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Abstract

Tree rings, ice cores and glacial geologic histories for the past several centuries offer an opportunity to characterize climate variability and to identify the key climate parameters forcing glacier expansions. A newly developed larch ring-width chronology is presented for Kamchatka that is sensitive to past summer temperature variability. This record provides the basis to compare with other proxy records of inferred temperature and precipitation change from ice core and glacier records, and to characterize climate for the region over the past 400 years. Individual low growth years in the larch record are associated with several known and proposed volcanic events that have been observed in other proxy records from the Northern Hemisphere. Comparison of the tree-rings with an ice core record of melt feature index for Kamchatka's Ushkovsky volcano confirms a 1–3 year dating accuracy for this ice core series over the late 18th to 20th centuries. Decadal variations of low summer temperatures (tree-ring record) and high annual precipitation (ice core record) are broadly consistent with intervals of positive mass balance measured and estimated at several glaciers, and with moraine building, provides a basis to interpret geologic glacier records.

1 Introduction and study area

Modern, near-global retreat of glaciers in response to rising temperatures is a clear demonstration of the relevance of glacier variations as a climate proxy (Oerlemans, 2001; Hoelzle et al., 2003). However the accuracy of moraine dating, the uncertain time lag between the climatic signal and fluctuations, as well as the unknown relative contribution of climate forcings have limited the use of glacial histories in modern quantitative reconstructions. The interpretation of the climatic significance of advance or retreat has also been a limitation on the use of these glacial geologic data as the signal can be interpreted as a mixture of precipitation and temperature. In Kamchatka this question is particularly relevant in this coastal region, as in coastal Norway and

New Zealand where glacier behavior may, in part, be triggered by precipitation as well as temperature (Muraviev et al., 1999; Chinn, 1999; Nesje and Dahl, 2003).

The Kamchatka Peninsula (56° N 160° E) is 1600 km long, almost 500 km wide at its widest (Fig. 1) and supports 29 active and 300 extinct volcanoes. Most of the glaciers of Kamchatka (446 glaciers covering about 900 km^2) are located in Sredinny and Eastern Ridges, oriented along the axis of the Peninsula on the coast (Fig. 1). This orientation of the mountain ranges protects the inner regions of the Peninsula from the influence of the North Pacific so that the climate in the interior is more continental. In general, the climate along the margins is cool and maritime. Annual precipitation is 600–1100 mm in the high mountains ranges and up to 2500 mm along the coast. Mean annual temperature is about 0°C in the south at Petropavlovsk. Winters are cool, snowy and windy, and summers are wet and cloudy. Glaciers occupy a wide zone from 300 to 4500 m a.s.l. and equilibrium line altitudes range from 700 m at Kronotsky Peninsula to 2800 m on Kliuchevskoy volcano (Fig. 1). Four vegetation belts are distinguished at the slopes of the mountains facing the Central Kamchatka depression. First, the dendroclimatically important species, spruce and larch *(Larix cajandery Mayr.)* grow generally up to 300–350 m elevation, stone birch (*Betula ermanii Cham.*) (up to 600–800 m), creeping pine, alder, and willow reach altitudes of up to 1000 m, alpine meadows, mountain tundra and glaciers and in the highest belt. Larch tree line rises to 1000 m.

Historical descriptions of glaciers in Kamchatka only go back to the early 20th century with mass balance measurements at several glaciers begun during the International Geophysical Year in 1957 (Vinogradov, 1975; Vinogradov, Muraviev, 1992). In order to extend these observational records of glacier variations into the past, moraines have been dated using tree-rings, lichenometry, tephrochronology and radiocarbon methods (Solomina et al., 1995; Solomina, 1999; Golub, 2002). Solomina and Calkin (2003) summarized these results and determined the main periods of glacier advance during the last 400 years.

This study adds to the growing development and analysis of proxy records from the western North Pacific Rim including the Kurile Islands (Jacoby et al., 2004; Solomina et al., 2005), and Hokkaido, Japan (Davi et al., 2002). Much of the interest in exploring the variability across the Pacific basin was spurred by the 1976 transition in Pacific climate and the subsequent interest in Pacific Decadal Variability (Mantua et al., 1997).

In this paper we compare the glacial histories in Kamchatka with two climatic proxies: a ring-width based warm-season temperature records, and an ice-core based annual precipitation record (Shiraiwa et al., 1997, 1999, 2001). This comparison helps to identify the climatic signals for glacier advances in Kamchatka as annual precipitation and summer temperature are the two primary drivers of glacier mass balance (Patterson, 1994). Glaciers act as a low-pass filter reacting to decadal and century-scale climate changes by changing their length. Due to the low frequency nature of the glacier record, we use smoothed values of the annually-dated tree-ring and ice core proxies to emphasize the decadal fluctuations for comparison with the glacier record. We also use the inferred temperature histories based on ring-width data and the Melt Feature Index (MFI) from the Ushkovky ice core to provide an assessment of the dating accuracy of the ice core records.

2 Climate and proxy records

Meteorological records, tree-ring chronologies, ice cores and glacier moraines used in this paper (Fig. 1) were primarily chosen based on and the goal of understanding regional climate change and glacier response to these changes. Recent (1920s–2000) trends in temperature and precipitation in Kamchatka are represented by the observational records from Kliuchi meteorological station (Fig. 2a and b). These records are among of the longest in the region and are located in the immediate area relevant to the tree-ring, ice core and glacier sites. In some cases, other stations were used to calibrate the tree rings and ice core records.

Temperature records from Kliuchi station (Fig. 2a) reflect the influence of the Siberian anticyclone and cold current along the Kamchatka coast. Decadal variations are most pronounced in spring in Kamchatka. There are statistically significant positive trends in the summer temperature record with warming becoming more pronounced after the major shift in the North Pacific that occurred in the mid 1970s (Mantua et al., 1997). The instrumental record at Kliuchi also shows an increase in winter (DJF) precipitation in central Kamchatka since the 1930s (Fig. 2b).

2.1 Tree ring records:

Until now few tree-ring records were available for Kamchatka. Most chronologies were developed from the interior of the Peninsula where the extensive larch forests thrive. In one of the first dendroclimatic studies a single larch ring width chronology, the Bystraya (BY; Table 1; Fig. 1) site, based on 12 living trees, was used to estimate summer temperature (Gostev et al., 1996). This preliminary reconstruction explained 38% of the variance of May-June temperature (Table 1). More chronologies have been developed since that early work including larch ring-width series from four locations near upper tree limit in the vicinity of the Village of Esso (ESS, ESN, KEL, EC), two sites from the upper tree line at Tolbachik (KR, KTL), a chronology from the Shiveluch active volcanoes (SHI) and one from Kronotsky Peninsula (BAR) (Table 1). In addition, a preliminary spruce (SHE) and one birch (AV) ring-width series are also available from the Shiveluch and Avacha volcanoes, respectively.

Larch chronologies from Kamchatka correlate well (Table 1) with one another, except for the KR site from the active Tolbachik volcano, which may be influenced by local conditions related to volcanism. One may expect different climate signals between the larch sites from the interior of the peninsula and the more maritime BAR site on the Kronotsky Peninsula, however this difference appears to be minor as BAR correlates well with the other larch chronologies (Table 1). The spruce chronology (SHE) also correlates well with the larch, but with a weaker correlation (Table 1).

Most tree-ring chronologies from Kamchatka are temperature sensitive and have significant correlations with May and June temperatures (Table 1). These larch chronologies (Table 1) better reflect the climatic conditions at the interior Kliuchi and Esso stations than of the coastal station at Petropavlovsk. The correlation of larch chronologies with summer temperature is significant and consistent, but is not strong enough for a formal reconstruction. However one can use a regional larch chronology (KAML) to roughly estimate summer (May, June) temperature variations.

We combined the larch series into a regional chronology (KAML; Fig. 3a) using standard dendroclimatological procedures (Cook and Kairiukstis, 1990). COFECHA was used (Holmes, 1983) for crossdating and quality control, and ARSTAN (Cook, 1985) for chronology development adopting a conservative detrending of negative exponential and straight line curve fits. The final chronology includes 144 cores for the period AD 1632–2003 with a series intercorrelation of 0.65. An average mean sensitivity is 0.32. The chronology has 22 missing rings in the years 1778, 1857, 1864, 1865, 1867, 1877, 1926, 1927 and 1947. This regional chronology compares well with the BY chronology (Gostev et al., 1996) on both annual and decadal timescales (Fig. 3b), except for early in the record, when the sample size is small and towards the end when anthropogenic disturbances are likely at the BY site after 1940 when the chronologies diverge (Fig. 3a and b).

Individual temperature minima inferred from the tree rings are, in part, related to climatically significant volcanic eruptions (e.g. in 1641, 1695, 1810, 1816, 1831), The multi-decadal variations of the KAML and the BY chronologies (Fig. 6) correlates strongly for 1770–1985 (r=0.63, 99% significance level); however the relationship deteriorates for the earlier period (AD 1652–1769).

2.2 Ice core records:

In addition to tree-ring records from Kamchatka, ice cores reveal much about past temperature and precipitation variability (Shiraiwa et al, 1999). These data include a Melt Feature Index (MFI; Fig. 4a) linked with temperature variability and snow accumulation data from the Ushkovsky volcano in Gorshkov Crater (Shraiwa et al., 1999). The Ushkovsky ice core was recovered in 1998 to 212 m depth, which is approximately 28 m above bedrock. The average annual accumulation rate at the central part of the Gorshkov crater of Ushkovsky volcano is estimated at 0.54 m a^{-1} in water equivalent and is dated on the basis of an ash layer erupted from the Bezymianny volcano in 1956. The annual average temperature at 10 m-depth is –15.8°C (Shiraiwa et al., 1999) and the borehole bottom age is estimated to be between AD 1395 and 1487 according to age-depth models (Shiraiwa et al, 1999). The annual accumulation records are available from AD 1828 (Fig. 5c), and the MFI extend back to AD 1503 (Fig. 4a).

According to annual layer counts of the Ushkovsky ice core an accuracy of +/–2 years is estimated to AD 1829. The age of the earlier, lower layers depends on the ice flow model. A difference of 92 years exists between the two models used to estimate maximum and minimum ages at the bottom of the ice core (240 m) (Shiraiwa et al., 1999).

The MFI is derived from ice inclusions of refrozen water within annual layers. In general their volume is considered as an estimate of summer temperature, although the quantification of this proxy is complicated (Koerner, 1977). Jacoby et al. (1983) previously demonstrated a correspondence between the smoothed values of MFI from Arctic Canada with reconstructed degree days above 10°C for June–July from a ring-width chronology from Central Alaska. Similarly, Solomina et al. (2000) compared a local chronology tree ring record from Kamchatka with the MFI from the Ushkovsky ice core. Here we note a general agreement between the smoothed values of the MFI and KAML chronology, although the correlation is low (Fig. 4a). The discrepancies may be may be due to the dating of the MFI series or to the different seasonality of the records. The strong agreement of individual years evident in the comparison between the unsmoothed data shows that most MFI minima correspond to the ring width minima with the accuracy of +/–1–3 years, suggesting this accuracy of the ice core back to AD 1750 (Fig. 4b). The maxima in both records ("warm" years), which are more prominent at the MFI curve, are not coherent with the ring-width chronology (Fig. 4b). This may be due to the more sensitve nature of the MFI to short melt intervals, and the potential of heating during the volcanic eruptions reflected in the ice cores, which may be unrelated to climatic warming (Shiraiwa et al., 2001). The Ushkovsky net accumulation rates

(11 year running mean) correlates with the local Kluchi station winter (r=0.75) and hydrological year precipitation (r = 0.69). This strong relationship occurs even though the station is located at the elevation about 4000 m lower than the ice core site. The accumulation has a clear multidecadal variability pattern and correlates with the Pacific Decadal Oscillation (PDO; Shiraiwa et al., 2001). As in the temperature records, the positive accumulation trend began earlier, before the start of the meteorological records in the late 19th century.

2.3 Glacier variations:

Analysis of instrumental temperature and precipitation observational data and the proxy records allow for general inferences to be made regarding climate forcing that then can be compared with the glacier record. The glacier record includes mass balance data and the moraine chronologies based on lichenometric, tephrochronological, tree-ring, and 14C dates (Solomina and Calkin, 2003; Golub, 2002). A combination of the Ushkovsky accumulation record (hydrological year precipitation) and the KAML tree-ring series as a record of summer temperature provides a basis with which to assess the potential forcing in the glacial geological records. According to the KAML chronology summer warming in Kamchatka began as early as the 1860s (Fig. 3a). The three most prominent intervals of summer cooling since 1630 are identified at 1705–1720, 1755–1790, 1860s–1920. A less prominent cool period is observed at the beginning of 19th century (1810s, 1830s). The 1860s–1880s were the coldest interval in the record, with an early summer cooling of about 1.5°C compared with the warmest during the mid 20th century (Gostev et al., 1996).

Periods with high precipitation and low summer temperature favor glacier expansion. Summer temperature and winter precipitation for Kamchatka have tended to be opposite in sign in 20th century (Fig. 5b and c) and therefore they either contribute together to a positive (negative) glacier mass balance.

Three periods favorable for glacier buildup occurred in the 20th century – during the 1910s–1920s, the 1940s–1950s and the 1960s–1970s (Fig. 5a). The mass balance reconstructions based on the meteorological records (Fig. 5a) show that maximum positive mass balances occurred in 1970s in the southern coastal Kamchatka (Kozelsky Glacier), whereas in central Kamchatka (Grechishkina Glacier) and the Kronotsky Peninsula (Koryto Glacier) a maximum occurred in the 1960s. In the 1940s, the balance of these regions was opposite with positive balance in the central and Kronotsky regions and negative in the south (Fig. 5a).

There is direct evidence of advances in the 1970s in the Kozelsky and Zavaritskogo glaciers in Avacha volcano area, at the Dvoinoy Glacier in Kliuchevskoy volcano area and for Grechishkina in the Sredinny Range. These advances occurred in all regions of Kamchatka as result of the positive mass balances in 1960s–1970s. Kapel'ka Glacier, located near the Kliuchevskoy volcano (Fig. 1) and Koryto Glacier (Kronotsky Peninsula) advance in the 1950s–1960s. End moraines were formed as result of the 1970s and 1950s–1960s advances; these were identified at Kozel'sky and Koryto Glaciers and were used as control points for the lichenometric growth curve (Solomina and Calkin, 2003).

An earlier advance from Kamchatka between 1910 and 1920 is poorly documented, however, comparison of photographs from 1908–1911 with the 2000 margins suggest that Zhelten'ky Glacier was larger than in the mid 20th century and later (Vinogradov, 1975). Mass balance of Kozel'sky glacier was positive according to the reconstruction (Fig. 5a). Ten moraines in Kamchatka are dated to the early 20th century at Novograblenogo, Elysovsky, Lavinshikov, Kozel'sky (Avacha), Koryto (Kronotsky), and Kropotkina (B.Semyachik volcano) Glaciers (Solomina et al., 1995, Solomina and Calkin, 2003) and these advances may have been forced by positive mass balance in 1910s.

Comparison of the KAML chronology with increased accumulation from Ushkovsky ice core (Fig. 5c) shows that the inferred coolings corresponding with increased precipitation was established in the 1870s. After the removal of the linear trend between AD 1876–1989 the 20 years running means of KAML and Ushkovsky accumulation series correlate at R=-0.49, (99% significance level). In the earlier portion of the record

(1838–1875) the Ushkovsky accumulation rates and KAML ring width index (both 20 years smoothed) correlate positively R=0.78 (99% significance level, 20 years running means) and neither have significant trends.

According to the proxy records (Figs. 5b, c) previous periods of high snow accumulation and low summer temperature occurred in 1880s. Eleven moraines dated in Kamchatka by lichenometry, 14C, tephrochronology, historical data and tree-ring counts (Solomina and Calkin, 2003) suggest ice advance and standstill during the second half of 19th century. In many cases these moraines are most prominent and sometimes the only moraines preserved and it is likely that the major advances collectively attributed to the second half of 19th century were actually formed in the 1880s.

The 1840s–1850s were generally less favorable for glaciers due to rather high temperature and low accumulation. However the low summer temperature in 1860s might be also followed moderate glacier advances. The accumulation series from the ice core record ends in 1820s and therefore the further comparisons are based on the KAML temperature record and the MFI (Fig. 4a).

Moraines older than the 19th century are rare in Kamchatka. According to tephrochronological dating, one of the moraines at Koryto Glacier predates the AD 1854 eruption of Avacha. This moraine can be tentatively attributed to the cooling of the 1810s–1830s. Two moraines deposited in 1690s–1700s are dated by lichenometry at the Avgusty Glacier on the Kronotsky Peninsula and Kozelsky Glacier on Avacha Volcano. This earlier date is also supported by a tephrochronology: the moraine of Kozelsky glacier includes the Avacha's ash dated at AD 1737, but does not include an earlier reference horizon dated to 320+/–40 yr. BP (GIN-6893) (1430–1650 cal yr. AD; Solomina, Muraviev, and Bazanova, 1995).

Possible earlier advances are reported by Golub (2002) based on a moraine at Kropotkina Glacier (Bolshoy Semyachik volcano) with a lichen *Rhizocarpon geographicum* of 80 mm diameter growing on its surface. This lichen size corresponds to an age of ca. AD 1500, and is preliminary due to the poor control of the growth curve during this interval.

Comparison of the moraine dates with the KAML ring-width chronology shows that the major advance in the second half of 19th century coincides with the longest period of coldest summer temperatures of the last 350 years (Fig. 3a). The advance during the early 1700s also coincides with a temperature minimum, although it is of less duration. Two summer temperature minima during the mid 19th and early 18th century (Fig. 3a and b) have not been detected in the moraines, although these moraines may have been destroyed by the major advance of the late 19th century.

In many cases the advances of 1870s–1880s marked the Little Ice Age (LIA) maximum, when glaciers were on the average 500–600 m longer and terminated about 100 m lower than at the end of 20th century (Solomina, 2000). Due to the recent summer warming trend (Fig. 2a), glacier advances since 1880s are less extensive and the size of the glaciers continues to decrease.

3 Discussion and regional comparisons

A new regional-scale, well-replicated larch ring-width chronology (KAML) from Kamchatka agrees well with the Bystraya chronology previously used for the reconstruction of May-June temperature. This new chronology is sensitive to June to August temperatures and provides a strong basis to compare with the ice core and glacier records.

Several known volcanic eruptions recognized in the KAML tree-rings (e.g. in 1641, 1695, 1810, 1816, 1831) are marked by narrow rings both in the Wrangell Mountains of southern Alaska (Davi et al., 2002) and more broadly with the Northern Hemisphere records (D'Arrigo et al., 2001). The year-by-year comparison of the minima of MFI minima from the ice core and the regional larch ring width chronology (KAML) suggests the Ushkovsky core has an accuracy of 2–3 years at least for the period since 1750.

Considering the glacier record as an indicator of low frequency, decadal to century-scale climate variability, the four intervals of glacier advance recognized in Kamchatka since AD 1500 occurred in the early 19th century, late 18th, early 17th, and the AD 1500s. The most prominent glacier advances in Kamchatka occurred in the second half of 19th century according to the moraine record. Based on comparisons with the tree-ring and ice core records, both high precipitation and cold summers contributed to these advances.

Moraines deposited in 1900s–1930s and in 1970s are located inside the 1800s complexes and mark less prominent advances or periods of front stabilization. Documented increases in precipitation have not been able to counterbalance the mass loss due to the ablation. More recent glacial activity in Kamchatka based on mass balance records show positive mass balance in the 1970s, which coincides with the PDO shift in the North Pacific in the maritime southern Kamchatka, whereas in more northern regions and in central Kamchatka the positive shift took place earlier, in the 1960s.

Older moraines (1690s–1700s) and possibly one about AD 1500 are rare in Kamchatka because of the later major advances obscure the earlier record. The late 18th century expansion coincides with the summer temperature decrease recorded by the ring width chronology, however, the AD 1500 advance is too old to be compared with the ring width records. Moraines of the last millennium older than 15th century are not found so far in Kamchatka. This might be because of the generally warmer climate (summers) in the area in 11th–14th centuries, when the glaciers were smaller than in the 15th–19th centuries. The AD 1500, late 18th century and late 19th century expansions are broadly consistent with the Alaskan moraine record (Wiles et al., 2004). The strong advance in the late 1800s, late 1600s and possible expansion during about AD 1500 corresponds with and may have been partially forced by a decrease in solar radiation during the Dalton, Maunder and Sporer solar minima as was reported in Alaska (Wiles et al., 2004) and in the Canadian Rockies (Luckman and Wilson, 2005). The broadly coherent glacier variations at these times across the North Pacific suggest similar forcing from both regions, which is consistent with solar forcing.

Since the 1870s–1880s the decadal variations of annual accumulation and larch ring width in Kamchatka tend to be opposite. This pattern is consistent with the observed fluctuations of annual precipitation and summer temperature in 20th century. The periods of high accumulation and low summer temperature favorable for the glaciers are identified by these records as 1910s–1920s, 1940s–1950s and 1960s–1970s. The instrumental records of temperature and precipitation records for the 20th century, as well as reconstructions of mass balance of three glaciers confirm this pattern. The advances of glaciers in 1940s–1950s and 1970s are instrumentally recorded, while those for the beginning of the century are supported by the dated moraines in both maritime and continental parts of Kamchatka.

Collectively the proxy records suggest that there was a change in character of circulation in the region about AD 1875. This variation is first detected in the change from positive to negative correlation of the KAML and Ushkovsky data about 1875. After 1875 cooler summer temperatures are associated with increased winter precipitation together forcing the major late 1800s moraine building maximum. Similar variations in proxy records have been detected for the North Pacific and the Pacific basin in general. Earlier comparisons have been made between tree-ring records from Hokkaido Japan and Kamchatka ring-width and density data (Davi et al., 2002). Davi et al. (2002) showed that temperature-sensitive series from the two regions were coherent from the early 15th century through the mid 1800s after which the relationship noticeably weakened. A similar shift was also reported in a larger inter-hemispheric comparison of Gulf of Alaska and Patagonia tree-ring records (Villalba et al., 2001). Villalba et al. (2001) identified a breakdown in the decadal mode of variability after AD 1850 and suggested that it may be attributed to a more energetic ENSO tropical forcing.

4 Conclusions

Tree rings, ice cores and glacial geologic histories characterize climate variability and to identify the key climate parameters forcing glacier expansions for Kamchatka over the past several centuries. The KAML larch ring-width chronology is a record of past summer temperature variability, which provides the basis to compare with other proxy records of inferred temperature and precipitation change from ice core and glacier records. Individual low growth years in the larch record are associated with several known and proposed volcanic events that have been observed in other proxy records from the Northern Hemisphere, and comparison of the tree-rings with the Ushkovsky ice core record of annual precipitation suggests a 1–3 year dating accuracy for the ice core from the late 18th through the 20th centuries. Decadal variations of low summer temperatures (tree-ring record) and high annual precipitation (ice core record) are broadly consistent with intervals of positive mass balance measured and estimated at several glaciers, and with moraine building, provides a basis to interpret geologic glacier records. The glacier record shows possible advance and moraine building about AD 1500, during the final decades of the 17th century, a strong expansion during the late 1800s and then decades of positive mass balance during the 20th century with moraine building during the 1950s through 1960s and the 1970s. Comparisons of this glacier history with records from Alaska and the Canadian Rockies suggests broadly consistent intervals of glacier expansion and inferred summer cooling during interval of solar irradiance minima.

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Table 1. Correlation matrix for tree-ring records from the Kamchatka Peninsula. In addition to the comparisons between sites correlations of May and June temperatures for Esso and Kliuchy are also shown. Correlations significant at the 99% level (bold), at the 95% level (plain) and those that are not significant (gray) are shown.

	BY	ESS	KEL	ESN	KTL	BAR	SHI	KAML 06
ESS	**0.69**							
KEL	**0.65**	**0.79**						
ESN	**0.75**	**0.66**	**0.79**					
KTL	**0.40**	**0.43**	**0.63**	**0.57**				
BAR	**0.57**	**0.42**	**0.55**	**0.60**	**0.40**			
SHI	**0.53**	**0.53**	**0.54**	**0.58**	**0.50**	**0.48**		
ESSO May	0.38	0.24	0.31	0.25	0.17	0.16	0.29	0.26
ESSO June	**0.44**	**0.58**	**0.62**	0.35	**0.42**	0.13	0.30	**0.43**
KLIUCHY May	0.21	0.13	0.20	0.13	0.18	0.20	0.17	0.17
KLIUCHY June	**0.36**	**0.46**	**0.43**	0.20	**0.40**	0.23	**0.31**	**0.39**

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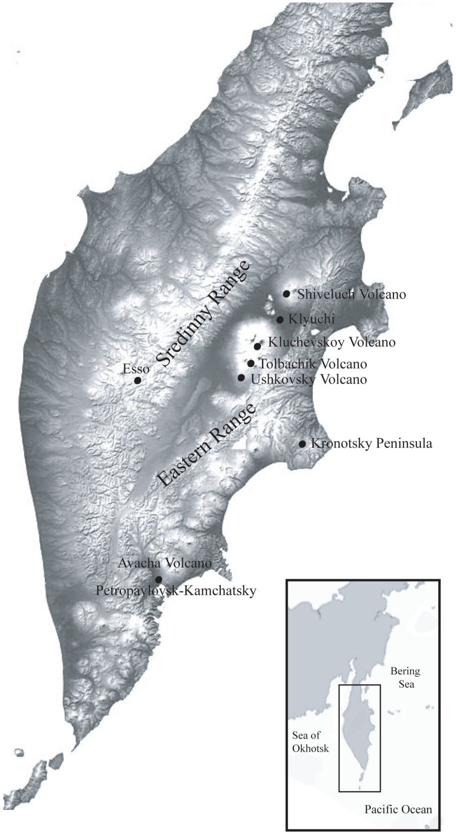

Fig. 1. Study area showing the location of tree-ring, glacier, ice core sites and meteorological stations used in this study.

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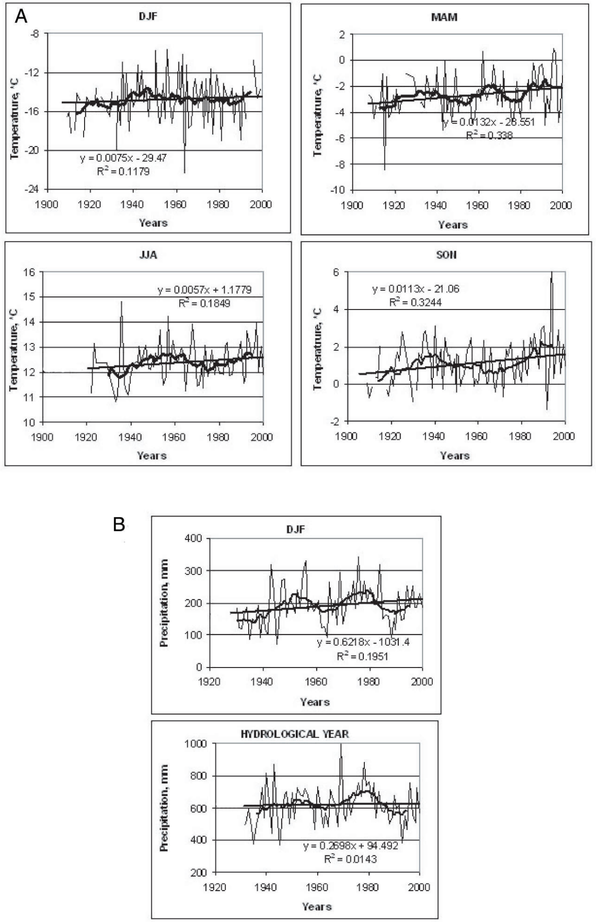

Fig. 2. Temperature and precipitation records from Kliuchi meteorological station in Kamchatka.

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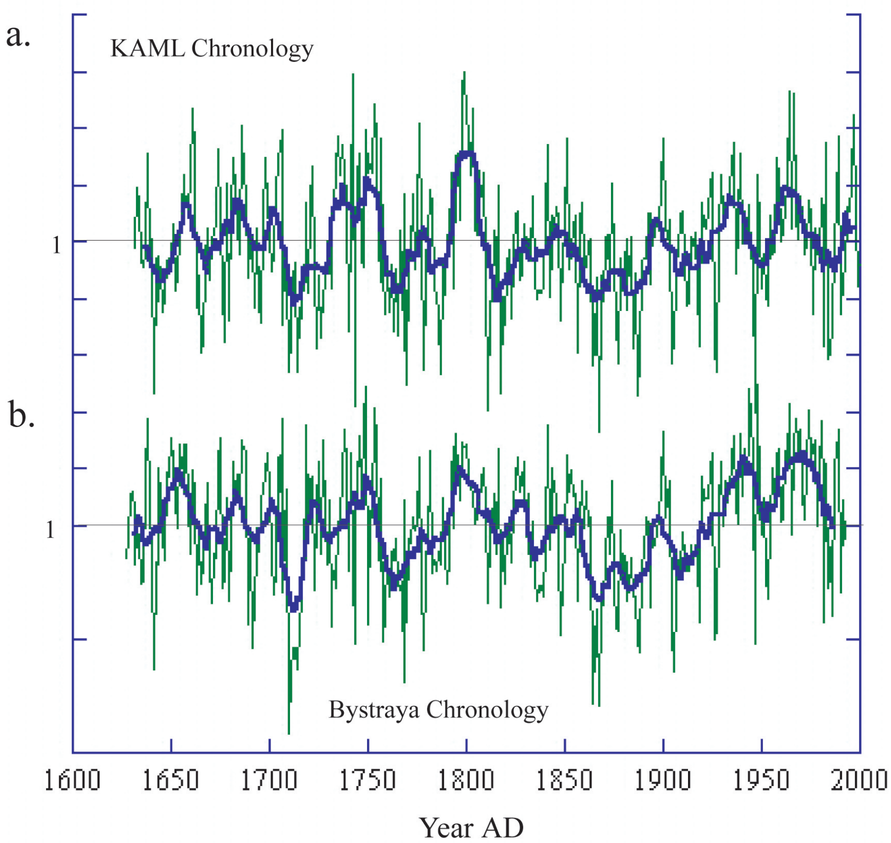

Fig. 3. Comparison of the KAML **(a)** and BY **(b)** ring-width standard chronologies. These records are considered to be proxies of (early) summer temperature.

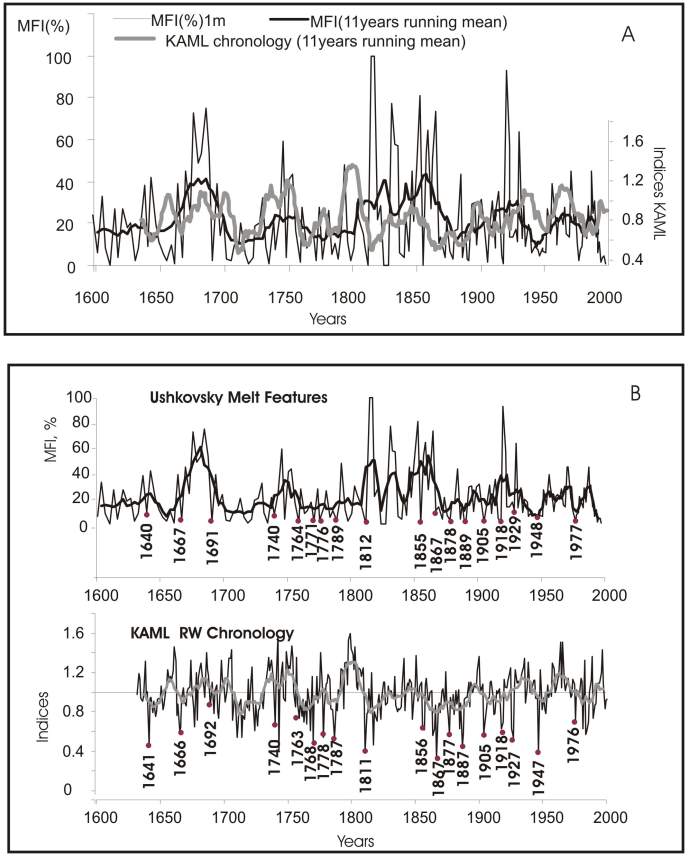

Fig. 4. **(a)** Smoothed values (11 years running mean) of the Melt Feature Index (MFI) of the glacier of Ushkovsky Volcano and the KAML ring-width chronology. **(b)** The unsmoothed values of the same parameters and dates of corresponding minima.

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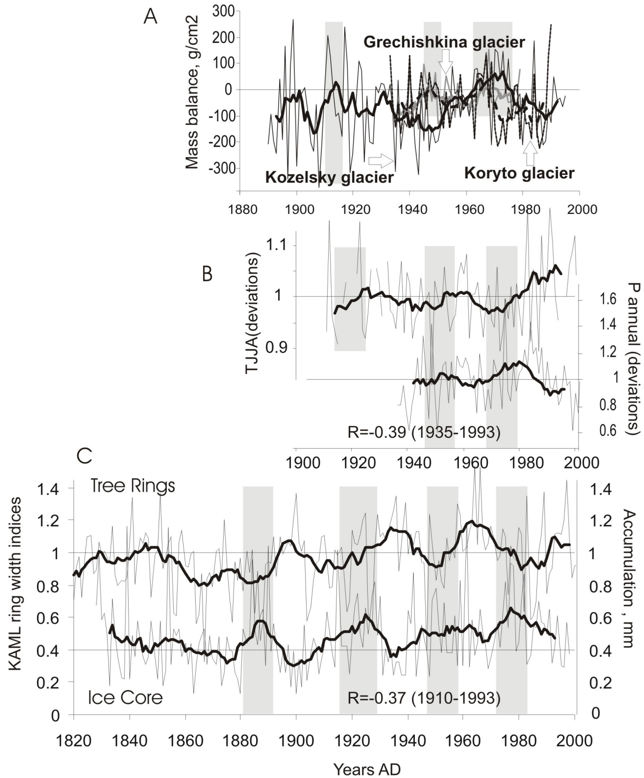

Fig. 5. (a) Mass balance of Kamchatka glaciers reconstructed using meteorological records: Kozelsky glacier (Vinogradov, Muraviev, 1992) Grechisknia glacier (Vinogradov, Muraviev, 1985), Koryto glacier (Muraviev et al., 1999), **(b)** Precipitation of hydrological year and June–August temperature (Kliuchi met.station) **(c)** KAML ring width chronology (proxy for summer temperature) and accumulation for Ushkovsky ice core. All series are 11-years smoothed. Shaded stripes are periods favorable to glacier advances.