

Linking two centuries of tree growth and glacier dynamics with climate changes in Kamchatka

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Abstract Glaciers around the world retreated as the climate warmed substantially. For the majority of alpine and arctic areas, however, the lack of meteorological data over a long period makes it difficult to build long-term climate and glacial fluctuation relationships, emphasizing the importance of natural proxy archives. Here we use the 230-year record of stem radial growth of birch trees (*Betula ermanii*) from the treeline forests above the receding glaciers in eastern maritime Kamchatka to analyse temporal variations of climate as well as glacial advance and retreat. Glaciers in Kamchatka Peninsula represent the southern limit of glaciation in far eastern Eurasia, which makes them prone to global warming. Using instrumental climate data (1930–1996) from local meteorological stations, we find that the July temperature had most prominent positive impact on birch growth. On the contrary, smaller ring increments are associated with the positive summer and net annual ice mass balance of Koryto Glacier. The prevailing trend of higher summer temperatures and lower snowfall over the past 70 years has enhanced tree growth while causing the glacier's surface to lower by about 35 m and its front to retreat by about 490 m. Assuming these same relationships between climate, tree growth, and glacier mass balance also existed in the past, we use tree rings as a proxy record of climatically induced temporary halts in the glacier's retreat over the past two centuries, which in total was over 1,000 m. Both direct observations and tree ring proxies indicate several

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prolonged warm periods (1990s, 1960s, 1930–1940s, 1880–1900s) interspersed with cooler periods (1984–1985, 1970–1976, 1953–1957, 1912–1926, 1855–1875, 1830–1845, 1805–1820 and 1770–1780) when the glacier re-advanced, creating several consecutive terminal moraine ridges. We conclude that birch tree-rings are suitable for assessing tree growth/climate/glacial relationships over a longer timescale in maritime Kamchatka.

1 Introduction

Alpine and arctic areas are among the most sensitive environments to climate change (Körner 2012; Duarte et al. 2012) with these cold areas becoming increasingly warmer during the last two centuries (Arndt et al. 2010). Many records suggest that the mid-19th century experienced particularly cold conditions, and served as the culmination of the Little Ice Age (LIA, Matthews 1992). Temperatures in the 20th century were significantly higher than previous centuries (Briffa et al. 1995), as indicated by instrumental climatic records (Bhutiyan et al. 2007), resulting in the worldwide recession of alpine and arctic glaciers (Solomina et al. 1995). The Earth's mean surface temperature increased by 0.74 K over the last century with some regions such as arctic and high-mountain biomes experiencing a much greater warming of 2–3 K (Alley et al. 2007). This has resulted in winters with less accumulated snow, a negative mass balance of most glaciers and their fast retreat due to longer summer seasons (Wilson and Nilsson 2009; Narozhniy and Zemtsov 2011). Understanding how different organisms cope with these changes and their synergistic effects are now major topics in ecology and conservation biology of cold environments.

Rising temperatures in cold regions cause pronounced changes in plant cover, including the revegetation of newly deglaciated areas (Burga et al. 2010; Dolezal et al. 2008) and plant species distribution shifts (Chen et al. 2011; Hedenas et al. 2011; Gottfried et al. 2012). These processes are interconnected through the positive impacts of rising temperature and melting snow on plant phenology (Callaghan et al. 2011a), growth (Bhattacharyya et al. 2006) and productivity (Saxe et al. 2001). These effects, however, are species and site-specific. While numerous studies have shown an increased plant performance and range extension following global warming (Callaghan et al. 2011b; Walker et al. 2012), others documented no significant response (Prach et al. 2010; Klimes and Dolezal 2010).

Trees in cold climate are predicted to react sensitively to warming because their tall and open canopies are coupled with ambient air conditions, causing them to closely track air temperature changes (Körner 2012). At sites where temperature is limiting, typically at high elevations and latitudes (Körner 2003), an increase in air temperature and glacier retreat may cause a rapid increase in tree growth, in particular at their upper distributional limits (tree-line). Trees retain information of such environmental influences in their annual increments (tree-rings), which can be revealed through dendroclimatological techniques (Schweingruber 1996). Dendrochronology provides high temporal and spatial resolution making it possible to track the past influences of various environmental drivers several centuries back (Büntgen et al. 2013; Altman et al. 2013). Trees confined at the upper tree line ecotone can be particularly sensitive to both rising temperatures and subsequent glacier retreats (Leonelli et al. 2008). Tree ring data from these trees are thus potential archives of temporal variations of climate as well as glacial fluctuations (Bhattacharyya et al. 2006; Linderholm et al. 2007).

This paper aims to assess the relationships between tree growth, climate change and glacial fluctuations in eastern Kamchatka, on the Russian Far East. Kamchatka's glaciers represent the southern limit of glaciation and permafrost occurrence in northern Eurasia, which makes them prone to environmental change such as recent global warming (Arndt et al. 2010). Owing to

extremely high snow accumulation in winter, maritime glaciers in Kamchatka develop as low as 300 m in elevation and are characterized by the most intense mass exchange so far observed in the whole of Eurasia (Shiraiwa et al. 1997).

In this paper, we explore whether the same driving forces impacted upon both tree growth and glacier dynamics; this would allow us to make a reconstruction of both climate and glacier dynamics from tree-ring proxies. Specifically, we tested whether the same climatic signal influencing the long-term changes in radial growth increments of treeline *Betula ermanii* specimens also impacted the ice mass balance of the Koryto Glacier. Assuming these same relationships between climate, tree growth, and glacier mass balance also existed in the past, we finally use tree rings as a proxy record of climatically induced glacier dynamics to date terminal moraine ridges (key landmarks) formed over the past two centuries in the cool periods of positive snow balance, when the glacier re-advanced and build new moraines.

2 Material and methods

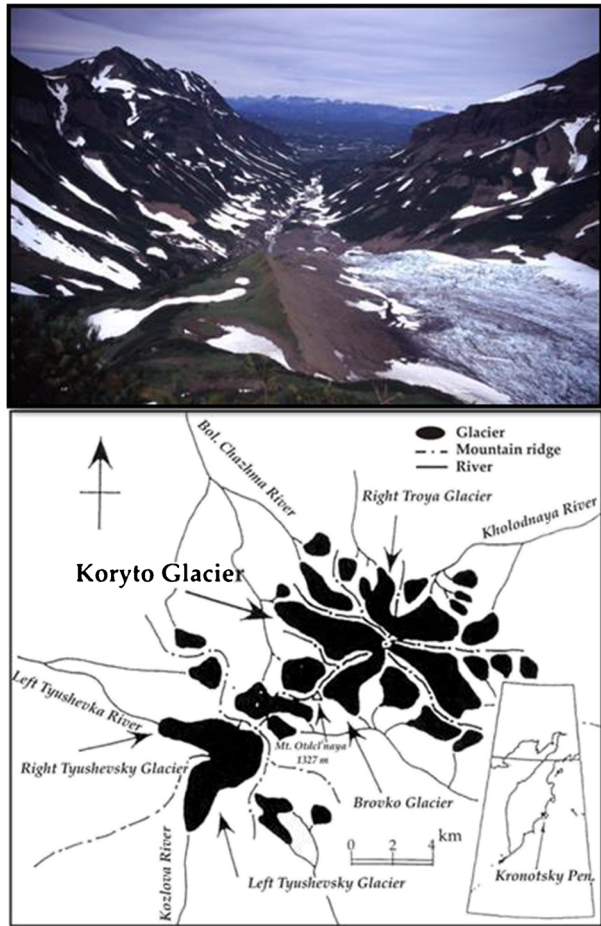
2.1 Study area

The research was conducted in Koryto Glacier Valley (54°45'N, 161°40'E) in the eastern part of the Kronotsky Mts. Biosphere State Reserve (Fig. 1), a coastal region in eastern Kamchatka with short, cool summers and long snowy winters and a nearly equal distribution of precipitation throughout the year. Koryto Glacier Valley is located in the upper part of the Bolshaya Chazma River. It has a U-shaped profile with lateral moraine slopes and cliffs that rise from the deglaciated foreland at 250 m up to rounded peaks at ca. 1,200 m. Bedrock is composed of pillow lava and hyaloclastite of submarine volcanic origin, overlain by heterogeneous glacio-fluvial deposits and volcanic ash. Mean monthly minimum (February) and maximum (July) temperatures are -22.6 and 17.4 °C and mean summer (snow-free period from June to August) and winter (September–May) temperatures are 8.2 and -7.5 °C, respectively. Annual precipitation is 600–1,100 mm in the high mountain ranges along central Kamchatka and up to 2,500 mm along the east coast, including Kronotsky Peninsula where most precipitation falls as snow. Snowpack of 5–10 m deep in accumulation zones has been reported (Shiraiwa et al. 1997). Snow accumulates mainly in leeward valleys, where it can be several meters deep (Shiraiwa et al. 1997) and persists into late summer and hence reduces the time available for plant growth. These topographically induced gradients in snow cover and avalanche activity have given rise to a diverse mosaic of plant communities composed of alpine tundra, snowbed vegetation and so-called Beringian woodland of *Alnus fruticosa* and *Pinus pumila* shrubs (Yakubov 1997; Doležal et al. 2013). *Betula ermanii* woods are less widespread, confined to elevated locations and rocky terraces where they escape snow avalanches (Krestov 2003).

2.2 Target species

The target species of this study, *Betula ermanii* (stone birch or Japanese mountain birch), is a widespread mountain tree species in the maritime and suboceanic regions of northeast Asia, extending from 33 to 58° N. In the southern half of its geographic range (Japan, Korea, NE China), *Betula ermanii* forms upper montane forest belts of 200 to 500 m of vertical spread, making up the uppermost limit of tree growth (treeline). *Betula ermanii* always occurs above the mixed mountain forest taiga dominated by different conifer species and creates an open treeline woodland at different elevations depending on latitude (Okitsu 1987; Gansert 2002; Yu et al. 2007; Doležal et al. 2012). According to Krestov (2003), about 70 % of all *Betula*

Fig. 1 *Top*: Northwestward view of the Koryto Glacier Valley in mid-August 1999. *Bottom*: Detailed map of the glaciers in the Kronotsky Peninsula Mountains, eastern maritime Kamchatka



ermanii forest area lies in Kamchatka, where it creates an extensive horizontal vegetation zone in coastal-suboceanic areas (Shamshin 1999), and treeline forests on volcanoes and in mountain ranges up to 600–800 m elevation (Dolezal et al. 2010). *Betula ermanii* occurs widely throughout Kamchatka over a wide range of ecologically different sites except for wetlands, permafrost areas, places with extremely high snow accumulation, avalanche-prone mountain slopes (Dolezal et al. 2013), and dry inner lowlands where it is outcompeted by spruce and larch (Krestov 2003).

2.3 Koryto glacier and its dynamics

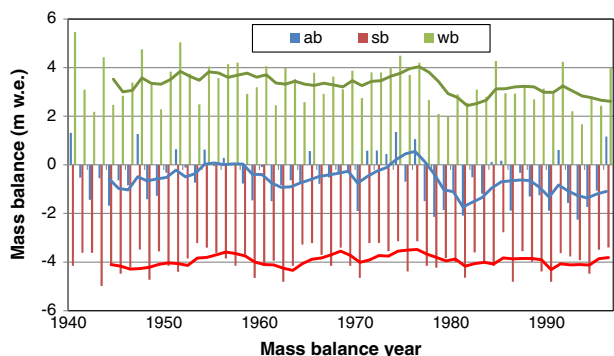
In Kamchatka, there are 448 glaciers with a total area of about 905 km² (Muravyev 1999). More than 80 % of the glacial area is concentrated in the Central (Sredinny) Mountains and the Klyuchevskaya Volcanic Group, where average altitude exceeds 3,000 m. About 10 % of the glacial area is found in the Kronotsky Peninsula, which is an extinct volcanic massif of tertiary origin near the Pacific Ocean. It is strongly glaciated although its summits seldom exceed 1,000 m elevation. Muravyev (1999) refers to 32 glaciers that occur as low as 250 m a.s.l. and

extend over an area of 92 km². Such glaciation is the result of a maritime climate with high snow precipitation and plateau-shaped landforms that allow glaciers to have extensive accumulation zones (Shiraiwa et al. 1997). The glaciers in this region have gentle surfaces and lack supraglacial debris on ablation areas. Koryto Glacier is one of the largest glaciers situated in the northeastern part of Kronotsky Mts. (Fig. 1), flowing in the northwesterly direction from 1,150 m to 250 m elevation with the terminus lying below the tree-line and forming the source of the Bolshaya Chazma River (Shiraiwa et al. 1997). This valley glacier is around 6.6 km long, 0.5–2 km wide and covers an area of about 7.55 km² (Muravyev 1999). Russian glaciologists studied the Koryto Glacier's mass balance in 1960, 1971, 1982, 1996 and 1997 (Preobrazhensky and Model 1965; Vinogradov and Khodakov 1973). During the first three observations, the net mass balance was negative to positive (−0.09 to 0.58), while in the years 1996 and 1997, the average winter mass balance was anomalously positive (5.9 and 6.21 m in water equivalent) resulting in average net balance of +1.14 and +2.35 (Muravyev 1999). Using a model developed for Koryto Glacier by Vinogradov and Khodakov (1973), area-averaged winter (September–May), summer (June–August) and net balances (winter minus summer balance) were calculated (Muravyev 1999) using summer air temperature, short wave radiation and winter snow precipitation data recorded at the nearby Kronoki meteorological station. Muravyev (1999) and Yamaguchi et al. (2008) reconstructed the Koryto Glacier mass balance over the past 70 years (Fig. 2), indicating a prevalent negative trend except for several short positive phases, creating a row of consecutive terminal moraine ridges. Uncertainty still remains about the precise dating of older moraines created during the Little Ice Age (17th–19th centuries).

2.4 Wood core sampling and climate-ice mass-growth analyses

To obtain a representative regional standard tree-ring chronology that could be used in future reconstructions of glacier dynamics in eastern Kamchatka, we obtained in total 83 wood cores from 69 trees from four native tree populations. First, twenty five trees were sampled in Kronotsky Mts. on the Kamchatka's Pacific coast, on a ridge separating Koryto Glacier and Pole Markova Glacier near the local treeline at an altitude of 500 m (Dolezal et al. 2013). The next three of our study sites were located along an altitudinal gradient (400, 500 and 600 m) on the NW slope (~10°) of Ushkovsky Volcano (UV, 3,943 m), ca. 150 km from Koryto Glacier. UV is a large compound volcanic massif located at the NW end of the Kliuchevskaya volcano group and is capped by an ice-filled 4.5 × 5.5 km caldera. It has been active during the Holocene, with the last eruption of the summit cone occurring around 1890 (Muravyev et al. 2007).

Fig. 2 The mass balance record for Koryto Glacier for mass balance years 1939/40–1996/97. Shown is winter balance (wb); summer balance (sb); annual net balance (ab) as difference between winter and summer balance; *thick lines*: 5-year running mean



The cores were extracted 1 m above the ground with an increment borer (Mora, Sweden), and transported to the laboratory. The cores were sanded and inspected for reaction wood and other aberrant properties. Tree-rings were counted from pith to bark and their widths measured to the nearest 0.01 mm with the aid of a microscope interfaced to a computer. PAST4 (www.sciem.com) was used for crossdating and quality control. ARSTAN (Cook 1985; Grissino-Mayer et al. 1992) was used for chronology development adopting a two stage detrending method; firstly using a negative exponential function and secondly, a cubic-smoothing spline with a 50 % frequency response cut-off of 70 % series length, with a minimum spline rigidity of 50 years (Cook 1985).

From the three chronologies (Standard, Residual, and Arstan) produced by ARSTAN, the residual chronologies (obtained by autoregressive modelling) with the strongest common high-frequency variation were used (Fig. 3). The residual and standard chronologies were, however, highly correlated (mean $r=0.95$). The mean sensitivity (MS) of ring width, which is a measure of year-to-year variability, ranged from 0.34 to 0.38; the expressed population signal (EPS) values ranged from 0.87 to 0.91; signal-to-noise ratio (SNR) ranged from 7.2 to 9.3; all these statistical characteristics indicating a strong climate signal in studied chronology (Wigley et al. 1984). Since the residual and standard chronologies from the four study sites were significantly intercorrelated (mean $r=0.65$), we combine them to produce one regional tree-ring chronology for the growth-climate analyses.

The most prominent climatic factors affecting tree growth were identified by establishing the mean relationships between the residual chronology and climate through simple

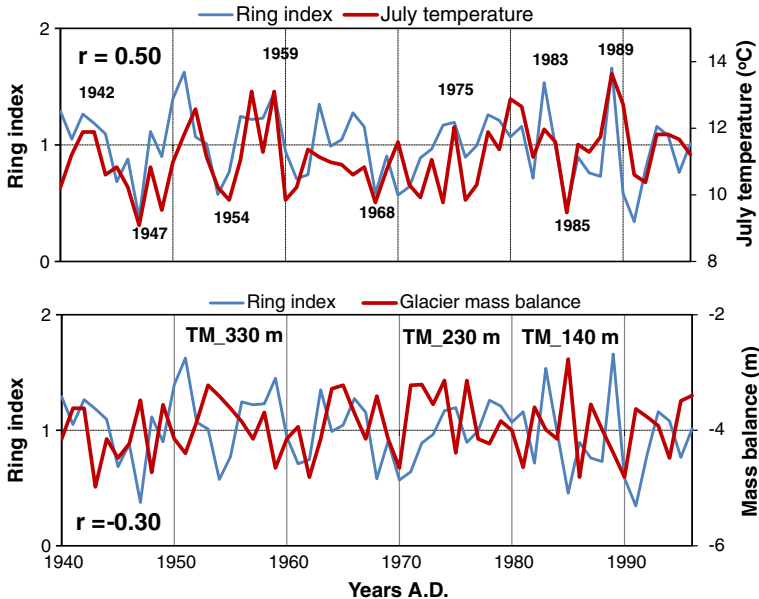


Fig. 3 Comparison of the *Betula ermanii* ring width chronology with the July temperature (*top Figure*) and summer mass balance of Koryto Glacier (*bottom Figure*). Pointer years for narrow/wide rings associated with extreme climate are indicated by calendar years in bold print. During the warm second half of the 20 century, the front of the Koryto Glacier retreated about 310 m, and the glaciated area decreased from 8.9 to 7.55 km². This rapid recession was stopped in cooler periods of 1954–1957, 1970–1976 and 1984–1985, less favourable for tree growth. During these temporary halts in the glacier’s retreat, unconsolidated debris was deposited, creating three moraine ridges (TM) that were about 330, 230 and 140 m distant from the glacier terminus in AD 2000

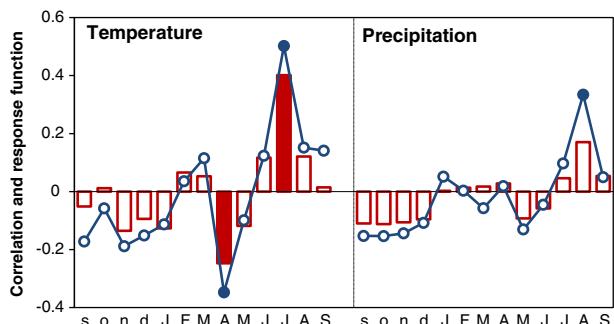
correlations and bootstrapped response-function analysis in the bootRes package (Zang 2012) in R 2.14 (R Development Core Team 2013). Monthly mean temperature and monthly total precipitation data were compiled from climate stations in Klyutchi (1931–1997, 150 km NW of the Koryto Glacier) and Kronoki (1939–1997, 40 km N of the Koryto Glacier). Explanatory climate variables spanned a 13-month window, from September of the previous year to September of the current growth year. Averaged winter, summer and net balances of Koryto glacier were also correlated with residual tree-ring chronology. The response function analysis was based on stepwise multiple regression, where climatic variables were used after their transformation into principal components. The significance was tested using bootstrap techniques (Zang and Biondi 2013).

3 Result and discussion

3.1 Climate-growth relations

A warm summer was positively associated with birch wood formation. In particular, tree-ring width was significantly and positively associated with July temperature ($r=0.50$, Fig. 4) and negatively associated with snow accumulation as expressed by the summer glacial mass balance ($r=-0.30$) or annual net glacial mass balance of Koryto Glacier ($r=-0.22$, in all cases $P<0.05$). The tree-ring width was also positively associated with mean growing season temperature (JJA, $r=0.36$), mean annual temperature ($r=0.35$), August rainfall ($r=0.34$) and negatively associated with April temperature ($r=-0.35$, Fig. 4). A visual comparison of these chronologies (Fig. 3) showed that narrow rings were associated with both low summer temperature and a positive glacial mass balance (and values above the long-term average) such as in the years 1947, 1954, 1956, 1968, 1973–74, 1976, 1985, 1991 and 1996, whereas wider rings were associated with higher temperatures and a negative glacial mass balance as in the years 1942, 1963, 1967, 1978, 1983, 1989 and 1993. Based on the above climate correlation analysis results, the ring-width chronology was selected to reconstruct the July mean temperature using the regression analysis (Cook and Kairiukstis 1990), with a split calibration-verification scheme to test the reliability of the temperature reconstruction. The period from 1931 to 1963 was used for verification and 1964–1996 for calibration. The correlation coefficient between the temperature reconstruction and Kronoki station is 0.654 ($p<0.01$, 1931–1996), demonstrating the validity of the regression model. On the basis of this model, the July mean temperature in the study area has been reconstructed (Fig. 5) for the period 1770–1999 (Series ≥ 5 , EPS ≥ 0.8) (Wigley et al. 1984).

Fig. 4 Correlation (dots on line) and response function (columns) of the indices of *Betula ermanii* tree ring widths to climatic variables calculated for a 13 month period (September of the previous year to September of the current year) for the years 1930–1995. Months with significant responses ($P<0.05$) are indicated by red full columns, blue bullets indicate months with significant correlations



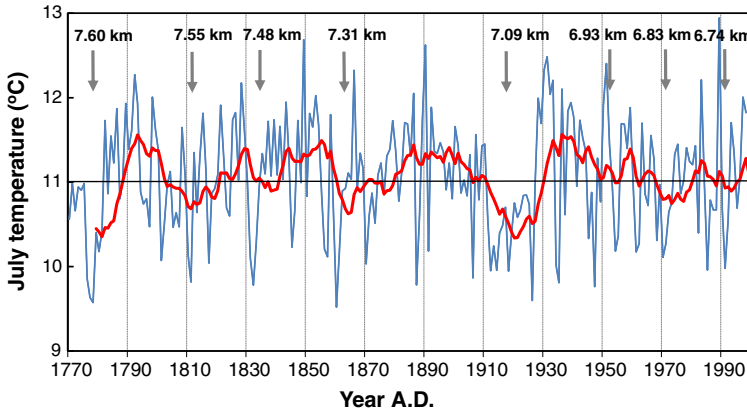


Fig. 5 Time-series plot of the reconstructed July temperature from 1770 to 1996 and changes in glacier front position over the past 230 years. In cooler periods less favourable for tree growth, the glacier re-advanced, creating several consecutive terminal moraine ridges, as indicated by *arrows* together with the glacier length in kilometres. The smoothed values (10 year running mean, *thick line*) of temperature are also shown

3.2 Glacier mass balance

The last century (1930–2000) records of temperature and precipitation in maritime Kamchatka show significant positive trends in spring and summer temperature, but a negative trend in winter precipitation since the 1930s (Dolezal et al. 2010). Summer temperature and winter precipitation have tended to be opposite in sign and therefore they either contribute together to a positive or negative glacier mass balance and birch tree growth. In general, enhanced radial growth in birch accompanied negative mass balance of Koryto Glacier over the past 70 years (Fig. 3); the average annual net mass balance (winter minus summer mass balance) of Koryto Glacier for the 1939–1997 period was -0.52 m yr^{-1} water equivalent (Muravyev 1999). The annual net mass balance was positively correlated with winter precipitation ($r=0.84$), and negatively with both the July temperature ($r=-0.48$, Kluychi station) and mean summer temperature ($r=-0.52$) recorded at nearby Kronoki station. During the warm second half of the 20 century, the terminal retreat accelerated, in particular after the 1970s (Yamaguchi et al. 2003), as related probably to the large-scale atmospheric circulation over the North Pacific Ocean (Bitz and Battisti 1999; Walters and Meier 1989). Since Kamchatka lies between the Siberian High and Aleutian Low, the annual amount of precipitation and consequently fluctuation of glaciers depends on variation of these pressure systems, as linked to The Pacific Decadal Oscillation (Biondi et al. 2001). From the late 1970s, Siberian High invaded Kamchatka, to shift Aleutian Low into Alaska, with the resulting positive balance of its coastal glaciers, while a negative trend prevailed over Kamchatka, and also over the North Cascade Mountains of Washington (McCabe and Fountain 1995).

The surface of Koryto Glacier decreased by about 35 m, its front retreated by about 310 m, and the glaciated area decreased from 8.9 to 7.55 km² since the 1930s. This rapid recession was stopped by a positive snow balance in 1953–1957, 1970–1976 and 1984–1985, when the terminus slightly re-advanced, depositing three terminal moraine ridges that were about 330, 230 and 140 m distant from the glacier in 2000. During these three cooler periods, birch showed consistently below-average radial growth (Fig. 3). A similar trend of prevailing negative glacier mass balance in the second half of 20th century and its inverse relation to

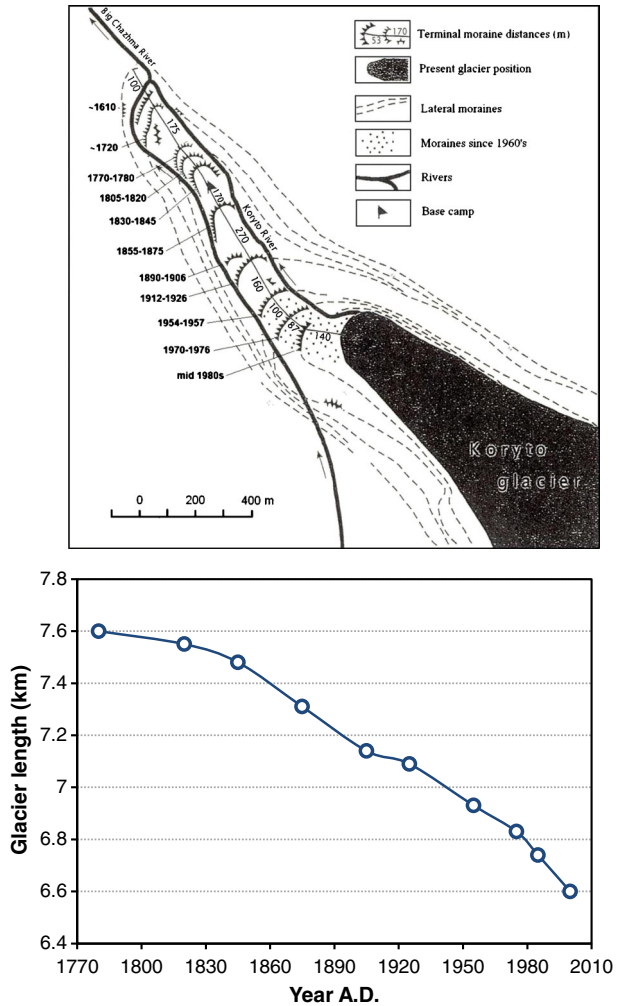
tree-ring width data was documented in southern Alps (Leonelli et al. 2008) and northern Scandinavia (Linderholm et al. 2007), disrupted by several short periods of positive mass balance that do not always correspond with those from Koryto Glacier (Alps: mid-1960s and late 1970s, Scandinavia: 1963–64, 1974–1976, 1981–82, 1992–93).

3.3 Reconstruction of glacier fluctuations

In this study we used data on reduced growth of local birch during the cold periods for the reconstruction of glacier dynamics and moraine depositions. The sensitivity of the tree growth to extreme climatic events such as cooling is relatively well known. Previous attempts to reconstruct the long-term dynamics of Koryto Glacier was based on early summer (May–June) temperatures reconstructed from tree-rings of a distant larch population growing in central Kamchatka under a dry continental climate (Yamaguchi et al. 2008). Such reconstructions can be also biased by the fact that larch growth in continental Kamchatka and the glacier dynamics in maritime Kamchatka are driven by different environmental factors. While the maritime glacier mass balances are affected by the amount of winter snowfall and peak-summer (July–August) temperatures (Muravyev 1999; Yamaguchi et al. 2008), the larch growth in continental Kamchatka depends on spring temperature and summer precipitation (Takahashi et al. 2001). Solomina et al. (2007) found that larch chronologies from interior Kamchatka are better correlated with the interior Klyutchi and Ezzo stations than the coastal station at Petropavlovsk. In addition to these site differences, there are different long-term precipitation trends in central and maritime Kamchatka, i.e. increasing winter snowfall at Klyutchi, while decreasing at Kronoki during the second half of the 20 century, respectively (Dolezal et al. 2010). Hence, caution should be taken against glacier dynamic reconstruction using climate proxies obtained from trees growing in different environments not corresponding with target study area. Long-term growth variations in birch did not correspond ($r=-0.02$, n.s., Online Resource 1) with those of larch from Plosky Tolbachik (Solomina et al. 1999), despite some agreement of individual minima (as in the years 1787, 1797, 1811, 1817, 1845, 1856, 1887–88, 1918, 1926–27, 1947, 1976, 1985).

Several studies have shown both positive and negative effects of snow on the distribution and growth of *Betula ermanii* in Kamchatka (Shamshin 1999; Krestov 2003; Dolezal et al. 2010, 2010). In the *Betula ermanii* dominated maritime areas, late snowmelt resulting from heavy snowfall causes a substantial shortening of the growing season, limiting the distribution of spruce and larch which outcompete the birch. On the other hand, *Betula ermanii* avoids snow-accumulation sites and avalanche paths, being scattered at elevated locations and rocky terraces (Dolezal et al. 2008). Hence, at both ends of snow depth gradient, growth suppression of birch can be expected, resulting in its smaller potential for allowing growth/climate/glacial dynamic reconstructions to be made. For these reasons, our tree-ring samples came from typical birch forests in maritime Kamchatka that were relatively uniform in soil and stand characteristics. Here, rising temperature and decreasing snow precipitation had a positive effect on the birch tree growth and a negative effect on the Koryto Glacier mass balance during the past 70 years. These common climatic signals therefore allow us to use local birch tree-rings as proxy records of climatically induced glacier advances and retreats over the past two centuries, from mid-18th to mid-20th centuries, when instrumental climate data are missing for the Koryto Glacier area. The length of the Koryto Glacier along its flow line was 6.8 km in 2,000 and ca. 7.8 km two centuries ago (Fig. 6). The deglaciated foreland is about 1.3 km long and consists of six older moraines created during the Little Ice Age (mostly during the nineteenth century) and four younger moraines deposited by short glacier advances during the twentieth century as evidenced from repeated photographs of the glacier tongue (Fig. 6). Previous

Fig. 6 *Top*: Detailed map of the deglaciated foreland with terminal and lateral moraines. *Bottom*: Re-constructed glacier length over the past two centuries



attempts at dating terminal moraines created behind the retreating Koryto Glacier, and hence the changes in glacier frontal position, combined historic accounts of glacier dynamics during the last 50 years with lichenometric (Solomina and Calkin 2003), alder (*Alnus fruticosa*) tree-ring (Dolezal et al. 2008) and tephra-layer dating of older moraines (Braisteva and Ponomareva 1997; Solomina et al. 2007). The moraine ridge located 490 m from the glacier terminus in AD 2000 was estimated from ring counts (60–70 rings) of the largest *Alnus* to be 70–80 years old, taking into account the time (5–15 year) alder needs to establish on new substrate (Dolezal et al. 2008). This corresponded with an age estimate of 83 year obtained from *Rhizocarpon* growth curves (Solomina and Calkin 2003). This large terminal moraine may have been deposited during the cool period from ca. 1912 to 1926, characterized by low birch growth, after which the glacier terminus started to retreat rapidly following warming in 1930s–1940s. The next moraine situated 540 m from the glacier terminus is much smaller and was probably deposited during short-term cooling between 1890 and 1906. The deposition of this small moraine was preceded by a warmer period starting in late 1870s and marking the

start of fast glacier retreat. The distinct moraine situated 760 m from the glacier terminus in AD 2000 may have been deposited between 1855 and 1875, the periods of high snow accumulation and low summer temperature are favourable for the glaciers but unfavourable for rapid wood formation. Solomina et al. (2007) concluded, based on larch tree-ring proxies of early summer temperatures, that the 1860s–1880s was the longest, coldest interval in the last 350 years. According to Gostev et al. (1996), the early summer cooling was about 1.5 °C at that time compared with the warmest during the mid-20th century. The moraine situated 930 m from the glacier terminus (Fig. 6) must have been deposited before 1854, as it is overlain by the ash deposited on this date by the Shiveluch Volcano. The Shiveluch 1854 tephra layer was absent on the next moraine ridge (~140-years old and 760 m distant from the glacier terminus) with a till deposit overlain by about 3 cm of loamy soil (Yamagata et al. 1999). Based on the low growth rates of studied birch trees, the three large consecutive moraines situated 930, 1,000 and 1,050 m from the glacier terminus in AD 2000 may have been deposited during the last three cold intervals of the LIA as indicated by the tree-ring records, suggesting cold/snowy periods ca. 1830–1845, 1805–1820 and 1770–1780. This is comparable with similar cooling events in Alps and Tatra Mountains, and is considered by some as the coldest period in last millennium (Büntgen et al. 2013). Overall, Koryto Glacier has retreated 1,300 m since the beginning of the 17th century, and 930 m since the middle of the 19th century.

4 Summary

The tree rings of stone birch (*Betula ermanii*) forming the treeline forests in eastern maritime Kamchatka provide archives suitable for analysing temporal variations in climate as well as glacial advance and retreat. Tree rings as proxies of climate variation and glacier fluctuation may prove useful in Kamchatka because: 1) the scarcity of meteorological stations and the short history of climate measurements, which makes it difficult to use instrumental climatic data to build long-term climate/tree growth/glacial fluctuation relationships; 2) mass balance data are not available for longer durations for most Kamchatka glaciers as systematic glacier monitoring was only started several decades ago, and; 3) glaciers in Kamchatka region represent the southern limit of glaciation and permafrost occurrence in northern Eurasia, which makes them sensitive indicators of environmental change such as global warming. Using instrumental climate data from local meteorological stations, we found that the growth of birch has a positive relationship with the peak growing season July temperature. Negative relationships were found with April temperature, and the average net glacier mass balance in the period 1930–1996. Hence, increased tree growth coincided with warmer periods of the rapid retreat of Koryto glacier, while decreased tree growth coincided with cooler periods when the glacier re-advanced, creating three consecutive terminal moraine ridges. This common climatic signal allowed us to use tree rings as a proxy record of climatically induced glacier retreat over the past two centuries, totalling a front retreat of over 1,000 m. Both historical accounts and tree ring proxies indicate several cooling periods (1996–1997, 1984–1985, 1970–1976, 1953–1957, 1912–1926, 1890–1906, 1855–1875, 1830–1845, 1805–1815 and 1770–1780) with positive glacier mass balance resulting in deposition of distinct terminal moraines. We conclude that tree-ring climate proxies of *Betula ermani* are suitable for assessing tree growth/climate/glacial relationships over longer timescales in maritime Kamchatka.

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