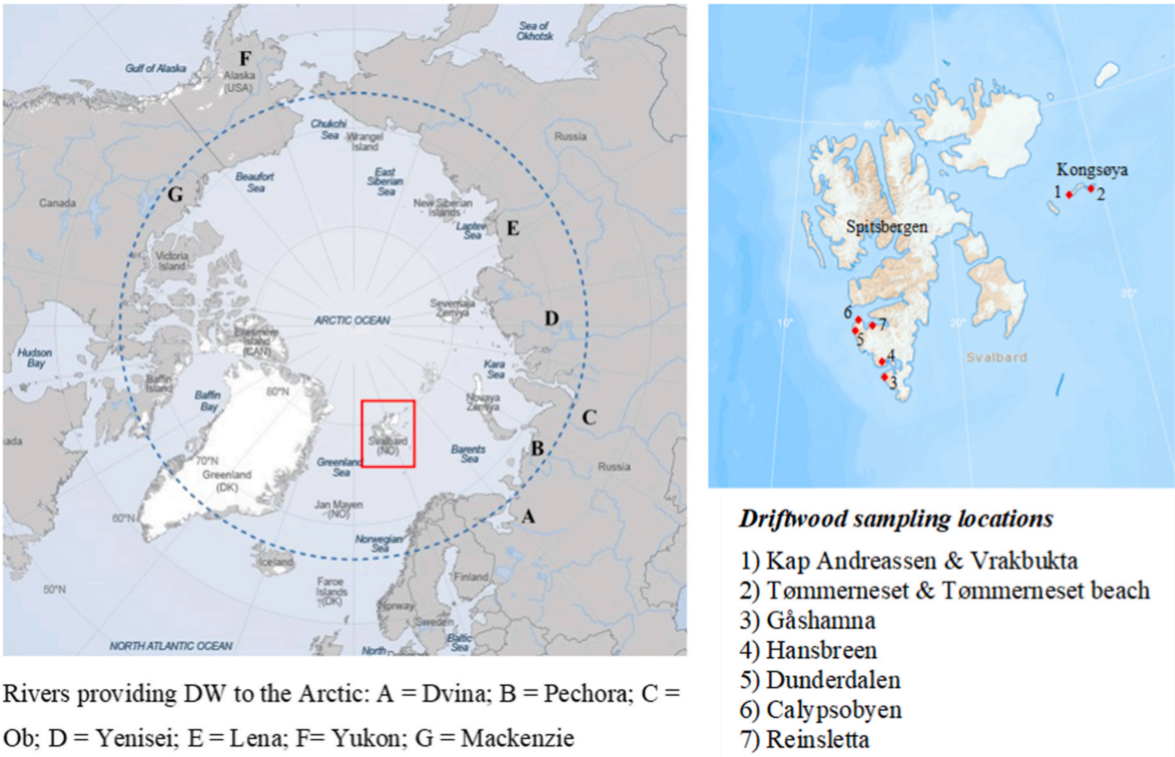

Fig. 1. The Arctic with the major rivers providing driftwood (DW) indicated (left), and the names and positions of the locations (red diamonds) on Svalbard where DWwere collected. The Arctic overview map was obtained from the Arctic Portal (https://arcticportal.org/maps-arctic-definitions), and the Svalbard map © Norwegian Polar Institute, was generated at https://toposvalbard.npolar.no/.

Fig. 2. Examples of driftwood (DW) and four of the sampling locations. From the top left corner and clockwise: DW fond at present beaches at Hansbreen (4), and Gåhamna (3), DW embedded in a relict (raised) beach at Kap Andreassen (3), and Larix sp. DW collected at ca 25 m a.s.l at Tömmerneset (4). Numbers refer to site locations in Fig. 1.

2.3. Tree-ring analysis

The widths of the annual rings were measured with a precision of 1/100 mm on a Lintab measuring device connected to the software TSAPwin (Rinntech, Heidelberg, Germany). At least two radii were measured from each sample, and the tree-ring patterns compared against each other to ensure that all rings were accounted for, a process known as crossdating (Fritts 1967). Then the radii were averaged into a series representing each tree. Similar to earlier Svalbard DW studies (Eggertsson 1994; Hellmann et al., 2017), we focused on the most abundant species, *Pinus*, *Picea* and *Larix*. When all samples of a specific genus had been measured, all series were crossdated against each other

Table 1
Information on the Svalbard sites where driftwood (DW) were sampled, including site name (numbers in parenthesis correspond to those in Fig. 1), position (Latitude and longitude), elevation range where samples were collected (given in m a.s.l.), sample id and number (#) of samples.

Site name		Lat. (N)	Lon. (E)	Elevation	Id	# DW
Kongsøya	Kap Andreassen & Vrakbukta (1)	78,86° 78,87°	27,84° 28,00°	c. 3–25 m c. 2–13 m	KA VB	26 20
	Tømmerneset & Tømmerneset beach (2)	78,84° 78,85°	29,27° 29,23°	c. 10–30 m c. 2–8 m	TN TNR	16 29
Hornsund	Gåshamna (3)	76,94°	15,76°-15,89°	c. 2–9 m	GH	84
	Hansbreen (4)	77,00°	15,66°	c. 2–6 m	HB	59
Dunderbukta	Dunderdalen (5)	77,45°	14,05°	1–2 m	DB	46
Bellsund	Calypsobyen (6)	77,57°	14,48°	1–2 m	CB	58
	Reinsletta (7)	77,51°	14,77°	2–3 m	RS	41

building up undated (floating) chronologies of samples that showed agreement based on statistical measures, including *t*-test values (Baillie and Pilcher 1973) ≥ 4.0 and significant “Gleichläufigkeit" scores (which indicates how well two samples match when overlapping). Additionally, all series agreements were visually controlled. To date and provenance the obtained DW chronologies, they were compared to a set of reference chronologies from trees growing in the watersheds of the major rivers entering the Arctic Ocean from where the DW was expected to have originated from (Table 2). Samples that could not be included in any chronology (e.g. because of limited overlap between samples from a region) were compared directly with the reference chronologies. The reference chronologies represented Dvina-Pechora, Yenisei, Ob and Lena in Eurasia (Hellman et al., 2015), and Yukon and Mackenzie in North America (Hellman et al., 2017). The dendro-provenancing (Bonde et al., 1997) followed the same procedure as the crossdating of the individual samples. The chronologies (see below) containing 10 or more overlapping tree ring-width series were further processed. The age trends, which most tree-ring series contain, were removed to obtain chronologies representing the common growth characteristics for a set of DW samples using the ARSTAN software (Cook and Krusic 2007).

3. Results

3.1. Composition of the driftwood

Of the 380 DW samples collected from Svalbard, five coniferous and four deciduous genera were identified (Table 3). *Pinus* sp. made up half of the sampled material, with a domination of *Pinus sylvestris* L. (PISY) whereas *Picea* sp. (PCSP) and *Larix* sp. (LASP) and *Abies* sp. (ABSP) roughly constitute the other half (46%). Only 12 deciduous wood samples were found, including *Salix* sp., *Populus* sp., *Betula* sp. and *Acer* sp., and together they constituted less than 4% of the total sampled material (Table 3). The genus of two samples could not be determined.

Table 2
Information on the *Pinus sylvestris*, *Picea* sp. and *Larix* sp. reference chronologies representing the main river basins entering the Arctic Ocean, used to dendro-provenance the Svalbard driftwood material.

Species	River catchment	Time span CE	Reference
Picea sp.	Dvina/Pechora	1616–2012	Hellman et al. (2016a)
	Ob	1601–2013	Hellman et al. (2016a)
	Yenisei	1630–2009	Hellman et al. (2016a)
	Mackenzie	1060–1992	Hellman et al. (2017)
	Yukon	978–2002	Hellman et al. (2017)
Larix sp.	Dvina/Pechora/Ob	1–2014	Hellman et al. (2016a)
	Yenisei	1611–2012	Hellman et al. (2016a)
	Lena	1211–2013	Hellman et al. (2016a)
	Kolyma	1338–2007	Hellman et al. (2016a)
Pinus sylvestris	Dvina/Pechora	1594–2011	Hellman et al. (2016a)
	Ob	1523–2009	Hellman et al. (2016a)
	Yenisei	1584–2010	Hellman et al. (2016a)
	Lena	1564–2003	Hellman et al. (2016a)

Table 3
Information on the driftwood (DW) sampled at Svalbard, including type, genera/species, total number (#) of samples for each genera/species, percent (%) of the total DW number, number of dated samples, percentage of undated samples and locations[a] of the samples (numbers refer to Fig. 1).

Type	Genera/ Species	# Samples	% of DW	# Dated	Undated	Sites present
Conifers	*Pinus sylvestris*	165	44	151	8.5%	All sites
	Pinus sibirica	24	6	0	100%	All sites
	Larix sp.	84	22	27	68%	All sites
	Picea sp.	80	21	50	37%	All sites
	Abies sp.	13	3	0	100%	All sites
Deciduous	*Salix* sp.	6	2	0	100%	1, 3, 4 & 5
	Populus sp.	4	1	0	100%	1, 6 & 7
	Betula sp.	1	<1	0	100%	4
	Acer sp.	1	<1	0	100%	7

[a] Note that this only refers to the Russian sites. The provenances of five Picea sp. samples was determined to be North America.

3.2. Dating and provenance of the driftwood

We focused on PCSP, LASP and PISY, for which suitable reference chronologies were available. These were also by far most abundant, making up 87% of all collected DW.

3.2.1. Picea sp. (PCSP)

The 80 PCSP samples made up about one fifth of the total DW, and were found at all seven locations (Table 3). However, the highest percentages were found in Bellsund (Calypsobyen and Reinsletta) where PCSP made up ca 30% of all DW, and at the other sites it contributed to the total with around 10–20% (Fig. 3). The lengths of the samples spanned from 27 to 201 years, with an average of 97 rings. In total, 50 PCSP DW samples could be dated and the provenance determined, although nine were uncertain. Most PCSP started growing (based on the innermost tree ring) during the nineteenth century (24), followed by the eighteenth (15) and twentieth (5) centuries. The dating of the PCSP with first rings in the seventeenth to eleventh centuries (one for each century except the fourteenth) are quite uncertain. Almost 90% of the last rings, indicating the earliest possible death year, were dated to the twentieth (31) and nineteenth (13) centuries.

Most PCSP DW (31) came from the Dvina-Pechora river system, 10 from Yenisei, 5 from Lena and 3 from Ob. Based on our dating and provenance criteria, five samples were found to originate from North America: three from the Yukon River region of Alaska (GHPA067: 1127–1205 CE, GHPA068: 1699–1781 CE and KA018: 1850–1924 CE), and two from the Mackenzie River region in Canada (CBPA007: 1510–1629 CE and TNPA008: 1779–1860 CE). Of the spruces originating from Dvina-Pechora, 26 were successfully combined into a chronology spanning 1705–1988 CE (Fig. 4a). Because of the low replication, the chronology is not very reliable in its early parts. There is a clear peak around 1900 in the replication. The majority of samples making up the chronology came from Calypsobyen (Fig. 4e).

3.2.2. Larix sp. (LASP)

In total LASP made up 22% of all DW (Table 3). The majority of LASP samples were found on Kongsøya and in Hornsund, twice as much as was found in Dunderdalen and Bellsund (Fig. 3). Of the 84 LASP samples

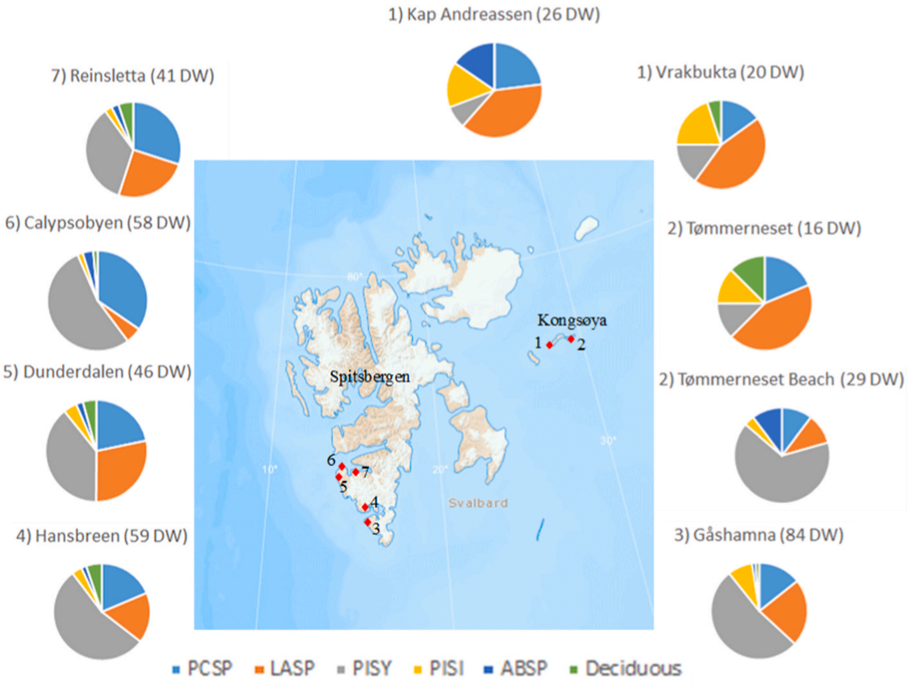

Fig. 3. The percentage of the main driftwood (DW) genera/species of the total sampled at each of the seven locations. Numbers correspond to those on the map. Also indicated are the total number of DW from each location. Svalbard map © Norwegian Polar Institute, generated at https://toposvalbard.npolar.no/.

collected, 80 samples were measured, with the number of rings spanning from 29 to 285, and an average of 137 rings. Only 27 samples could be dated and the provenance determined. Most of the dated LASP started growing in the eighteenth and nineteenth centuries (37% each). One tree started growing in the twelfth and one in the fourteenth century, both originating from Dvina-Pechora. Only one tree started growing in the twentieth century. Seventy four percent (20 trees) of the outermost rings dated to the twentieth century, where most (16) end years were before 1970. One tree ended in the eighteenth century and four in the nineteenth century. The outermost rings of the two oldest trees dated to the fifteenth and sixteenth centuries.

Of the dated samples, 19 LASP from Yenisei (the remaining 8 came from Dvina-Pechora) were compiled into a chronology spanning the period 1671 to 1988 CE (Fig. 4b). Given the low number of samples, the representation of the chronology for the *Larix* sp. population in the Yenisei region is quite limited, except for the mid-1800s where most trees coexisted. The chronology was mainly made up of LASP from Hornsund, especially Gåshamna, with only few samples from Kongsøya (Fig. 4e), from where a large number of samples could not be dated. The high amount of undated LASP at Kongsøya is likely due to most DW having been collected from elevations of 20–30 m a.s.l., corresponding to beaches of much older dates than the reference chronologies (see further discussion below).

3.2.3. *Pinus sylvestris* (PISY)

PISY was the most commonly found DW species and found at all seven locations (Table 3). PISY made up 50–65% of the sampled DW at most low-level sites (Gåshamna, Calypsobyen, Hansbreen and Tømmerneset beach), around 40% at Dunderdalen, but only between 8 and 15% at the higher elevation sites (Kap Andreassen, Vrakbukta and Tømmerneset) (Fig. 3). Of the 165 PISY samples collected, 151 could be dated and the provenance determined. The lengths of the samples spanned from 29 to 368 years, with an average of 138 rings. Of the dated Scots pines, 47% (71) had their innermost rings in the nineteenth century, 36% (55) in the eighteenth century, 7% each (11) in the seventeenth and sixteenth centuries, and c. 1% (2) in the fifteenth century. Only one tree started growing in the twentieth century. Seventy five percent (113) of the outermost rings dated to the twentieth century. Because the vast majority displayed signs of having been cut or sawed (only five did not), it is clear that most trees had been harvested. The majority of the twentieth century pines (81) were felled before 1960. Of the remaining trees, 16 ended in the nineteenth (all but two showing signs of cutting), 9 in the eighteenth (4 likely cut), 11 in the seventeenth (6 likely cut), and two in the sixteenth century (not cut).

The bulk (111) of the dated samples originated from the Yenisei river catchment. They were combined into an independent (of the reference) chronology spanning from 1477 to 1988 CE (Fig. 4c). Yenisei DW was found at all sites. High (>10 trees) replication is attained in the 1700s, making the first part quite uncertain. The 29 samples originating from the Dvina-Pechora catchment were also assembled into a chronology spanning the period 1525–1982 CE (Fig. 4d). Similar to the Yenisei data, the chronology was mainly made up by recent wood. Both Yenisei and Dvina-Pechora chronologies showed the highest replication between c. 1850 and 1920. The majority of the samples contributing to both chronologies were from south-western Svalbard (Fig. 4e). Additionally, eight PISY samples originated from Lena, and three from Ob.

4. Discussion

4.1. The origin of DW on eastern and south-western Svalbard

Most DW from eastern and south-western Svalbard originated from northern Russia, and the majority of the dated DW on the present beaches showed signs of logging. This is in agreement with recent studies on Svalbard (Häggblom 1982; Eggertsson 1994; Hellman et al. 2013, 2017). Almost 90% of the forested areas of the former Soviet Union were located in its northern regions (Katkoff 1940), which are drained by large rivers into the Arctic Ocean. Because limited access by railways or roads into those regions, harvested timber was transported, floated, on rivers. However, large amounts of timber were lost during the floating because of raft wreckage, spring floods and storms (Alekseyenko and Titova 1988). Thus, the relative abundance of pine, spruce and larch, and their provenance, in the modern material, reflect the logging activity at the time of their harvesting, but also the dominating forest types

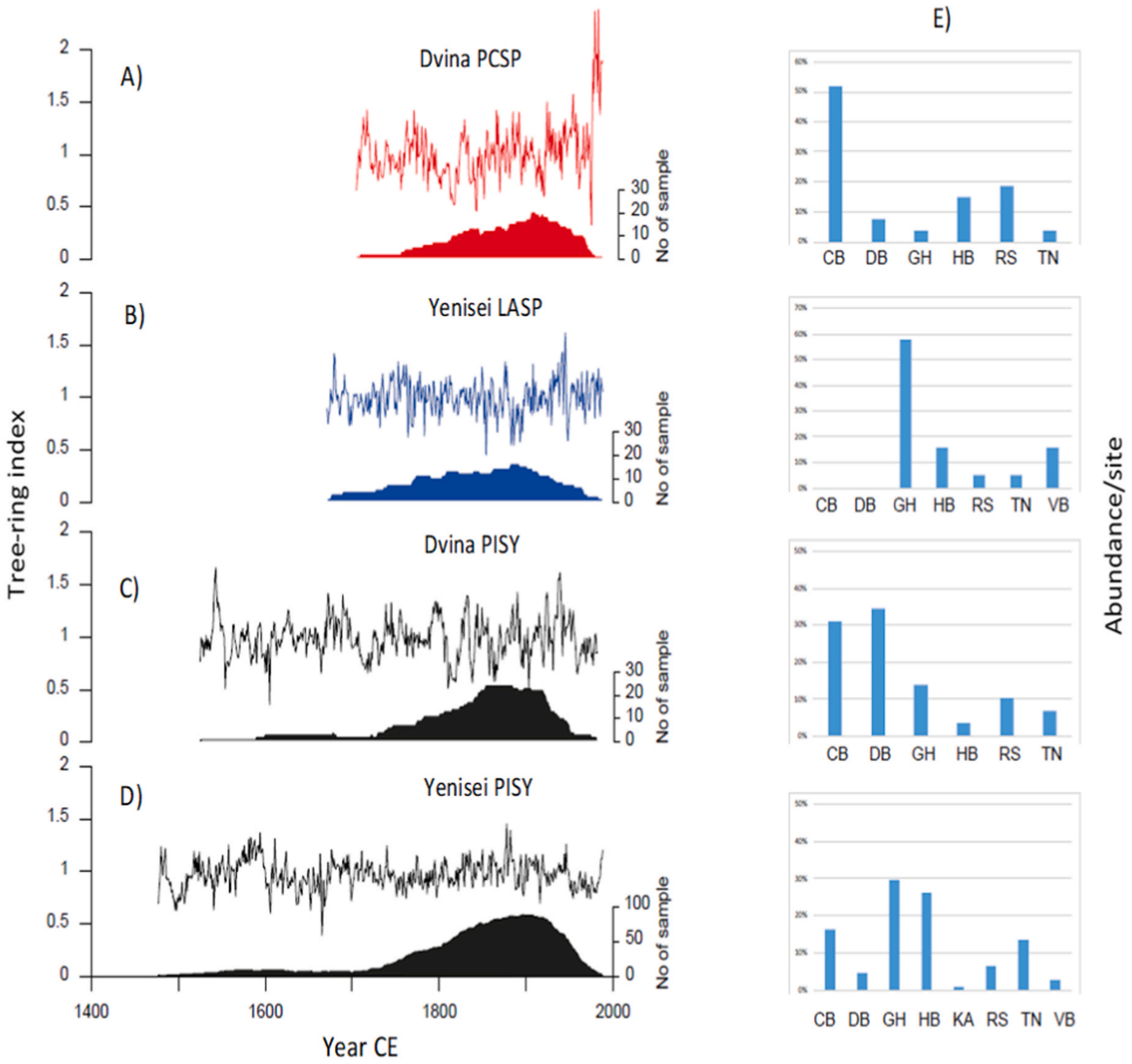

Fig. 4. The four tree-ring width chronologies derived from Svalbard driftwood, showing the tree-ring index (top) and number of samples (bottom) for A) Dvina *Picea* sp.; B) Yenisei *Larix* sp.; C) Dvina *Pinus sylvestris*, D) Yenisei *Pinus sylvestris*. In E) is shown the relative abundance of the DW samples in respective chronology from the investigated locations: CB = Calypsobyen; DB = Dunderbukta; GH = Gåshamna; HB = Hansbreen; RS = Reinsletta; TN = Tømmerneset and VB = Vrakbukta. See Fig. 1 for locations.

of the regions of their origin (Hellman et al., 2016c). Most dated LASP and PISY were derived from the Yenisei river catchment, with a clear predominance of PISY. The Yenisei is the largest river with the highest average annual discharge of the Eurasian rivers draining into the Arctic Ocean (Peterson et al., 2002), and pine and larch are common forest types in that region (Hellman et al., 2016c). Spruce was more dominant in the DW derived from north-western Russia, emerging from the Dvina and Pechora Rivers. Logging activities in the Arkhangelsk region started already in the seventeenth century, but the region became one of Russia's main forest industry regions in the 1930s–1940s (Pashkevich 2003). The higher abundance of PCSP in this region relative to PISY and LASP reflects the forest composition, where spruce is by far the most common tree species (Karvinen et al., 2006), and has also been indicated by DW composition in the Northern Dvina delta (Johansen 2001).

Finding PCSP DW from North America in Svalbard is unusual, but not unique. Our results corroborate those of Salvigsen (1981) and Salvigsen and Mangerud (1991), who found a few samples of *Picea mariana* on Svenskøya, located ca. 20 km southwest of Kongsøya, and at Agardhbukta, eastern Spitsbergen. Because the Mackenzie River feeds directly into the Arctic Ocean, finding DW from that region is not surprising. Wood from the Yukon River, however, needs to be transported northwards through the Bering Strait to enter the Arctic Ocean. This is facilitated by the Alaskan Coastal Current, and a multi-decadal mean northward transport through the Bering Strait, especially during summer (Danielson et al., 2014). Although some southward sea ice transport from the Chukchi Sea into the Bering Sea may occur during winter, it is usually short lived (Babb et al., 2013). Thus, any ice bound DW entering the Arctic Ocean is likely to enter the Beaufort Gyre (BG) and eventually the Transpolar Drift (TPD) rather than returning to the Pacific Ocean. However, it is likely that most DW originating from North America, especially from the Yukon River, ends up closer to their sources.

Having entered the Arctic Ocean, DW must to be frozen into sea ice to reach deep into the Arctic. The sea ice drift is controlled by the BG and the TPD, the latter being a strong current reaching from the Siberian coast to the Fram Strait west of Svalbard (Olason and Notz 2014), where the drift speed is related to wind forcing (Hakkinen et al., 2008). Sea ice from most Russian rivers drift towards and then become transported by the TPD, and it has been estimated that ice-rafted material from the northern Russian coast drifts towards Fram Strait with an average speed of 7 km per day (Krumpen et al., 2019), resulting in a journey of at least

2–3 years (Dalaiden et al., 2018). As noted above, North American DW ending up on Svalbard will likely have experienced a passage through the Beaufort gyre, making its journey across the Arctic much longer.

To estimate the time it takes DW to end up on Svalbard, several factors need to be considered. As noted in section 1, there are limits to how long a tree can stay afloat (see Hägglund 1982). However, it is possible that a stranded tree (e.g. caught in a riverbank or washed up on a beach) can continue its journey several years after having been deposited if it dries out sufficiently. This likely also applies to DW, where pieces of wood can be displaced from one beach, by e.g. storms, and subsequently washed up on another beach (this has actually been observed by the authors on Greenland). Moreover, changes in the speed and placement of the TPD, linked to shifts in high latitude storm tracks and the Arctic Oscillation (Rigor et al., 2002; Hakkinen et al., 2008), can affect the transition time for DW, where in periods of a colder than present Arctic the drift is slower. Together with the possibility that parts of the trees have been eroded during the passage across the Arctic Ocean, causing a loss of the outermost rings, these factors make it difficult to get an accurate estimate of the time it takes a tree from dying/logging until it reaches Svalbard.

4.2. DW dating

There were notable differences among the three leading genera/species regarding the dating/provenance success, and there are several reasons for this. Samples containing few annual rings are difficult to crossdate, where in general at least 80–100 rings are required to get a reliable dating. How many rings are required depends on the growth patterns, where series from complacent trees (i.e. those showing little year-to-year growth variability) require more rings to date than those from trees more sensitive to climate and the environment. In addition, trees having grown close to the river banks may develop anomalous growth patterns if they start to tilt before falling into the water, so called reaction wood, which can cause problems when crossdating. Missing rings, commonly found in larch (see below) can also hamper dating.

Another reason could be that the DW dates before the reference chronologies. While the majority of the DW was collected at the present beaches, with clear signs of having been logged, part of the material was collected at elevations above the present storm beach elevation, estimated to be above ca. 6 m a.s.l. at the sampled locations (Forman et al., 2004). This applies to DW samples from Kongsøya (Kap Andreassen and Tömmerneset), but also some of the samples from Gåshamna. Other DW samples, e.g. from Dunderdalen and Reinsletta were found at long distances from the water (>100 m) or being buried, suggesting old age.

4.3. DW as sea-ice indicators

The occurrence of DW has been associated with multi-year sea ice being present at that time (Hägglund 1982; Funder). Thus, periods without DW would indicate low sea-ice concentrations or reduced perennial ice. On the other hand, sea-ice being in contact with land can hinder DW from being delivered to beaches. Fig. 5 shows the average sea-ice extent in September, the month with least sea ice, around Svalbard. During the last four decades, neither Kongsøya nor the coast of south-western Svalbard have been blocked by sea ice during summer, suggesting a free DW transport to (and from) the beaches. However, it is possible that during colder climates, sea-ice has been present also in the outer parts of Bellsund and Hornsund, and surrounding Kong Karls Land, restricting DW to reach the beaches. Thus, in order to interpret DW abundance in terms of sea-ice variations, knowledge of local sea ice conditions would add to the validity of the interpretations. This can be obtained from proxies such as coralline algae, which are sensitive to light conditions and produce growth bands similar to bivalves, and have been used to reconstruct sea-ice cover variations in Svalbard and the Canadian Arctic (Halfar et al., 2013; Hetzinger et al., 2019). In this respect, also temporal variations in the warm Norwegian/West Spitsbergen Current system, which influences sea ice around Svalbard (Stein 2019), could be relevant.

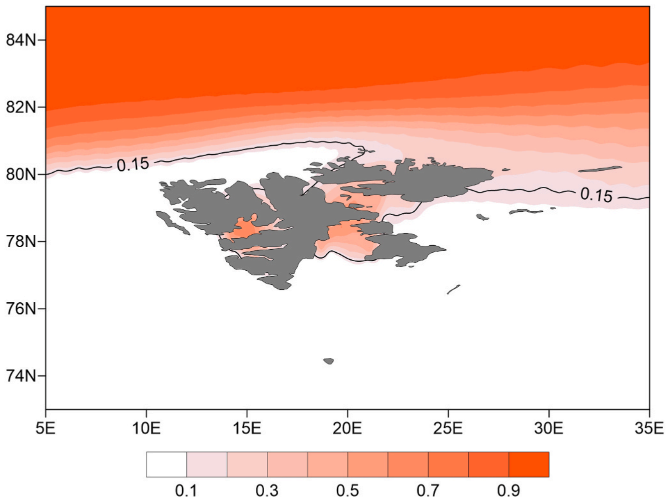

Fig. 5. Average sea-ice coverage rate (from no ice = 0.0, to full cover = 1.0) around Svalbard in September 1979–2019 from the NOAA/NSIDC Climate Data Record of Passive Microwave Monthly Northern Hemisphere Sea Ice Concentration (version 3) (Peng et al., 2013; Meier et al., 2017).

Another factor that need to be considered when assessing DW as an indicator of sea-ice variations, are the temporal patterns of DW export from the source river basins where the tree grows. Trees falling into rivers are mainly due to bank or undercutting erosion, and maximum erosion occurs when water levels are high, e.g. during floods (Alix 2005); very large quantities of wood can be moved during extreme flood events (Mao et al., 2013). Pulses of DW export can reflect decadal to multi-decadal discharge patterns redistributing wood derived from bank erosion and channel migration (Kramer et al., 2017). Moreover, DW has been important sources for building material, fuel and artefacts for Arctic communities (Alix 2005; Mooney 2016), resulting in continuous removal of DW through time.

4.4. Extending pan-arctic tree-ring chronologies with DW

One of the main results from this study was that four independent chronologies were constructed from the Svalbard DW material. Although only two chronologies extended beyond the reference chronologies (Dvina PISY DW 1525–1982 vs reference 1594–2011 and Yenisei PISY DW 1477–1988 vs reference 1584–2010), our results show that there are good possibilities for further extensions of existing northern Russian tree-ring chronologies. The next step will be to compile all existing data from DW and living trees to update and extend the pan-Arctic tree-ring data network. By adding the DW time series to the existing regional chronologies, more robust and reliable time series will be obtained, and this will be especially beneficial in the early, less well-replicated, parts of the original chronologies. Furthermore, it is possible to increase the spatial precision of where the DW originated (see Hellman et al., 2017). Thus, using local-scale reference chronologies, it is possible to determine more precisely (compared to a vast river catchment) the growth place of a DW. In addition to adding more detailed spatial climate information from the tree rings, this could be useful when understanding river dynamics associated with the DW formation.

The potential of finding DW in the Arctic from most of the Holocene have been demonstrated in many studies using ^{14}C dating of wood material (see synthesis by Hole and Macias-Fauria, 2017). However, the paleoclimatological potential of the already collected data is limited, since they were not collected with focus on dendrochronological analyses. Interestingly, the early DW studies included measuring of ring-widths to establish the growth environments of the determined species: larger rings from southerly regions and smaller rings from northerly ones (Agardh 1869; Ingvarson 1903). However, there are good potentials to extend tree-ring chronologies far beyond the present. Well-preserved DW from above the present beaches can provide old material useful for dendrochronological studies. A recent study from Nordaustlandet, northeastern Svalbard, showed that DW from elevations of ca. 10–30 m a.s.l., corresponding to where most of our old material was found, were between 3000 and 9000 years old (Schomacker et al., 2019). Nevertheless, to find several thousand years old DW overlapping in time, which can be used to build chronologies, is a difficult task if only data from a few locations are used. However, the chance to achieve this would increase if all DW collected over the years could be compiled and analysed together.

Based on earlier findings from Svalbard, as well as from the present study, LASP is the species which is most abundant throughout the Holocene. Of the dated DW samples from Svalbard presented by Hole and Macias-Fauria (2017), more than 50% were LASP. Both PCSP and PISY are more rarely found preserved. Unfortunately, of these three DW species, LASP offers problems to crossdate due to frequent missing rings (up to 5–10% in one radius, Hantemirov and Shiyatov, 2002), making it more difficult to date and provenance. On the other hand, there exist some millennial long *Larix* chronologies from Russia (see Hellman et al., 2016a), which could be useful as references. If future LASP collection is focused on DW in relatively good conditions (i.e. not severely decomposed) with sufficient number of rings (>c. 150), there are good possibilities to improve and extend existing *Larix* chronologies well back in time. This would provide much needed climate information from a region largely devoid of accessible long-term paleoclimate data.

5. Conclusion

Out of nearly 400 DW samples, the majority belonged to the genera/species *Picea* sp., *Larix* sp. and *Pinus sylvestris*. Of the 60% that could be dated and the provenance determined using dendrochronological methods, all samples, except five originating in North America, came from northern Russia. The high dating success relates to most DW samples having been found on or close to the present beaches, corresponding in time to the nineteenth and twentieth centuries, periods with high logging activity in Russia. Four partly well replicated tree-ring width chronologies, which crossdated with existing reference chronologies, were assembled representing the Dvina-Pechora and Yenisei regions, demonstrating the potential to extend regional chronologies back in time. The undated material (mainly *Picea* and *Larix*) collected from relict beaches on elevations above the present beach zones, were likely older than the reference chronologies, providing means to extend pan-Arctic tree-ring chronologies back in the Holocene. In order to utilise Arctic DW as a proxy for past sea ice conditions, efforts are needed to compile and date more, and especially older, material, and combine DW data with other sea-ice proxies, to reduce the uncertainties associated with the timing of transportation and deposition of DW in the Arctic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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