Pleistocene and Holocene Glacier fluctuations upon the Kamchatka Peninsula

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Abstract

This review summarises landform records and published age-estimates (largely based upon tephrochronology) to provide an overview of glacier fluctuations upon the Kamchatka Peninsula during the Holocene and, to a lesser degree, earlier phases of glaciation. The evidence suggests that following deglaciation from the Last Glacial Maximum (LGM), the peninsula experienced numerous phases of small-scale glacial advance. During the Late Glacial, moraine sequences appear to reflect the former presence of extensive glaciers in some parts of the peninsula, though little chronological control is available for deposits of this period. During the Holocene, the earliest and most extensive phase of advance likely occurred sometime prior to c. 6.8 ka, when glaciers extended up to 8 km beyond their current margins. However, these deposits lack maximum age constrains, and pre-Holocene ages cannot be discounted. Between c. 6.8 ka and the onset of 'Neoglaciation' c. 4.5 ka, there is little evidence of glacial advance upon the peninsula, and this period likely coincides with the Holocene climatic optimum (or 'hypsithermal'). Since c. 4.5 ka, numerous moraines have been deposited, likely reflecting a series of progressively less extensive phases of ice advance during the Late Holocene. The final stage of notable ice advance occurred during the Little Ice Age (LIA), between c. 1350 and 1850 C.E., when reduced summer insolation in the Northern Hemisphere likely coincided with solar activity minima and several strong tropical volcanic eruptions to induce widespread cooling. Following the LIA, glaciers upon the peninsula have generally shown a pattern of retreat, with accelerated mass loss in recent decades. However, a number of prominent climatically and non-climatically controlled glacial advances have also occurred during this period. In general, there is evidence to suggest that millennial scale patterns in the extent and timing of glaciation upon the peninsula (encompassing much of the last glacial period) are governed by the extent of ice sheets in North America. Millennial-to-centennial scale fluctuations of Kamchatkan glaciers (encompassing much of the Holocene) are governed by the location and relative intensity of the Aleutian Low and Siberian High pressure systems. Decadal scale variations in glacier extent and mass balance (particularly since the LIA) are governed by inter-decadal climatic variability over the North Pacific (as reflected by the Pacific Decadal Oscillation), alongside a broader trend of hemispheric warming.

Keywords

Holocene

Glaciation

Kamchatka

North Pacific

Climate

Chronology

1. Introduction

The Kamchatka Peninsula is the largest glacierised area in NE Asia, and is occupied by ~446 small glaciers, covering a total area of ~900 km^2 (Solomina et al., 2007) (figure 1). The peninsula is also occupied by extensive moraine sequences and other terrestrial and off-shore evidence reflecting the former presence of extensive ice-masses (Vinogradov, 1981; Bigg et al., 2008; Nürnberg et al., 2011; Barr and Clark, 2012a). Despite such information, the extent and timing of former glaciation upon the peninsula remain poorly understood (Stauch and Gualtieri, 2008; Barr and Clark, 2012b), though some key investigations were undertaken in the 1960s and 70s (e.g. Olyunin, 1965; Braitseva et al., 1968; Kuprina, 1970), and have continued episodically thereafter (e.g. Bäumler and Zech, 2000; Solomina and Calkin, 2003; Barr and Clark, 2012b). Recent studies have focused upon ice extent during the global Last Glacial Maximum (gLGM; c.21 ka) (e.g. Leonov and Kobrenkov, 2003; Barr and Clark, 2011), or past millennium (e.g. Solomina et al., 1995, 2007; Yamaguchi et al., 2008), and few investigations have focused upon the Holocene as a whole (Savoskul and Zech, 1997; Savoskul, 1999; Yamagata et al., 2000, 2002), despite Kamchatka offering one of the best-resolved Holocene tephra sequences anywhere in the world (Braitseva et al., 1997; Ponomareva et al., 2007, 2013). With this in mind, the purpose of this paper is to summarise current understanding of Holocene glacier fluctuations upon the Kamchatka Peninsula (Solomina et al., 1995, 2007; Savoskul and Zech, 1997; Savoskul, 1999; Yamagata et al., 2002; Solomina et al., 2007; Yamaguchi et al., 2008), and to place this information in a wider palaeoglacial and palaeoclimatic context. In order to achieve this aim, an overview of ice extent upon the peninsula during earlier (pre-Holocene) phases of glaciation is also outlined.

2. Geographic setting

The Kamchatka Peninsula is situated in the NW Pacific, and separates the Sea of Okhotsk to the west from the North Pacific to the south and East (figure 1). The peninsula is occupied by a series of active and inactive volcanoes, extending to a maximum elevation of 4,750 m (a.s.l), and topography is dominated by two key mountain chains (the Sredinny and Vostočny) which extend in a NE-SW direction (figure 1). Climate across the peninsula is highly variable, at least partly because of the region's size (~270,000 km^2) but also because mountain chains act as orographic barriers to atmospheric flow. Broadly speaking, during winter months, the Siberian High (which develops to the NW) dominates regional climate, whilst during summer months, the Pacific High (which develops to the SE) prevails (Shahgedanova et al., 2002; Yanase and Abe-Ouchi, 2007). These patterns bring cold-continental conditions from the NW during winter, and drive warm-moist air masses across the peninsula, from SE to NW during summer months. This results in a climate which generally varies from 'maritime' along the peninsula's Pacific coast, to 'continental' in central and NW sectors. This climatic variability is reflected in modern equilibrium-line altitudes (ELAs), which rise from ~700 m (a.s.l.) along the Pacific coast, to ~2800 m (a.s.l.) in the Sredinny Mountains (Kotlyakov et al., 1997). Thus, coastal glaciers typically occupy a maritime climate whilst glaciers in interior regions experience more continental conditions (Vinogradov, 1971). This contrast between 'maritime' and 'continental' glaciers is likely to have persisted through the Holocene, and partly regulated glacier response to climate-forcing (with maritime glaciers typically being more responsive).

3. Methods

The studies summarised in this paper are largely based upon morphological and sedimentological analyses of moraines and other glacial deposits. Published age-estimates for glacial advances upon the peninsula are derived through tephrochronology (based upon radiocarbon dated tephra layers), lichenometry, dendrochronology, and through historical observations. The first historical records of glaciers in this region go back to the beginning of 20th century, but such information is rather sparse. Dendrochronology is also of limited value in constraining the timing of glaciations in the region, because moraines are often devoid of trees, though some support bushes (*Alnus hirsuta*, *Pinus pumila*). As a result of these limitations, age-estimates derived through dendrochronology are often limited to the past 100–200 years (Solomina and Calkin, 2003).

Lichenometry has been used extensively to date Holocene moraines in Kamchatka (Solomina et al., 1995; Savoskul and Zech, 1997; Savoskul, 1999; Solomina, 1999; Golub, 2002; Solomina and Calkin, 2003; Manevich, 2011), but conflicting growth curves for both *Rhizocarpon geographicum* and *Rhizocarpon alpicola* currently exist. This creates problems with deriving accurate and consistent lichenometric dates, and is discussed in detail by Solomina and Calkin (2003). Given this limitation, in this paper we use lichenometry only to assess the ages of moraines deposited during the Little Ice Age (LIA) and more recently, as these age-estimates are considered more 'robust' and are based on a growth curve supported by eleven control points covering the last three centuries (320 ± 40 years BP) (1977, 1956, 1946, 1945, 1941, 1926, 1900-1910, 1854-1807, 1854, 1737) (Solomina and Calkin, 2003). New control points recently obtained from moraines of Zavaritskogo Glacier, at Avacha volcano (~53.265°N, 158.844°E) (Manevich, 2011), and glaciers of Koryaksky volcano (~53.321°N, 158.711°E) constrained by the Ksudach (1907) and Avacha (1926) tephras confirm these growth rate estimates (Manevich and Samoilenko, 2012). These growth rates are also similar to those established for the Southern Alaska (Wiles et al., 2010), where climatic condition are similar to Kamchatka.

Tephrochronology is the most reliable method for dating moraines and other Holocene deposits upon the Kamchatka Peninsula, as a sequence of key-marker tephra layers is well established, rather detailed, and chronologically-controlled by hundreds of ^{14}C dates (Braitseva et al., 1997; Ponomareva et al., 2007, 2013). However, this approach is limited as tephrochronology only provides minimum and/or maximum dates for moraines, and chronological gaps between successive tephra layers can span millennia (table 1). In this paper, published radiocarbon dates for tephra layers are calibrated at the 2 sigma level using the IntCal09 calibration curve (Reimer et al., 2009) and CALIB 6.1.0 program (Stuiver and Reimer, 1993, 2011). All tephra ages are hereafter reported in calibrated years BP (i.e. prior to 1950 Common Era; C.E.). Original uncorrected radiocarbon ages are shown in table 1, where details about specific tephra layers cited in the text are provided.

4. Pre-Holocene glaciation

The sedimentary and landform record of former glaciation upon the Kamchatka Peninsula appears to preserve evidence of at least three phases of pre-Holocene ice advance: one during the Middle Pleistocene, and two during the Late Pleistocene (Braitseva et al., 1968, 1995; Otsuki et al., 2009) (figures 2 and 3). There is also possible evidence for ice advance during the Late Glacial (Savoskul and Zech, 1997; Savoskul 1999), though very few investigations have focused upon this period.

4.1. Middle Pleistocene

The oldest known glaciation upon the Kamchatka Peninsula is considered to have occurred during the Middle Pleistocene (Braitseva et al., 2005). Some have attributed this phase to a period c. 110–100 to 50–55 ka (Oleinik and Skurichina, 2007) (MIS 5d to 5c) but this estimate lacks direct chronological control. By contrast, ice-rafted debris (IRD) records from the Sea of Okhotsk, dated on the basis of stable isotopes ($\delta^{18}O$) and accelerator mass spectrometry (AMS) radiocarbon dating, suggest glaciers extended beyond the Kamchatkan coastline, and terminated off-shore at c. 138 ka, c. 135 ka, c. 129 ka, and c. 128 ka (Nürnberg et al., 2011) (figure 2). These age-estimates would appear to suggest that the 'Middle Pleistocene' phase of glaciation occurred during late MIS 6, prior to the last interglacial (MIS 5), rather than between c. 110–100 and 50–55 ka, as previously suggested. This is the most extensive phase of Kamchatkan glaciation identified in the terrestrial or off-shore record, and an ice sheet likely covered the entire peninsula. A possible depiction of glaciation during this period is presented in figure 3a, though this reconstruction is based upon limited offshore evidence (see Bigg et al., 2008).

4.2. Late Pleistocene

The prevailing view is that two phases of ice advance occurred upon the Kamchatka Peninsula during the Late Pleistocene (Flint and Dorsey, 1945; Olyunin, 1965; Braitseva et al., 1968, 1995), resulting in 'inner' and 'outer' moraine sequences upon, and around, many of the region's mountains (Barr and Clark, 2012a,b). The earlier of these two phases (often referred to as 'phase I') is considered to have been the more extensive, with glaciers extending up to ~240 km in length, and, in places, terminating in the North Pacific and Sea of Okhotsk (figure 3b) (Braitseva et al., 1968). There is very little direct chronological control upon the timing of this phase, but it has generally been assigned an age of c. 79–65 ka (MIS 4), based on stratigraphic analogues in North America (Braitseva et al., 1995), and the presence of a c. 44 ka tephra (from the Opala volcano) (table 1) draped upon moraines on the SW coast of the Peninsula (Bäumler and Zech, 2000). However, IRD records from the Sea of Okhotsk (Nürnberg et al., 2011) indicate that glaciers extended offshore, and discharged ice-bergs into the Sea of Okhotsk at c. 60 ka, c. 51 ka, c. 42 ka, c. 38 ka, c. 36 ka, and c. 31 ka (i.e. during MIS 3) – a suggestion supported by IRD records from the NW Pacific (Bigg et al., 2008). On this basis, it might be argued that 'phase I' of Late Pleistocene glacial advance occurred during MIS 3, sometime between c. 60 ka and c. 31ka (figure 2).

The more recent phase of Late Pleistocene glaciation upon the peninsula (often referred to as 'phase II') was less extensive, and characterised by mountain glaciation (Olyunin, 1965; Braitseva et al., 1968; Kraevaya et al., 1983; Velichko et al., 1984; Zech et al., 1996, 1997; Leonov and Kobrenkov, 2003; Barr and Clark, 2011, 2012b) with glaciers extending up to ~80 km in length (figure 3c) (Barr and Clark, 2012b). This phase is considered to coincide with the gLGM (MIS 2) (figure 2), though this timing is only constrained by limited radiocarbon dating (Vtyurin and Svitoch, 1978; Kraevaya et al., 1983; Melekestsev and Braitseva, 1984; Braitseva et al., 2005) and comparison with analogues in North America (Braitseva et al., 1995). Ultimately, the record outlined above appears to indicate that the extent and timing of Middle-to-Late Pleistocene glaciation upon the Kamchatka Peninsula was typically out-of-phase with much of the Northern Hemisphere (figure 2), and that over millennial timescales, the Laurentide Ice Sheet, in particular, was an important control upon the extent and timing of Kamchatkan glaciation (Stauch and Gualtieri, 2008; Yanase and Abe-Ouchi, 2010; Krinner et al., 2011; Barr and Clark, 2012b; Barr and Spagnolo, 2013) (see section 6.2)

4.3. Late Glacial

In the palaeoglaciological literature there is very little discussion of ice extent upon the Kamchatka Peninsula during the post-gLGM/pre-Holocene period (i.e. the Late Glacial). Some evidence, which appears to relate to this period, is found within the Topolovaya Valley (~53.153°N, 158.014°E) (see site location in figure 1), where moraines are located 2.5–3.5

km inside inferred gLGM ice limits (Savoskul and Zech, 1997). Though direct age-estimates for these moraines are lacking, Savoskul and Zech (1997) consider them to be of Late Glacial age because of a down-valley moraine which is assigned to the gLGM on the basis of 'soil properties' and an overlying Kuril Lake Caldera tephra (KO) dated to c. 8.5 ka (table 1). A comparable group of moraines, considered to have been deposited during the Late Glacial (Savoskul, 1999), is found within the headwaters of Sredniya Avacha (~53.891°N, 158.187°E) (see site location in figure 1). These moraine sequences would appear to reflect the former presence of 4–5 km long glaciers, though again, no direct chronological control has been obtained.

5. Holocene fluctuations

5.1. Early to Mid-Holocene (11.7–4.5 ka)

Numerous sites upon the Kamchatka Peninsula provide potential evidence of glacier advance, and moraine formation during the Early to Mid-Holocene. First, in the Topolovaya Valley, Savoskul and Zech (1997) identify moraine sequences (see moraines M2, M3, M6 and M7 in table 2) reflecting the former presence of glaciers ~1.5–1.8 km long (figure 4), which are assigned to the Early to Mid-Holocene on the basis of the KO tephra (c. 8.5 ka) (table 1), which drapes their surfaces (Savoskul and Zech, 1997). Savoskul (1999) finds similar evidence in the headwaters of Sredniya Avacha. In this instance, a group of moraines (see 'Event A' moraines in table 2) is found to be draped by the Ksudach-2 (KS_2) tephra (6.8 ka) (table 1), reflecting the former presence a glacier up to 3.5 km long sometime prior to this period (figure 4). Finally, Yamagata et al. (2000, 2002), find evidence for the advance (between 3 and 8 km) of Bilchenok (part of the Klyuchevskaya group of glaciers), West Ichinsky (~55.693°N, 157.658°E), and Koryto (~54.846°N, 161.758°E) glaciers sometime prior to 8.5–9.0 ka (see figure 1 for site locations) (figure 4). At Bilchenok and Koryto, this advance is reflected by a till layer found beneath the Kizimen (KZ) tephra (c. 8.3 ka) (table 1), whilst at West Ichinsky, the till layer is found beneath the KHG tephra (c. 7.8 ka). Despite the above evidence to suggest Early to Mid-Holocene phases of advance upon the Kamchatka Peninsula, maximum age constraints are not available for any of these deposits, and pre-Holocene ages cannot be discounted.

5.2. Late Holocene [4.5 ka to LIA]

In the Topolovaya Valley, Savoskul and Zech (1997) find evidence to suggest two phases of ice advance and moraine formation during the Late Holocene. A minimum age constraint for these moraines (M4, M8, LM8 in table 2) is provided by the Ksudach 1 (KS_1) tephra (c.1.8 ka), which drapes their surfaces. A maximum age constraint is based upon the absence of the Ksudach 2 (KS_2) tephra (c. 6.8 ka). During the earlier phase, a ~1 km long glacier occupied the valley; whereas during the more recent phase, the glacier extended ~550 m. Savoskul and Zech (1997) suggest that this more recent event might correspond to a phase of ice advance c. 2 ka, reported in northern Kamchatka by Braitseva et al. (1968), but emphasise that the radiocarbon age obtained by Braitseva et al. (1968) should be regarded as approximate, since it derived from river terraces which were correlated with moraines in the mountains.

In the headwaters of Sredniya Avacha, Savoskul (1999) find deposits which suggest numerous Late Holocene advances, though age constraint upon these events is limited. There is some evidence to suggest two phases of advance (marked by ‘Event B’ moraines in table 2) between c. 2.9 and c. 6.8 ka, based on the presence and absence of the Zavaritsky (ZV) and KS_2 tephras, respectively; and evidence to suggest multiple phases of advance between c.2.9 ka and the LIA (figure 4). Savoskul (1999) suggests that the absence of the OP tephra upon the innermost of these moraines ('Event C' moraines in table 2), reflects their deposition during the past 1.4 ka (figure 4).

Yamagata et al. (2000, 2002) find evidence that Bilchenok, West Ichinsky, and Koryto glaciers, advanced beyond their present margins by ~3, 6.5 and 3.5 km, respectively, at c. 3 ka. For each of these glaciers, this age constraint is based upon a till found between the Khangar (KHG) (c. 7.8 ka) and Shiveluch 5 (SH_5) (c.2.6 ka) tephra layers (table 2). There is also evidence that Bilchenok Glacier advanced and extended up to 1.5 km beyond its present position c. 2 ka (figure 4) (Yamagata et al., 2002), based upon a till (moraine labelled '?' in table 2) found between the SH_5 (c.2.6 ka) and KS_1 (c.1.8 ka) tephra layers; and that West Ichinsky Glacier advanced ~4 km beyond its current margin c. 1.5 ka (figure 4), based upon a till found between the KS_1 (c.1.8 ka) and OP (c.1.4 ka) tephra layers (table 2) (Yamagata et al. 2000, 2002). In addition, Bilchenok and Koryto glaciers extended beyond their current margins by ~3 km and 2 km, respectively, at c.1 ka (figure 4). At Bilchenok, this age-estimate is based on a till found between the Shiveluch 3 (SH_3) (c.1.3 ka) and Shiveluch 2 (SH_2) (c.0.9 ka) tephra layers (table 2). At Koryto, this age-estimate is based upon a till found between the Shiveluch 3 (SH_3) (c.1.3 ka) and Shiveluch 1 (SH_1) (1864 C.E) tephra layers (table 2) (Yamagata et al., 2000, 2002). Finally, Manevich (2011) records evidence of moraine deposition at the Avacha group of glaciers around 2 ka (see figure 1 for site location), based upon the OP tephra (c. 1.4 ka) which covers the moraine surfaces.

5.4. "Little Ice Age" (*1350 to ~1860 C.E.*)

LIA glacier advances upon the Kamchatka Peninsula are predominantly dated through lichenometry, and all age-estimates should be considered as preliminary due to the unresolved problem of lichen growth rates (see section 3, and Solomina and Calkin, 2003).

To estimate the age of the LIA moraines, here we use the growth rate based upon control points covering the last four centuries and avoid using lichenometric ages derived from older deposits. At Koryto glacier, lichenometric dating suggests the LIA occurred in the 1710s C.E., with evidence of numerous prominent advances since, particularly during the 1760s, 1840s, and 1860s C.E. (Solomina, 1999; Solomina and Calkin, 2003; Yamaguchi et al., 2008). Some evidence in support of this timing is provided by the SH_1 (1854 C.E.) tephra found overlying LIA moraines (Yamagata et al., 2000) (figure 4). Evidence for LIA advance is also found at West Ichinsky glacier, though this is not well-constrained by tephra deposits (Yamagata et al., 2000); whilst evidence for the LIA extent of Bilchenok glacier is considered to have been overridden and removed by glacier surging in the 1960s C.E. (Yamagata et al., 2000, 2002). At Avgusty (~54.822°N, 161.861°E) and Kozelsky Glaciers (~53.229°N, 158.859°E) (see figure 1 for site locations), Solomina et al. (2007) find evidence of moraines deposited during the 1690s to 1700s C.E. period (based on lichenometry), whilst Solomina et al. (1995), in considering moraines upon volcanoes of the Avacha (~53.259°N, 158.841°E) and Klyuchevskaya groups (~56.056°N, 160.645°E), find numerous LIA moraines (dated by lichenometry) reflecting former phases of glacier advance since the 1690s C.E. Similarly, Sato et al (2013) analyse ice core data from Gorshkov crater glacier, at the top of Ushkovsky volcano (~56.092°N, 160.461°E) (see figure 1 for site location), and find evidence to suggest increased accumulation rates (based on modelled values) at 1810–1860 C.E., considered to coincide with the LIA.

5.5. Post LIA

Following the LIA, glaciers upon the Kamchatka Peninsula typically experienced retreat towards current margin positions. However, this pattern is by no means ubiquitous, and numerous phases of climatically and non-climatically controlled advance have occurred since the LIA (see section 6.3). For example, a number of moraines are dated to the early 20th century, including those at Kropotkina Glacier (figure 5), which suggest some advance during this period (Solomina et al., 1995, 2007; Solomina and Calkin, 2003). During the 1920s to 1950s C.E., minor glacial advances are recorded by a sequence of moraines at the Avacha complex of glaciers (Manevich, 2011), whilst both Kapel'ka (part of the Klyuchevskaya group) and Koryto Glaciers advanced during the 1950s and 1960s C.E., (Solomina et al., 2007). Similarly, Yamagata et al. (2002), find evidence for advance of Bilchenok Glacier in the 1960s C.E., an age-estimate based upon the absence the BZ tephra (1955 C.E.) (table 1), and Sato et al (2013) suggest increased accumulation rates (based on modelled values) at Gorshkov crater glacier in 1920 and 1970 C.E. Manevich and Samoilenko (2012) provide evidence of recent advance at Koryaksky volcano, where three glaciers currently overlie older (LIA) moraines, and a number of end moraines described in 1960s are no longer evident (and were presumably overridden). There is also evidence from aerial photographs to reveal that in 1947, Koryaksky-V glacier terminated ~150–200 m up-valley from its current position (Manevich and Samoilenko, 2012).

Direct mass balance observations for Kamchatkan glaciers are rare and typically rather short (Vinogradov and Muraviev, 1992; Dyurgerov, 2002). The longest continuous series of measurements have been obtained for Kozelsky Glacier, covering 1973 to 1995 C.E., (Dyurgerov, 2002). This short time series has been used, alongside meteorological records, to reconstruct mass balance data for much of the 20th and early 21st centuries (figure 6a). In the case of Kozelsky glacier, mass balance reconstructions cover the period from 1890 to ~2004 C.E., (Vinogradov and Muraviev, 1992), but records at other glaciers are shorter (figure 6a). Golub and Muraviev (2005) illustrate generalised (7-year running-mean) reconstructed mass balance data for Koryto, Kozelsky, and Kropotkina (~54.322°N, 160.007°E) glaciers from the

1940s to 2005 C.E. (figure 6a). These data show that annual mass balance has generally been negative over the period, but that positive, or less negative, values occurred between ~1955 and 1977 C.E. After this period (which peaked in the 1970s C.E.), the records show a pattern of generally negative mass balance over the 1973–2000 C.E., period (figure 6b). As an example of this overall trend of 20th century mass loss, by 2000 C.E., Koryto Glacier had retreated ~1.3 km from its LIA position (in 1710s C.E.), with accelerated retreat since the 1970s (Yamaguchi et al., 2008).

5.6. Summary of Holocene fluctuations

As outlined above, there is evidence to suggest that glaciers upon the Kamchatka Peninsula experienced numerous phases of advance during the Holocene. A number of publications indicate that the most extensive advance occurred during the Early to Mid-Holocene, sometime prior to c. 6.8 ka (e.g. Savoskul and Zech, 1997; Savoskul, 1999; Yamagata et al., 2000, 2002) (figure 4). However, no maximum age constraints are available for these deposits, and pre-Holocene ages cannot be discounted. Between c. 6.8 ka and c. 4.5 ka, there is little evidence of glacial advance upon the peninsula, but again, age constraints are limited (figure 4). By contrast, there is widespread evidence of numerous moraines deposited from c. 4.5 ka to the LIA, and these likely reflect a series of progressively less extensive, phases of advance, as glaciers gradually diminished in extent during the Late Holocene. The final stage of notable ice advance upon the peninsula occurred during the LIA, with comparatively robust evidence of glacier advances in the 17th, 18th and 19th centuries. Following the LIA, glaciers have generally retreated, yet a number of climatically and non-climatically driven advances have occurred. Many of the region's valleys are now ice-free, and modern glaciers are restricted to the highest mountains of the Sredinny Range and to regions bordering the Pacific coast (figure 1).

6. Discussion

6.1. Wider context

According to the summary provided by Davis et al. (2009), often (but not always) following advances during the Younger Dryas cold interval, many Northern Hemisphere glaciers experienced recession and/or were restricted in extent during the Early Holocene (e.g. Barclay et al., 2009; Ivy-Ochs et al., 2009; Menounos et al., 2009). At a number of sites, ice advance occurred during the well-known c. 8.2 ka cooling event (Alley et al., 1997; Kerschner et al., 2006), and this may also be true of glaciers upon the Kamchatka Peninsula, though evidence of this event is mostly found in the North Atlantic regions. During the Early to Mid-Holocene, Northern Hemisphere glaciers typically experienced net retreat, before advancing again during the 'Neoglacial' (from c. 4.5 ka) (Wanner et al., 2008), and evidence for such 'Neoglacial' advance is certainly found upon the Kamchatka Peninsula. A number of studies also identify evidence of glacial advance during the first millennium C.E. (e.g. Holzhauser et al., 2005; Yang et al., 2008; Barclay et al., 2009; Koch and Clague, 2011) and, again, this pattern is broadly consistent with trends upon the Kamchatka Peninsula (figure 4). Finally, the most recent period of significant glacial advance identified in numerous records globally occurred during the LIA, and in many regions of the Northern Hemisphere, this represented the maximum extent of Holocene advance (Davis et al., 2009). Though Kamchatkan glaciers appear not to have reached their Holocene maximum extents during the LIA, there is certainly evidence for significant glacial advance during this period.

Since the LIA, glaciers globally have typically experienced consistent retreat and mass reduction (Oerlemans, 2005), with the rate of mass loss accelerating since the 1950s C.E., and again since 2000 C.E., (Solomina et al., 2007). Generally, glaciers in Washington State in the USA have experienced very similar mass balance trends to those upon the Kamchatka Peninsula, with positive mass balance during the 1970s C.E., followed by significant, and generally consistent, mass reduction thereafter (figure 6b) (Hodge et al., 1998; Shiraiwa and Yamaguchi, 2002). Alaskan glaciers (part of the 'North Pacific' complex of glaciers considered here) have also experienced significant mass loss over recent decades, but the initiation of accelerated loss was delayed, relative to Kamchatka and Washington, until the late 1980s C.E. (figure 6b).

It is of note that in many regions of the Northern Hemisphere, glacier advances typically increased in extent during the Holocene (towards a maximum at the LIA), yet upon the Kamchatka Peninsula the opposite appears to be true. This likely reflects local climatic control upon the glaciation of Kamchatka, overprinted upon a broader (hemispheric) trend of orbital forcing (see section 6.2).

6.2. Possible climatic controls

Though chronological control for former periods of glaciation upon the Kamchatka Peninsula remains limited, and the extent and dynamics of glaciers is partly governed by non-climatic factors (see section 6.3), some of the broader patterns in the region's glacial history can be linked to regional and global palaeoclimate. For example, during the last glacial cycle, Northern Hemisphere cooling led to the growth of the Laurentide Ice Sheet in North America. This, in turn, led to negative pressure anomalies over the North Pacific (Yanase and Abe-Ouchi, 2010; Barr and Spagnolo, 2013), which reduced the on-land advection of moisture to Eastern Russia, and reduced precipitation upon the Kamchatka Peninsula, and preventing extensive ice sheets from developing during phases 'I' and 'II' of Late Pleistocene glaciation (figure 3b and c) (Stauch and Gualtieri, 2008; Yanase and Abe-Ouchi, 2010;

Krinner et al., 2011; Barr and Clark, 2012b; Barr and Spagnolo, 2013). Earlier, during MIS 6, ice extent in North America (and globally) was generally reduced (figure 2), potentially allowing an extensive ice sheet to occupy the entire Kamchatka Peninsula (as in figure 3a). Thus, during periods of global cooling, the extent and timing of millennial-scale glaciation upon the Kamchatka Peninsula appears to have been regulated by the availability of moisture from the North Pacific, which was, in turn, governed by the growth and decay of ice sheets in North America (Krinner et al., 2011; Barr and Clark, 2012b; Barr and Spagnolo, 2013).

At a hemispheric scale, climatic variability during the Holocene appears to be largely regulated by orbital-forcing of summer insolation, variations in solar activity, volcanic eruptions, internal variability (such as the El Niño Southern Oscillation), changes thermohaline circulation, and feedbacks between oceans, atmosphere, sea ice and vegetation (Wanner et al., 2008). This hemispheric-scale forcing explains the general correspondence between glacier and climate records throughout the Northern Hemisphere during this period (Wanner et al., 2008). Upon the Kamchatka Peninsula specifically, this hemispheric-control is partly reflected in the position and strength of the Aleutian Low (AL) and Siberian High (SH) pressure systems, which regulate seasonal temperatures and moisture-availability in the NW Pacific (Rikiishi and Takatsuji, 2005; Katsuki et al., 2010). In general terms, variations in these pressure systems resulted in a trend of Early to Mid-Holocene (c. 12-6 ka) warming upon the Kamchatka Peninsula (Dirksen and Dirksen, 2008), which culminated in a Mid-Holocene climatic optimum (c. 6.6-5 ka BP), witnessed elsewhere in the NW Pacific (Razjigaeva et al., 2012), and Northern Hemisphere generally (Rossignol-Strick, 1999). There is no evidence of glacial advance upon the peninsula during this interval (figure 4).

From the Mid-Holocene, cooler winter conditions were experienced, as the Pacific influence gradually diminished, and the SH progressively strengthened (Dirksen and Dirksen, 2008). From c. 4.5 to 3.7 ka, chironomid records indicate decreased continentality, and cool summer temperatures, and this likely reflects a weakened SH during summer months (Nazarova et al., 2013). This is supported by pollen records, which indicate cold, wet conditions during the period (Dirksen and Dirksen, 2008). These climatic conditions likely led to the onset of Late Holocene 'Neoglacial' advances (figure 4). This transition from a mid-Holocene climate optimum to a late Holocene 'Neoglacial' cooling is identified at many sites upon the peninsula (e.g. Hoff, 2010; Hoff et al., 2013) and in other regions globally (Wanner et al., 2008).

Between c.3.7 and c.2.8 ka, the chironomid record (Nazarova et al., 2013) suggests summer warming, before temperatures declined between c.2.8 and c.2.5 ka (Hoff, 2010). Again, this latter period of cooling likely resulted in glacial advance upon the peninsula (as reflected in figure 4). Between c. 2.5 and 1 ka, conditions again warmed (Hoff, 2010; Nazarova et al., 2013), before LIA cooling, and associated glacier advance, when lower summer insolation in the Northern Hemisphere coincided with solar activity minima and several strong tropical volcanic eruptions (Wanner et al., 2008).

Since the LIA, glacier fluctuations upon the Kamchatka Peninsula are partly attributed to inter-decadal climatic variability over the North Pacific, combined with a general trend of hemispheric warming. For example, accumulation rates reconstructed from Ushkovsky ice core data (Kamchatka) and mass balance records from western North America suggest a relationship with the prevailing mode of the Pacific Decadal Oscillation (PDO) (Walters and Meier, 1989; Hodge et al., 1998; Bitz and Battisti, 1999; Shiraiwa and Yamaguchi, 2002;

Josberger et al., 2007; Sato et al., 2013). This association with the PDO is also evident from diatom records upon the Kamchatka Peninsula, where the beginning of the LIA coincides with a change in the mode of the PDO, from negative to positive values (Hoff, 2010). There was an equivalent shift in the mode of the PDO in 1977 C.E., (Mantua et al., 1997) and this is reflected in North Pacific climate records, and in a shift from positive to negative mass balance values upon the Kamchatka Peninsula and in western North America (Mantua et al., 1997; Hodge et al., 1998; Shiraiwa and Yamaguchi, 2002; Josberger et al., 2007) (figure 6a). As a result of this 'North Pacific' driving forcing, mass balance records from Kamchatkan glaciers generally show strong correspondence with glaciers in western North America (figure 6b). However, the maritime glaciers of Alaska are an exception, and appear to have been responding differently to this 'North Pacific' forcing prior to the 1980s, but have since responded in synchrony with glaciers of Kamchatka and Washington, as broader hemispheric warming has come to dominate (figure 6).

6.3. Problems with reconstructing Kamchatka's glacial history

A number of factors limit our ability to derive a robust understanding of the Holocene glacial history of Kamchatka. The factors considered here are specific to Kamchatka, and we choose not focus upon broader issues relating to glacier reconstructions in general (e.g. the accuracy or precision of dating methods), as these are considered in detail elsewhere (e.g. Winkler and Matthews, 2010).

One of the principal difficulties with reconstructing the glacial history of Kamchatka is that a number of the region's glaciers occupy the calderas and slopes of volcanic peaks, which are either active, or were active during the Late Quaternary and/or Holocene (Avdeiko et al., 2007). A limitation of occupying such peaks is that volcanic activity can potentially destroy glaciers and/or influence glacier dynamics. For example, the glacier located in the caldera of Plosky Tolbachik (55.823°N, 160.378°E) lost two-thirds of its surface area (1 km^2) during an eruption in 1975/76 (Vinogradov et al., 1985), and during the eruption of Bezymianny in 1955 C.E., the glacier upon its NW slope was completely destroyed (Vinogradov, 1985). Volcanic activity can also influence glacier dynamics by contributing to surges, as rising ground-temperatures lead to the accumulation of water at the ice-bed interface. This is particularly pertinent for Kamchatkan glaciers, as a number are known to be of 'surge-type' (Yamaguchi et al., 2007), and 20th century surges related to the volcanic activity have been observed at Ermanna, Sopochny, and Vlodavets glaciers (each part of the Klyuchevskaya group of glaciers) (Vinogradov, 1985). These surges are not only unrelated to climatic variations, but can also remove geomorphological evidence of earlier ice advances (e.g. at Bilchenok Glacier).

Volcanic eruptions can also impact upon ice-mass dynamics through the accumulation of tephra upon glacier surfaces, leading to the insulation of the underlying ice. Observations at Kozelsky glacier show that a 5 cm tephra layer decreases the melting of ice by 7 times; a 20 cm layer by 21 times; and a 50 cm layer by 150 times (Vinogradov, 1985). As a result of this insulation, a number of Kamchatka's glaciers have stagnated or advanced over recent years, in response to tephra deposition (Kotlyakov, 2006). This is illustrated by Kozelsky glacier (figure 7), which advanced by ~250 m between 1977 and 2004, as a result of protection by a ~1 m thick tephra layer.

Thus, volcanic processes result in glacier advance (surging), retreat (destruction), and stagnation, which are not connected to regional climate. Unfortunately, data collection to date has been insufficient to allow us to be selective about the glaciers analysed in this study, and, for this reason, some of the records presented here should be considered with caution.

7. Conclusions

In this paper, landform records and published age-estimates are summarised to provide an overview of glacier fluctuations upon the Kamchatka Peninsula during the Holocene and, to a lesser degree, earlier phases of glaciation. The key points to be drawn from this are the following:

1. There is evidence for at least three phases of pre-Holocene ice advance upon the peninsula: one during the Middle Pleistocene (MIS 6), and two during the Late Pleistocene (during MIS 3 and MIS 2) (Braitseva et al., 1968, 1995; Otsuki et al., 2009; Barr and Clark, 2012b). There is also possible evidence for ice advance during the Late Glacial (Savoskul and Zech, 1997; Savoskul 1999), though very few investigations have focused upon this period.
2. During the Holocene, the most extensive phase of ice advance possibly occurred sometime prior to c. 6.8 ka, but no maximum age constrains are available for this period, and a pre-Holocene age cannot be discounted.
3. Between c. 6.8 ka and the onset of 'Neoglaciation', c. 4.5 ka, there is little evidence of glacial advance upon the peninsula, and this period likely coincides with the Holocene climatic optimum (or 'hypsithermal').
4. Since c. 4.5 ka, numerous moraines have been deposited upon the peninsula, likely reflecting a series of progressively less extensive phases of advance during the Late Holocene 'Neoglacial'.

5. The final stage of notable ice advance occurred during the LIA, when glaciers were on average 500–600 m longer, 100 m thicker, and terminated about 100 m lower, than at the end of 20th century (Solomina, 1999).
6. Following the LIA, glaciers have generally shown a pattern of retreat, with accelerated mass-loss in recent decades, though a number of prominent climatically and non-climatically driven glacial advances have also occurred.
7. There is evidence that millennial scale patterns (encompassing much of the Last glacial period), in the extent and timing of glaciation upon the Kamchata Peninsula are governed by the extent of ice sheets over North America; millennial-to-centennial scale patterns (encompassing much of the Holocene), are governed by the location, and relative intensity of the AL and SH pressure systems; and decadal scale patterns (particularly since the LIA) are partly governed by inter-decadal climatic variability (as reflected by the PDO), and wider, hemispheric warming.

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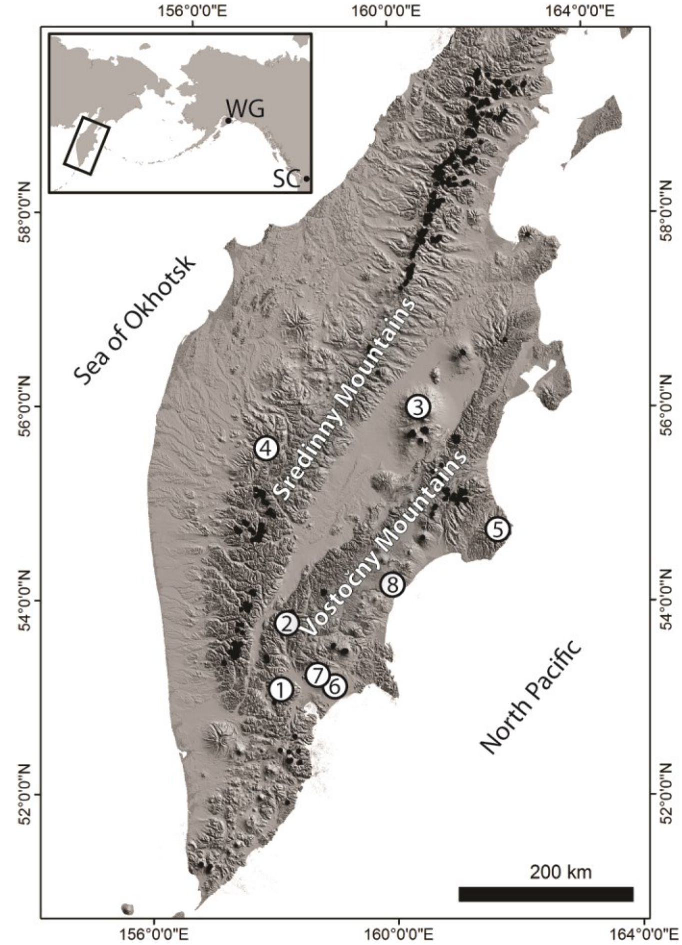
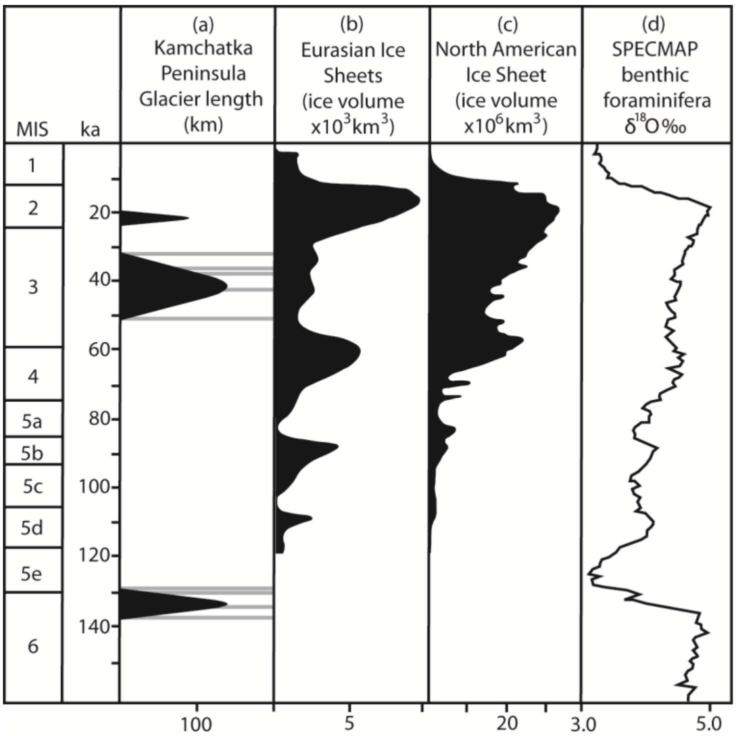
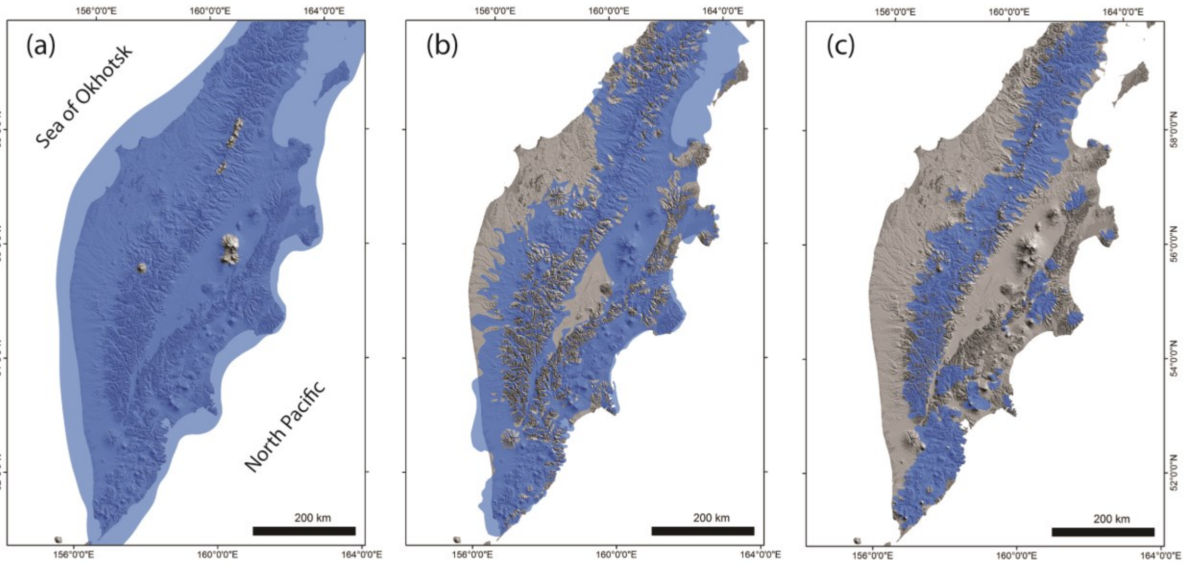
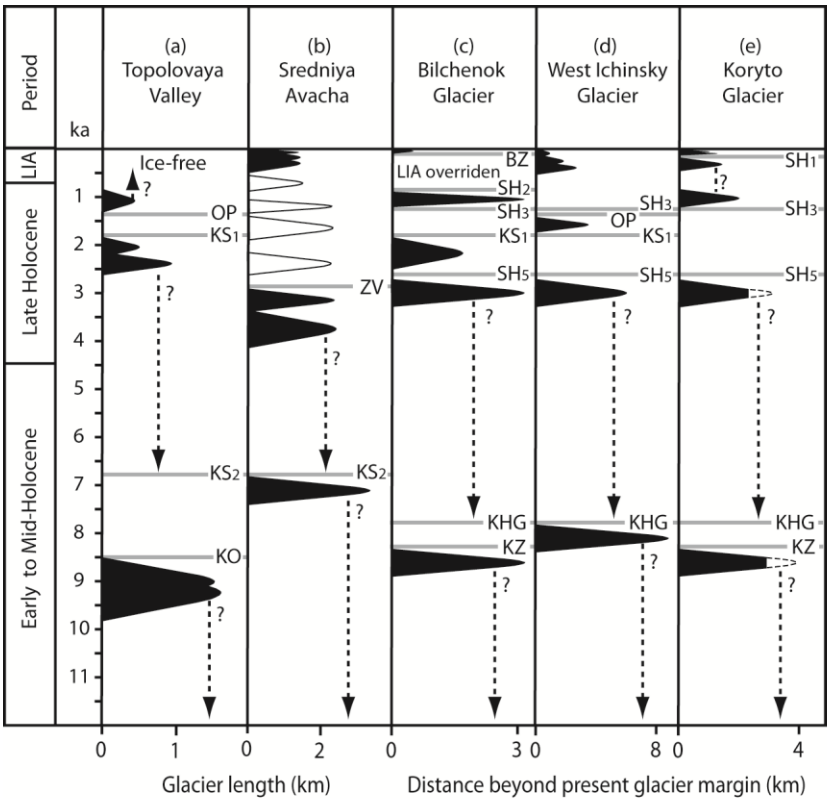
Figure captions






(a)
Sea of Okhotsk
North Pacific
(b)
(c)
200 km
156°0'0"E
160°0'0"E
164°0'0"E
58°0'0"N
56°0'0"N
54°0'0"N
52°0'0"N


Period
ka
(a) Topolovaya Valley
(b) Sredniya Avacha
(c) Bilchenok Glacier
(d) West Ichinsky Glacier
(e) Koryto Glacier
LIA
Late Holocene
Early to Mid-Holocene
Ice-free
LIA overriden
BZ
SH2
SH3
SH1
SH5
OP
KS1
KS2
ZV
KHG
KZ
KO
Glacier length (km)
Distance beyond present glacier margin (km)

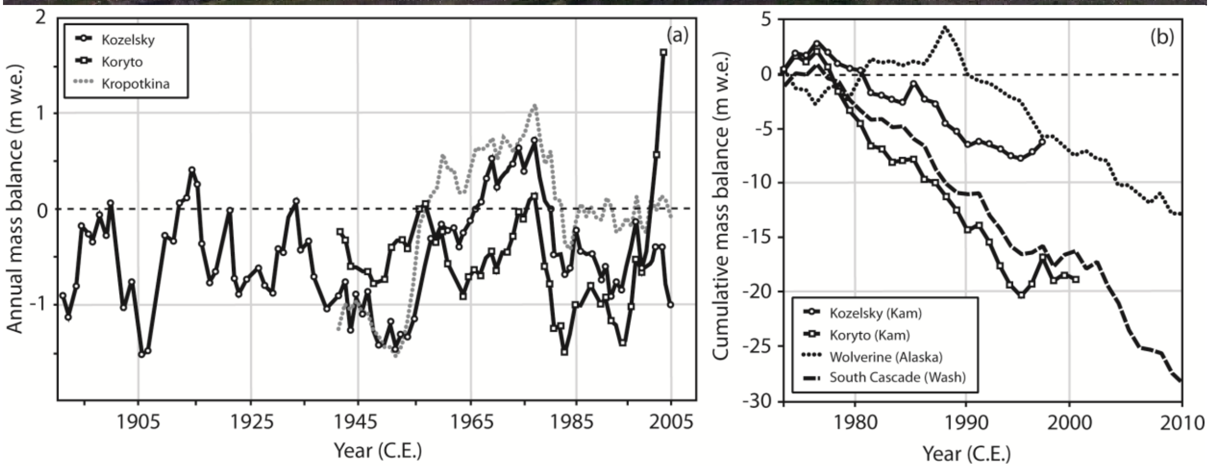

(a)
Kozelsky
Koryto
Kropotkina
Annual mass balance (m w.e.)
2
1
0
-1
1905
1925
1945
1965
1985
2005
Year (C.E.)
(b)
Kozelsky (Kam)
Koryto (Kam)
Wolverine (Alaska)
South Cascade (Wash)
Cumulative mass balance (m w.e.)
5
0
-5
-10
-15
-20
-25
-30
1980
1990
2000
2010
Year (C.E.)

Figure 1. Map of the Kamchatka Peninsula. Points (black dots) correspond to modern glaciers. Labels Numbered locations are discussed in the text. 1. Topolovaya Valley; 2. Sredniya Avacha; 3. Klyuchevskaya group of glaciers (including those upon Ushkovsky and Bezymianny volcanoes); 4. West Ichinsky Glacier; 5. Kronotsky Peninsula glaciers (including Koryto and Avgusty glaciers); 6. Avacha group glaciers; 7. Koryaksky volcano; 8. Kropotkina Glacier; WG, Wolverine Glacier; and SC, South Cascade Glacier.

Figure 2. (a) Time-distance diagram depicting current understanding of pre-Holocene ice extent upon the Kamchatka Peninsula. Horizontal grey lines correspond to inferred periods of iceberg discharge into the North Pacific and Sea of Okhotsk (Bigg et al., 2008; Nürnberg et al., 2011). Also shown are curves depicting modelled volumes of (b) the Eurasian (Scandinavian, British and Barents-Kara) Ice Sheets (redrawn from Svendsen et al., 2004; based upon Siegert et al., 2001), (c) the North American Ice Sheet (redrawn from Marshall et al., 2002), and (d) global ice volume over the past 160 ka, as recorded by the SPECMAP benthic foraminifera record (from Lisiecki and Raymo, 2005). Comparison with Eurasian and North American ice sheets emphasises how the timing of former glaciation upon the Kamchatka Peninsula is out-of-phase with much of the northern Hemisphere. Figure based upon Barr and Clark (2012b).

Figure 3. Reconstructions depicting the extent of glaciation upon the Kamchatka Peninsula (a) during the Middle Pleistocene (MIS 6), (b) during 'phase I' of Late Pleistocene glaciation (c. 40 ka) (reconstruction based upon Braitseva et al., 1968), and (c) at the global Last Glacial Maximum ('phase II' of Late Pleistocene glaciation) (reconstruction based upon Barr and Clark, 2012b).

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Figure 4. Time-distance diagram of Holocene glacier fluctuations upon the Kamchatka Peninsula. (a) In the Topolovaya Valley (based upon Savoskul and Zech, 1997); (b) at Sredniya Avacha (based upon Savoskul, 1999). Here, advances shown in white reflect a lack of robust chronological constraint (all that is known is that several periods of advance have occurred since the deposition of the ZV tephra); (c) at Bilchenok Glacier, (d) West Ichinsky Glacier, and (e) Koryto Glacier (based upon Yamagata et al., 2000, 2002). The '?' symbols, and associated dashed arrows, reflect a lack of chronological control upon periods of ice advance. Horizontal grey lines reflect tephra layers (labels are detailed in table 1).

Figure 5. Kropotkina Glacier and associated LIA and 20th century moraines. Photograph courtesy of Ya. Muraviev.

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Figure 6. (a) Generalised (7-year running-mean) mass balance data for Kozelsky, Koryto, and Kropotkina Glaciers (Kamchatka). Pre-1943 C.E., data is derived from Vinogradov and Muraviev (1992). Post-1942 C.E., data is redrawn from Golub and Muraviev (2005). (b) Cumulative mass balance record for Kozelsky (1973 to 1997 C.E.); Koryto (combination of direct observations and modelled data for the 1973-2001 C.E., period) (from Maravyev et al, 1999); Wolverine Glacier, Alaska (1973-2010 C.E.); and South Cascade Glacier, Washington (1973-2010 C.E.). Direct mass balance data derived from Dyurgerov (2002) and WGMS (2008, 2012).

Figure 7. Kozelsky Glacier in 2008 C.E. As a result of protection by a ~1 m thick tephra layer, the glacier advanced by ~250 m between 1977 and 2004. Moraines in the foreground were deposited in the early 19th century. Photograph courtesy of Ya. Muraviev.

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