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A sub-centennial, Little Ice Age climate reconstruction using beetle subfossil data from Nunalleq, southwestern Alaska

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ABSTRACT

There is myriad evidence that global warming is exerting a profoundly disruptive influence on the lifeways of modern native (Yup'ik) communities living in the Yukon-Kuskokwim (Y-K) delta of southwestern Alaska. Yup'ik subsistence is intimately tied to seasonal change and the ability to accurately predict the availability of plant and animal resources. It therefore seems reasonable to suggest that periods of climatic instability such as the Little Ice Age (LIA) may have had a deleterious effect on Yup'ik communities in the past. However, at present there are no palaeotemperature records that document the localised climatic changes of the last millennium in the Y-K Delta region. This lack of data hinders our understanding of the archaeological record from the site of Nunalleq, which is situated at the heart of the delta and was occupied during the LIA. To address this oversight, this paper presents the results of a Coleoptera (beetle) based climate reconstruction from a peat profile in the vicinity of Nunalleq to investigate the magnitude of Late Holocene climatic changes. Using the Mutual Climatic Range (MCR) method, we reconstruct mean summer and winter temperatures from the mid-15th to late-19th centuries. The results indicate that the past environments of Nunalleq were characterised by a climate significantly cooler than the present. The earliest definitive evidence for Little Ice Age cooling dates from the late 16th century, when mean summer temperatures were at least 1.2°C below the modern mean. Temperatures appear to have remained lower than modern until the early 19th century. The coolest Nunalleq record – 1.3°C below the modern mean summer temperatures – is centred on AD 1815, after which there is evidence for climatic amelioration. These data present differences with observations from other regions of Alaska and underline the importance of more local palaeoclimate reconstructions, particularly when interrogating the relationships between past climatic and social change.

1. Introduction

Arguments for the influence of climate on the successes and failures of past human societies are well rehearsed (Diamond, 2005; Van de Noort, 2013). Understanding the weather and climate of a locality is essential in planning for both short- and long-term eventualities. The ability to accurately predict the beginning and duration of seasons was essential for agriculturalists and hunter-gatherers alike. Indeed, there are myriad examples across the world that are posited as attempts by past societies towards predicting and influencing the arrival of seasons (Chamberlain, 2000; Robbins, 2000; Burroughs, 2005). Similarly, there are many archaeological examples of the consequences for human societies when such knowledge is absent (e.g. early European settlers in

the New World [Rockman, 2010; Stahle et al., 1998]) or breaks down (e.g. Dugmore et al., 2007a, 2012; Carleton et al., 2017).

Nowhere are such considerations more relevant than in the circumpolar regions of the globe, where lifeways rely on the ability to predict the seasons and weather (Ford and Smit, 2004) and climatic changes are more rapid and pronounced than at temperate latitudes (IPCC, 2013). Ever since the first high-resolution climatic records from the Greenland Ice Sheet became available (Dansgaard et al., 1975), there has been the temptation to view human endeavours in the Arctic through the lens of climate. For instance, the Norse colonisation of Greenland (Barlow et al., 1997; Diamond, 2005) and the Thule migration (McGhee, 2001, 2009) have often been explained in terms of climatic changes associated with anomalies such as the Medieval

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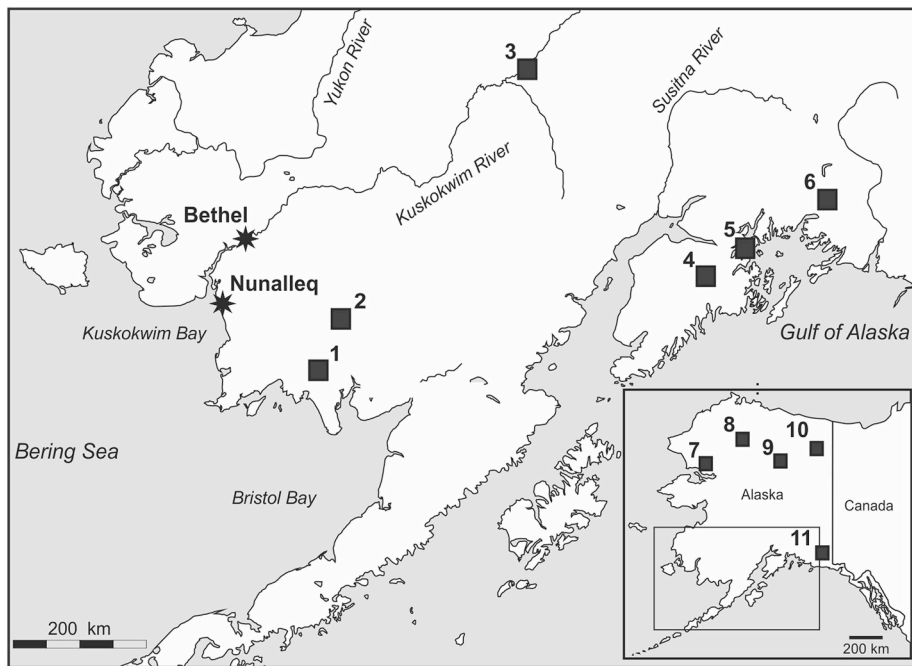


Fig. 1. The Yukon-Kuskokwim Delta, illustrating the location of Nunalleq and other locations discussed within the text, including sites for which published palaeoclimatic data exists: [1] Ongoke Lake; [2] Akhlun Mountains; [3] Farewell Lake; [4] Western Prince William Sound; [5] Mica Lake; [6] Hallet and Greyling Lakes; [7] Site 412; [8] Arrigetch Peaks; [9] Blue Lake; [10] Sheenjok; [11] Iceberg Lake.

Climate Anomaly (MCA) and Little Ice Age (LIA). There are problems with this approach, however, as climate change is both spatially and temporally variable. For example, the intensity and spatial expression of climate anomalies such as the MCA and LIA as experienced in northern Europe was not the same as that in the western Arctic (IPCC, 2013). Therefore, to accurately reconstruct the influence of climate change on human communities, local or regionally specific records of climate change are required. This is being increasingly recognised, and climatic explanations have become nuanced beyond the simplistic interpretations of warmer temperatures promoting migration and colder temperatures leading to extinction (e.g. Dugmore et al., 2012). Climate change is now more often viewed as a factor that initiates changes in the environment, technology, or cultural attitudes, which ultimately influence the trajectories of human society.

Nunalleq, an archaeological site located in the Yup'ik territories of the Yukon-Kuskokwim (Y-K) delta of southwestern Alaska (Fig. 1), serves as a good example of the interactions between climate change and human societies. Late Yup'ik prehistory (15th to 18th century) was characterised by a period of intense warfare known as the 'Bow and Arrow Wars' (Funk, 2010; Pratt, 2013; Fienup-Riordan and Rearden, 2016). This period of conflict was coincident with the LIA, the nadir of which was centred on the late 16th to mid-17th centuries, with mean summer temperatures of between 0.6 °C and 1.7 °C below the modern mean (Overpeck et al., 1997; Hu et al., 2001; Bird et al., 2009). The coincidence of this cooling trend and evidence for conflict, both at Nunalleq and more widely in the Y-K delta, may be suggestive of a link between the two events. However, there is a lack of suitable climatic data to evaluate this possibility, as the nearest quantitative climate reconstruction record is sourced from Farewell Lake (Hu et al., 2001), a montane lake in the foothills of the Alaska Range c. 500 km northeast. Temperature reconstructions from this site cannot be assumed to accurately reflect changes in the lowland delta region. Today, Alaska, in common with elsewhere in the Arctic, is experiencing a period of rapid climate change (Serreze et al., 2000). In the Y-K delta this has been characterised by mean summer temperatures consistently rising since the 1980s (Fig. 2) and an increase in the number and severity of winter storms (Terenzi et al., 2014). The rapid and unprecedented nature of these changes is already beginning to appreciably affect the semi-subsistence economy of native Yup'ik communities in the region, as the past can no longer be used to accurately predict the future (Fienup-

Riordan and Rearden, 2012; Chapin et al., 2014).

To date, there are no palaeo-temperature reconstructions from the vast expanse of the Y-K delta. Therefore, in order to facilitate an exploration of how past climatic change affected late prehistoric Yup'ik society at the Nunalleq site, and to provide a contextual baseline to modern climate change, local palaeoclimatic data is essential. To this end, this paper presents the results of a high-resolution palaeoclimate reconstruction from a sediment profile closely associated with this late prehistoric Yup'ik archaeological site. By applying the Mutual Climate Range method (Atkinson et al., 1986) this paper aims to: (i) reconstruct past summer and winter temperature variation in the vicinity of Nunalleq; (ii) compare these data to modern long term meteorological observations from Bethel Airport, and; (iii) explore how this record compares to other regional data.

2. Background

2.1. Physical geography

The study site is located on the coast of the Bering Sea in southwestern Alaska, approximately 5 km south of the village of Quinhagak, in the vast Yukon-Kuskokwim delta (Fig. 1). The relief of this deltaic wetland is relatively flat, and elevations in the vicinity of the study location range from 2 to 3 m above mean sea level. The region is characterised by numerous small lakes/ponds and meandering rivers and sloughs (Jorgenson, 2000) and is underlain by discontinuous permafrost (Jorgenson et al., 2008). Local geology is uncomplicated and comprises recent alluvial deposits of sands, silts and clays of Quaternary age capped by a thin layer of peat (Wilson et al., 2015). Vegetation is dominated by tundra communities (Babcock and Ely, 1994) characterised by a mixture of graminoid-rich meadows and dwarf shrub tussock tundra of *Betula nana*, *Rubus chamaemorus* and *Empetrum nigrum*.

2.2. Observed climatic data

Climatically, the region is located in the sub-arctic and the west coast climate division of Bienek et al. (2012). The nearest long-term observational climatic data comes from Bethel airport, located 120 km northeast of Nunalleq (NOAA, 2017). Continuous observation of

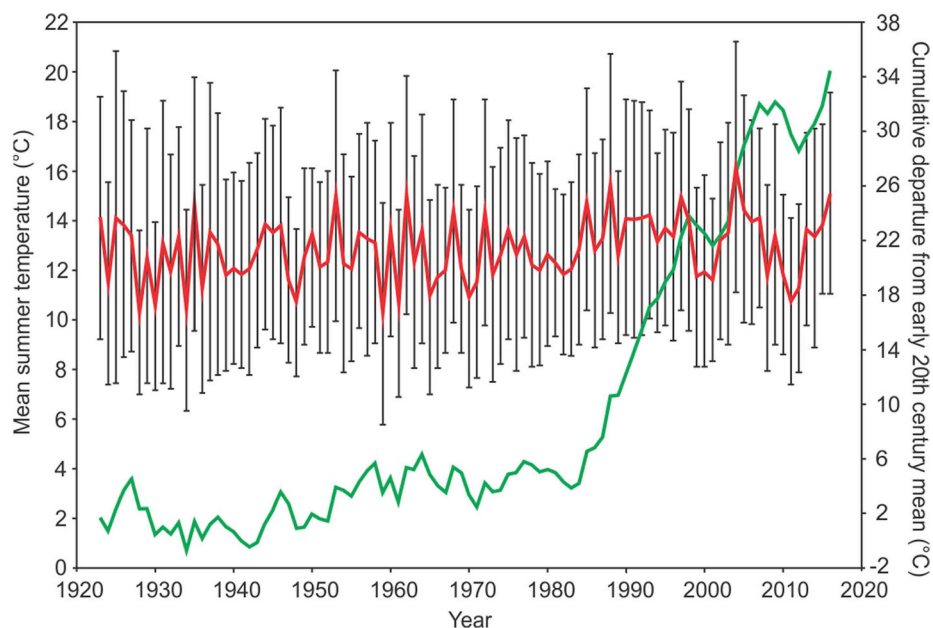


Fig. 2. Modern climate data from Bethel illustrating the summer (July) mean (red line) with error bars illustrating mean summer minima and maxima recorded in each year. The green line tracks the cumulative mean summer temperature departures (cf. Dugmore et al., 2007b) from the early 20th century mean (1923–1952). For each year the deviation from the long term mean is calculated, then, starting at the oldest data point, Year 1 (1923) represents the deviation from the mean, Year 2 (1924) is the deviation of that year plus the deviation from Year 1 (1923), Year 3 (1925) is that year's deviation in addition to the deviations from both Year 1 and Year 2, and so on. This neatly illustrates the general trend of increasing summer temperatures since the early 1980s. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

The mean winter (January) and summer (July) climate as recorded at the Bethel Airport Meteorological Station.

Location	Early to mid- 20th Century		Mid to late 20th Century		Modern	
	Winter (1929–1958)	Summer (1923–1952)	Winter (1959–1988)	Summer (1953–1982)	Winter (1989–2016)	Summer (1983–2016)
Bethel Airport	−14.7 °C	12.5°C	−13.7°C	12.6°C	−14.4°C	13.4°C

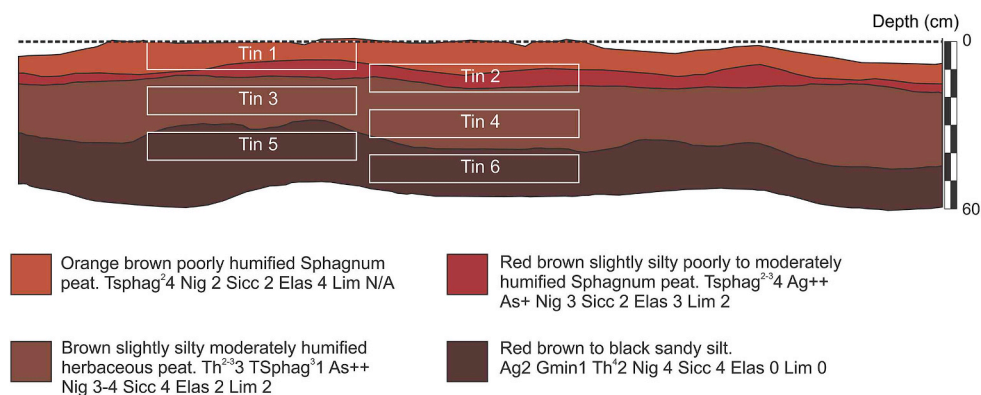


Fig. 3. Schematic of the sampled profile illustrating the location of samples and general lithostratigraphy.

summer (July) temperatures at this station date from 1923, while winter (January) temperature observations date from 1929. The early part of this instrumental record, until the 1980s, is characterised by a summer climate approximately 1°C cooler than the modern summer mean of 13.4°C (Table 1). Although the period from the mid-1980s is characterised by sustained summer warming (Fig. 2), it is also notable for a sharp increase in mean summer temperature variability. Mean winter temperatures are more variable than those from the summer and record a marked increase in the winter mean from −14.7°C (1929–1958) to −13.7 (1959–1988) in the mid-20th century, which falls again towards the modern day (Table 1).

2.3. Archaeology

Archaeological excavations at Nunalleq began in 2009 and since then have uncovered the deeply stratified remains of a prehistoric Yup'ik village. Preservation conditions at the site are superb and have

permitted the recovery of a diverse assemblage of over 60,000 artefacts constructed from a variety of materials including wood, pottery, grass and stone (Knecht, 2014). Activity at the site is sub-divided into a number of phases and occupation likely began between c. AD 1570–1630. It ended with the destruction of the village c. AD 1650–1670 (Ledger et al., 2018) during the Bow and Arrow Wars, a conflict episode that opposed different Yup'ik and neighbouring villages and ended as a result of contact with Russians in the 19th century (Fienup-Riordan and Rearden, 2016).

3. Methods

3.1. Sampling

In July 2015, a 60 cm deep trench was excavated approximately 30 m east of the archaeological site and sampled from the surface to a depth of 50 cm, using a series of large monolith tins (Fig. 3). Further

details of field sampling are outlined in Ledger (2018). Contiguous subsampling of 2 cm-thick samples (approximately 2 L volume) for Coleoptera analysis was undertaken in Quinhagak, in order to attain sub-centennial chronological resolution. Samples were placed into large reinforced plastic bags and subsequently transported to the palaeoecology laboratory at the University of Aberdeen where they were stored at 4 °C.

The density of Coleoptera subfossils in any substrate will vary according to the nature of that substrate. Palaeoentomologists typically collect samples varying between 2 and 5 l (or 1 and 5 kg) volumes (e.g. Bain, 2001; Kenward, 2009; Panagiotakopulu and Buckland, 2013; Vickers et al., 2011) but there has not been an investigation of the influence of sample size on the representativity of beetle subfossil assemblages. Generally, less organic substrates produce fewer beetle fossils than more organic ones (Elias, 2010) and due to the accumulation of organic matter and nutrient enrichment in and close to human settlements, anthropogenic sediments also tend to harbour higher densities of beetle (and other arthropods) than naturally accumulated deposits located further away from human occupation sites. Following preliminary analysis of samples from archaeological floors at Nunalleq (Forbes et al., 2015), our approach has been to privilege increased temporal resolution over higher counts for single samples. Despite the smaller volume of samples analysed in the present study, our MNIs are consistently equal to, or higher than, those obtained from other studies of Coleoptera subfossils extracted from peat bogs (e.g. Buckland et al., 2009; Khorasani et al., 2015; Panagiotakopulu and Buckland, 2013; Vickers et al., 2011).

3.2. Coleoptera analysis

In total, twelve contiguous 2-cm thick samples, from a depth of 39 to 15 cm, and a further sample from 13 to 11 cm, were processed and analysed for Coleoptera. In the first instance samples were placed into large buckets and soaked in a cold solution of weak (< 2%) NaOH for a period of up to one week to promote disaggregation of the sediment matrix. Samples were then processed through paraffin floatation (Coope and Osborne, 1967; Kenward et al., 1980) to separate the Coleoptera from the bulk of the plant macrofossil content. The floatants were hand-sorted under a binocular microscope to allow the collection of beetle sclerites. Insect fossils were stored in vials of ethanol prior to identification.

Identifications were undertaken through direct morphological comparison with specimens from the first author's reference collection and from the Canadian National Collection of Insects, Arachnids and Nematodes in Ottawa. These were aided by consultation of entomological publications (Campbell, 1978, 1982; 1983a, 1983b; 1991; Goulet, 1983; Klimaszewski, 1979; Lindroth, 1961, 1963; 1966, 1968; 1969a, 1969b; Shavrin, 2016). Although most identified taxa are represented by head, pronota, and elytra, the genitalia and terminal abdominal segments of certain taxa were also recovered and identified (Fig. 4). Taxa identifications were undertaken by the first author and some specimens were identified or had their identification confirmed by taxonomic specialists. A full list of identified Coleoptera, along with the minimum number of individuals (MNI) for each insect taxon calculated from the most abundant anatomical part, is provided in the Supplementary Information (SI1). Taxonomy and nomenclature follows Bousquet et al. (2013).

3.3. Chronology

The profile chronology was constructed on the basis of a series of 12 AMS radiocarbon dates, a 14-sample ¹³⁷Cs profile and ²¹⁰Pb measurements, processed with a constant rate of supply model (Appleby and Oldfield, 1978). Radiocarbon dating was undertaken at the Oxford Radiocarbon Accelerator Unit (ORAU) and calibrated using the IntCal13 calibration curve (Reimer et al., 2009). Bayesian age-depth

modelling of the profile accumulation combined short-lived radionuclide measurements and radiocarbon dates using Bacon (Blaauw and Christen, 2011). A detailed description of the chronology and data is presented in Ledger (2018). The age-depth model indicates that each of the samples analysed in the present study represent between 20 and 50 years of deposition.

3.4. Palaeoenvironments

Information regarding the ecology of individual taxa was compiled from habitat records and descriptions in the literature (Anderson, 1989; Arnett and Thomas, 2001; Ball, 1966; Betz et al., 2018; Bousquet, 1991; Bousquet et al., 2013; Campbell, 1973, 1978; 1982, 1983; 1984, 1991; Chernov et al., 2014; Clark et al., 2008; Erwin, 2007; Forbes and Sikes, 2018; Hieke, 2002; Hinton, 1941; Keen, 1958; Klimaszewski, 1979; Klimaszewski et al., 2013; Laroche and Larivière, 2003; Larson et al., 2000; Lindroth, 1961, 1966; 1968; Majka and Langor, 2011; Majka and Sörensson, 2010; Majka et al., 2010; Puthz, 2014; Robinson, 2005; Ryvkin, 2007; Shavrin, 2016; Smetana, 1971; Ullrich and Campbell, 1974; Watrous, 1980; Webster et al., 2012). The results of the literature review (SI1) was used to classify taxa into broad habitat categories (Fig. 5).

The classification used here slightly differs from that used in Forbes and Sikes (2018): it focuses on macro-habitats only, so that the original categories 'in decomposing matter' and 'plant-associated' were dropped. Instead, taxa that are known to occur in microhabitats provided by decomposing organic matter have been highlighted in red font. A new category, 'Eurytopic', was created to include taxa that can be found in a wide variety of environmental settings.

Based on this classification, three different percentage diagrams were generated to allow an appreciation of changes in local palaeoenvironmental conditions through time (Fig. 6). The first (Fig. 6a) was produced using all five ecological groups, the second (Fig. 6b) excluding the 'Eurytopic' group in order to better display patterns obscured by the presence of wide-tolerance taxa, and the third (Fig. 6c) displaying the proportion of taxa associated with microhabitats available in organic matter.

3.5. Mutual climatic range method

We used the Mutual Climatic Range (MCR) method to reconstruct air temperature variations based on coleopteran subfossil data (Atkinson et al., 1986). The basic principle of the method is to establish the range of climatic conditions within which predator and scavenger beetle taxa identified in a subfossil assemblage can live (the Mutual Climatic Range, or MCR). Only predator and scavenger beetle taxa are utilised as these groups are not bound to particular plant species or communities and respond rapidly to climatic change (Elias, 2010). We employed continent-wide climate envelopes based on North American species records and associated climatic data (Elias, 1996; Elias et al., 1996). In order to incorporate taxa that could only be identified to the level of genus, subgenus or group, we also constructed a series of 'grouped envelopes'. Here, the principle was to account for the maximum climatic range of species occurring within the same taxonomic group, allowing us to include taxa such as for example *Pterostichus brevicornis* group (sensu Ball, 1966), *Eucnecosom* spp. and *Pycnoglypta* spp., which are particularly difficult to identify to species. This was achieved by combining all established climate envelopes for species of a given taxonomic group recorded in Alaska into an expanded climate envelope. Not all scavenger and predacious taxa were included in the climate reconstruction, as a number of species do not have established climatic envelopes.

MCR envelopes were generated for each of the samples analysed and these are available as Supplementary Information (SI2). This was achieved by superimposing the climate envelopes of each taxa present in a given assemblage and identifying the area of overlap between

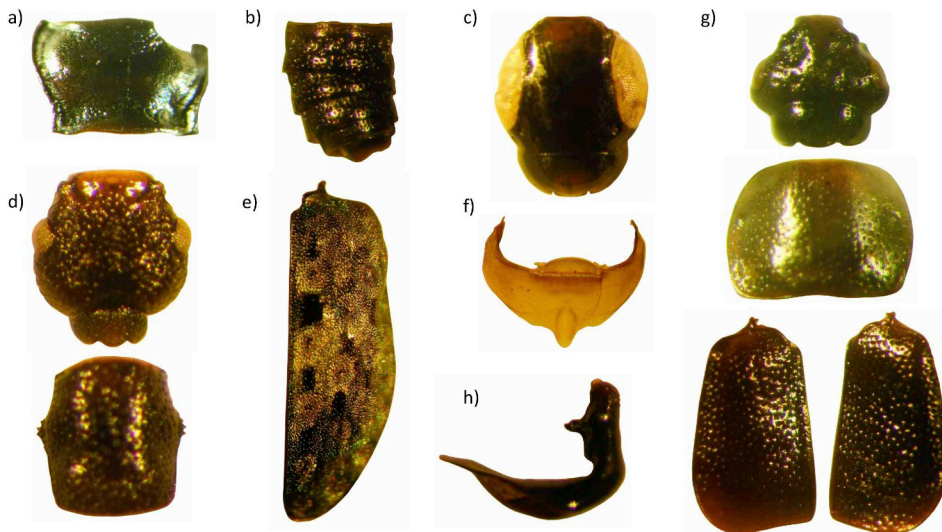


Fig. 4. Photographs of some of the subfossil specimens: (a) Pronotum of *Pelophila borealis* [23–25 cm] (with damaged right shoulder); (b) Abdomen of *Stenus noctivagus* [25–27 cm]; (c) Head of *Quedius fellmani* [25–27 cm]; (d) Head and pronotum of *Boreaphilus henningianus* [27–29 cm]; (e) Right elytron of *Elaphrus (Elaphrus) americanus/trossulus* [27–29 cm]; (f) male abdominal sternite VIII of *Pycnoglypta lurida* group [29–31 cm]; (g) Head, pronotum and elytra of *Eucnecusum* sp. [31–33 cm]; (h) Aedeagus of *Pterostichus nivalis* [37–39 cm].

Xeric	Hygro-riparian	Aquatic
<i>Notiophilus borealis</i> <i>Notiophilus aquaticus/borealis</i>	<i>Pelophila borealis</i> <i>Elaphrus americanus/trossulus</i> <i>Elaphrus americanus/tuberculatus</i> <i>Elaphrus (Elaphrus) sp.</i> <i>Elaphrus sp.</i> Platynini indet. <i>Acidota crenata</i> <i>Acidota quadrata</i> <i>Olophrum boreale</i> <i>Olophrum latum</i> <i>Olophrum spp.</i> <i>Boreaphilus henningianus</i> <i>Gymnusa variegata</i> group <i>Gymnusa sp.</i> <i>Stenus noctivagus</i> <i>Stenus umbratilis</i> <i>Stenus ageus</i> <i>Stenus austini</i> <i>Stenus mammops</i> <i>Stenus melanarius melanarius</i> <i>Stenus immarginatus</i> <i>Stenus spp.</i> <i>Lathrobium sibiricum</i> <i>Quedius fellmani</i> <i>Quedius boops</i> group <i>Quedius simulator</i> Donaciinae indet. <i>Simplacaria elongata</i> <i>Notaris aethiops</i> <i>Isochnus sp.</i>	<i>Hydroporus morio</i> <i>Hydroporus cf. morio</i> <i>Hydroporus sp.</i> Hydroporinae indet. <i>Agabus sp.</i> <i>Ilybius vittiger</i> Dytiscidae indet.
Mesic	Eurytopic	
<i>Carabus truncaticollis</i> <i>Diacheila polita</i> <i>Pterostichus brevicornis brevicornis</i> <i>Pterostichus nivalis</i> <i>Pterostichus cf. nivalis</i> <i>Pterostichus brevicornis/nivalis</i> <i>Pterostichus brevicornis</i> group <i>Pterostichus pinguedineus</i> <i>Pterostichus pinguedineus/ventricosus</i> <i>Pterostichus similis</i> <i>Pterostichus (Cryobius) spp.</i> <i>Pterostichus agonus</i> <i>Eucnecusum brachypterum</i> <i>Eucnecusum brunnescens</i> <i>Eucnecusum tenue</i> <i>Eucnecusum spp.</i> <i>Holoboreaphilus nordenskioldi</i> <i>Pycnoglypta campbelli</i> <i>Pycnoglypta heydeni</i> <i>Pycnoglypta lurida</i> group <i>Pycnoglypta spp.</i> <i>Tachinus apterus</i> <i>Tachinus apterus/brevipennis</i>	<i>Notiophilus sp.</i> <i>Pterostichus sp.</i> <i>Amara erratica</i> <i>Amara cf. erratica</i> <i>Amara (Amarocelia) sp.</i> <i>Amara sp.</i> Carabidae indet. Acrotrichinae indet. Omaliinae indet. <i>Proteinus sp.</i> <i>Ischnosoma longicorne</i> <i>Ischnosoma splendidum</i> <i>Ischnosoma sp.</i> <i>Mycetoporinus nigrans</i> Mycetoporini indet. Aleocharinae indet. <i>Veraphis sp.</i> Eutheini indet. <i>Euaesthetus sp.</i> <i>Quedius (Raphirus) sp.</i> <i>Quedius sp.</i> <i>Latridius protenticollis</i> <i>Stephostethus sp.</i> Latridiinae indet. Corticariinae indet. Coleoptera indet.	

Fig. 5. Grouping of identified taxa according to their habitat/ecology. In red font are those taxa that are eurytopic or belong to mesic, hygrophilous and riparian environments, but that are known to be associated with microhabitats available in decaying organic matter (e.g. rotting wood, leaf litter, floor debris, dung, carrion). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

them. T_{MAX} (mean temperature of the warmest month) and T_{RANGE} (difference between the mean temperature of the warmest and coldest months) were calculated from the extreme values of these MCR

envelopes. T_{MIN} (mean temperature of the coldest month) was calculated by subtracting reconstructed T_{RANGE} from T_{MAX} values (Table 2).

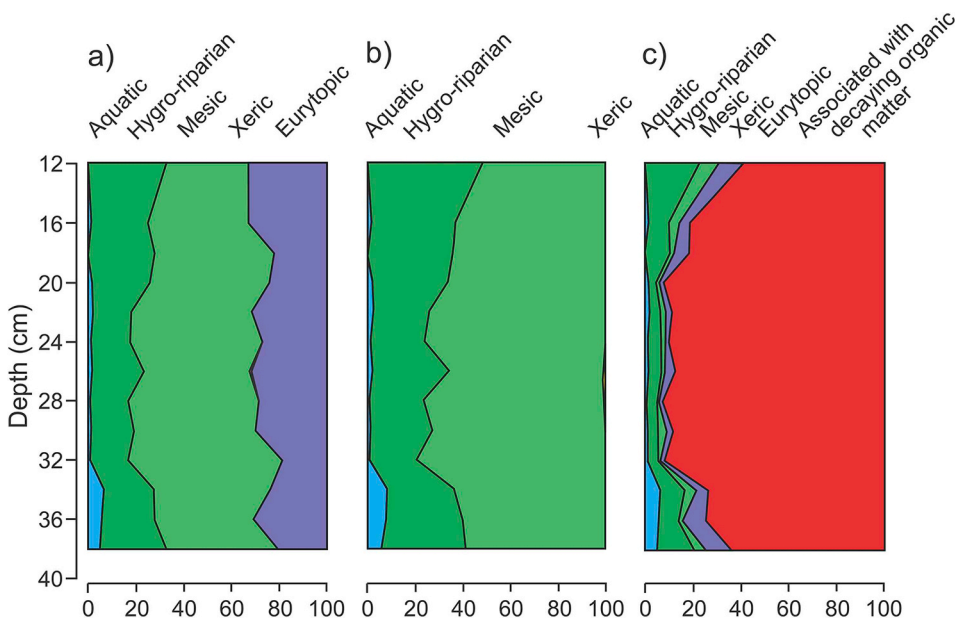


Fig. 6. Percentage diagrams comparing the proportion of each ecological group (as defined in Fig. 5) throughout the Nunalleq profile: (a) including all five ecological groups, (b) excluding eurytopes and (c) showing the proportion of taxa associated with microhabitats available in decaying organic matter (in red, as in Fig. 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Results of the MCR climatic reconstruction for each sample analysed from the profile.

Sample depth (cm)	Age of sample (cal. AD)	T _{MAX} (°C)		T _{RANGE} (°C)		T _{MIN} (°C)	
		Min	Max	Min	Max	Min	Max
11–13	1905	10.9	15.5	26.8	43.2	−32.3	−11.3
15–17	1850	10.9	15.1	26.7	42.2	−31.3	−11.6
17–19	1815	9.4	12.1	29.2	36.5	−27.1	−17.1
19–21	1785	9.5	14.3	29.2	42.2	−32.7	−14.9
21–23	1735	9.5	12.8	29.2	42.2	−32.7	−16.4
23–25	1680	9.0	14.2	29.2	43.0	−34.0	−15.0
25–27	1640	10.4	14.4	29.6	41.2	−30.8	−15.2
27–29	1605	12.2	14.2	30.2	42.2	−30.2	−16.0
29–31	1570	11.8	12.2	35.5	37.8	−26.0	−23.3
31–33	1540	11.5	13.3	30.0	36.8	−25.3	−16.7
33–35	1510	8.8	14.3	29.0	43.0	−34.2	−14.7
35–37	1490	8.8	14.3	29.1	43.2	−34.4	−14.8
37–39	1465	9.2	14.5	29.5	42.2	−32.9	−15.0

4. Results

4.1. Insect assemblage

A total of 88 different beetle taxa were found in the samples from the Nunalleq peat profile. This includes 39 taxa identified to species plus 49 other taxa identified to lower taxonomic levels (e.g. tribe, family, genus, subgenus or group). Rove beetles (Staphylinidae) and ground beetles (Carabidae) dominate the assemblage, which also contains Dytiscidae, Ptiliidae, Latridiidae, Byrrhidae, Chrysomelidae, Brachyceridae and Curculionidae. Two lice (order Phthiraptera) species were also recovered: the human louse, *Pediculus humanus* L., and the dog-biting louse, *Trichodectes canis* (De Geer), which are parasitic on humans and canids, respectively.

The majority of the beetle taxa (72%) are Holarctic, the remaining being of worldwide or Nearctic distribution. Notably, this dataset includes the first record of the pill beetle *Simplocaria elongata* J.R. Sahlberg for the state of Alaska. Forty-two of the 88 taxa identified in the profile have been documented to occur in the modern environment surrounding the archaeological site of Nunalleq (SII, also see Forbes and Sikes, 2018).

Although there are variations in the taxa represented in the different parts of the section, each assemblage is generally indicative of subpolar

tundra environments. Two taxa, *Notiophilus borealis* Harris and *N. aquaticus* (L.)/*borealis*, are predacious on rather dry substrates with little to no vegetation cover (Lindroth, 1961) and therefore have been placed the group ‘Xeric’ (Fig. 5). Taxa that are typical of mesic habitats, such as the shrub tundra and moderately moist areas of the open tundra, have been attributed to the ‘Mesic’ group. This includes *Pterostichus* taxa belonging to the subgenus *Cryobius*, typical inhabitants of the boreo-arctic tundra, where they can be found in moss and decaying organic matter (Chernov et al., 2014; Lindroth, 1966). Several rove beetle taxa that are commonly found in willow and alder litter or similar decaying vegetal material in moist situations (e.g. *Eucnecosum* spp., *Holoboreaphilus nordenskiöldi* (Mäklin), *Pycnoglypta* spp., *Tachinus apterus* Mäklin and *T. apterus/brevipennis* J.R. Sahlberg, Campbell, 1973, 1978, 1984, 1988; Shavrin, 2016; Webster et al., 2012) have been included in this group as well. The ‘Hygro-riparian’ group comprises beetles living in waterside or wet habitats. This includes predators such as *Elaphrus* spp., which hunt insects near the border of standing and running waters, and can occur by the seashore (Lindroth, 1961), as well as on bogs, swamps and meadows. Some of these taxa, including *Olophrum* spp. and *Boreaphilus henningsianus* C.R. Sahlberg, are associated with moss and emergent subaquatic vegetation in such settings (Campbell, 1978, 1983b). Others, such as *Acidota crenata* (Fabricius) and *A. quadrata* (Zetterstedt), are also common in organic materials such as leaf litter, carrion and dung (Campbell, 1982). All members of the ‘Aquatic’ group belong to the order Dytiscidae, predaceous beetles that spend most of their lifecycle submerged in water (Larson et al., 2000) but are also good flyers. The dytiscid taxa identified in this assemblage occur in small bog and tundra pools, and some can also be found in slow-flowing streams (Larson et al., 2000). The remaining group, ‘Eurytopic’, includes a series of taxa that are found in a wide variety of habitats.

In the context of a palaeoecological reconstruction, where the aim is to evaluate local ecological conditions, it is important to pay special attention to species micro-habitat preferences (cf. Forbes and Sikes, 2018). Obligate synanthropes such as those infesting stored food products in northern and continental Europe are typically absent from northern indigenous foragers sites (Forbes et al., 2015, 2017), where they appear to be replaced by indigenous species living in nutrient-rich microhabitats. Hence, those taxa from the Nunalleq palaeoentomological assemblage that are known to be associated specifically to niches provided by decomposing organic matter (e.g. decaying vegetation, leaf litter, rotting fungi, carrion, dung) have been highlighted in red font

(Fig. 5). Most of the taxa included in the ‘Mesic’ group and close to half of those in the ‘Hygro-riparian’ group are thus considered members of the decomposer fauna. A large proportion of taxa in the ‘Eurytopic’ group may also be considered decomposers.

4.2. Palaeoenvironmental reconstruction

Our dataset encompasses the mid-15th to the early 20th century, and ends just prior to the beginning of instrumental records in the Y-K delta from the weather station at Bethel Airport (Fig. 2). Palynological analysis of the Nunalleq peat profile identifies evidence for human activity and occupation of the archaeological site from a depth of 33 cm, dating to c. AD 1490–1660. The end of occupation is difficult to ascertain from the palynological record, however, it likely occurs at 21 cm, between AD 1725 and 1815 (Ledger, 2018). These age ranges are in agreement with the findings of radiocarbon dating from the archaeological site (Ledger et al., 2018). The sedimentary profile therefore encapsulates the entirety of the Nunalleq occupation and provides both pre- and post-occupational palaeoenvironmental and climatic baselines to human activity at the site.

Insect assemblages from the lower part of the peat profile suggest that local ecological conditions were wetter prior to the occupation of the site (pre- AD 1490–1660), with dytiscids forming about 5% of these assemblages (Fig. 6). From the time of the site's occupation to the end of the sequence, assemblages are dominated by the ‘Mesic’ group and ‘Hygro-riparian’ groups, which suggest moist to humid conditions, such as occurs in the area at the present-day, which is characterised by wet tundra. The proportion of beetles associated with decomposing organic matter microhabitats is high throughout the profile, but it is remarkably higher (reaching more than 80% of the assemblage) in the interval between 20 and 32 cm, which correspond to the period of occupation of the site. We interpret this as evidence for nutrient-enrichment of the bog in the vicinity of the occupation site, likely derived from trampling, disturbance and the transport, processing and deposition of organic materials (e.g. hunted animals, sod, grass, dog and human faeces) on the ground. The detailed palaeoecological implications of this dataset will be the object of a forthcoming paper, which will compare faunas from the peat profile with those extracted from occupation floors layers from the sod dwelling's interior at Nunalleq.

4.3. Climatic reconstruction

Thirty-seven of the identified taxa, all of which represent scavengers and/or predators, were included in the climate reconstruction (see SI1). On the basis of the MCR envelopes (SI2), mean summer (T_{MAX}) and winter (T_{MIN}) temperature variation was reconstructed (Table 2, Figs. 7 and 8).

4.3.1. Summer temperatures

For the most part, the reconstructed mean summer temperatures throughout the sequence were marked by wide MCRs. A majority of samples produced T_{MAX} estimates with ranges of between 3.0 °C and 6.5 °C and results that encompassed both the early 20th century and modern summer means (Fig. 7). Nevertheless, there are three samples from which the Coleoptera assemblages permitted reconstructions of T_{MAX} with MCRs of between 0.4 °C to 2.7 °C.

The temperature reconstruction can be sub-divided into three main parts: the pre-occupation baseline, the occupation period and the post-occupational period. The results from the pre-occupation period produce very similar T_{MAX} values, estimating mean summer temperatures at somewhere between 8.8 °C and 14.5 °C for the period from cal. AD 1465–1510. The T_{MAX} values for the first few decades of settlement from cal. AD 1540 are more precise. The first sample from the occupation period (31–33 cm) indicates mean summer temperatures somewhere between 11.5 °C and 13.3 °C during the early years of occupation at Nunalleq. The T_{MAX} value from 29 to 31 cm (cal. AD 1570) indicates

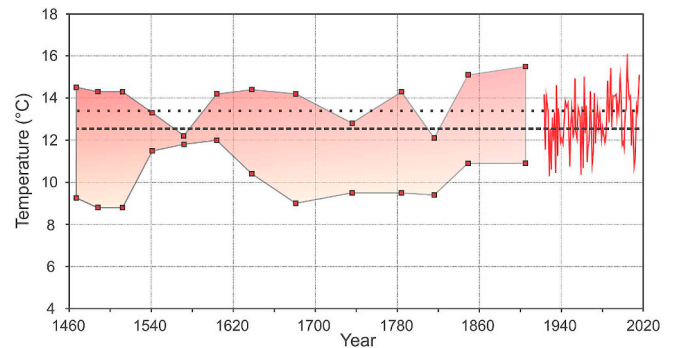


Fig. 7. Summer climate variation in the Y-K delta during the period AD 1465–2016. Square markers indicate the samples analysed in this study with the shaded red envelope between these points indicating the mutual climatic range of the Coleoptera in each sample. The red line tracks the mean July temperature at the Bethel Airport Weather Station between AD 1923 and 2016. The dashed and dotted lines respectively illustrate the early 20th century (AD 1923–1952) and modern (1983–2016) July means. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

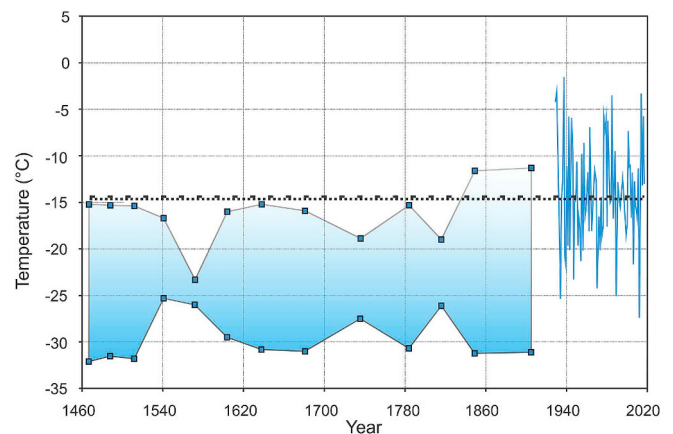


Fig. 8. Winter climate variation in the Y-K delta during the period AD 1465–2016. Square markers indicate the samples analysed in this study with the shaded blue envelope between these points indicating the mutual climatic range of the Coleoptera in each sample. The blue line tracks the mean January temperature at the Bethel Airport Weather Station between AD 1927 and 2017. The dashed and dotted lines respectively illustrate the early 20th century (AD 1923–1952) and modern (1983–2016) July means. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mean summer temperatures were somewhere between 11.8 °C and 12.2 °C. From this point onwards T_{MAX} estimates become less constrained. Despite this, it is possible to deduce that the latter part of the late 16th century and early 17th century were characterised by stability, or potentially a slight warming. Sample 27–29 cm (cal. AD 1605) provides a T_{MAX} estimate of between 12.2 °C and 14.5 °C and the lower end of this estimate equals the maximum value from the preceding sample. For the remainder of the occupation period, the data is less constrained, with T_{MAX} values varying from 9.0 °C to 14.4 °C.

There is little change for the period immediately following site abandonment. However, there is potential evidence for cooling at the turn of the 19th century. The sample from 17 to 19 cm (cal. AD 1815) indicates mean summer temperatures at somewhere between 9.4 °C and 12.1 °C. The latter 19th century and early 20th century is then notable for a possible warming trend with T_{MAX} estimates of between 10.9 °C and 15.5 °C. Indeed, the T_{MAX} value obtained from the last sample of the profile (cal. AD 1920) is remarkably consistent with temperature measurements for the period 1923–1980.

4.3.2. Winter temperatures

Caution must be exercised when interpreting T_{MIN} values reconstructed from beetle subfossil assemblage in coastal regions of the boreo-arctic zones. MCR reconstructions of modern beetle assemblages have been demonstrated to produce T_{MIN} estimates that are much lower than observational data. This is likely a result of beetles adapted to living in the boreo-arctic zone being able to enter a phase of dormancy and/or seek shelter from the cold during the winter (Elias, 2010; Elias et al., 1999a). In addition, it has been shown that modern beetle faunas from coastal regions in Alaska represent species that are able to withstand extreme cold weather events that occur for a few days or weeks of the winter, rather than species that would normally be associated with the relatively mild winter temperatures associated with oceanic climate (Elias et al., 1999a). The reconstruction of mean winter temperatures must therefore be viewed as a crude estimate of winter temperature variation.

Our results suggests that from the mid-15th to the early 16th century, prior to the human occupation at Nunalleq, January mean temperatures varied from c. -14.7°C to -34.2°C . Data for the latter half of the 16th century (Fig. 8; Table 2), which is contemporary with the beginning of occupation at Nunalleq, indicate a cooling or ameliorating climate. At around cal. AD 1540, T_{MIN} is estimated at between -16.7°C and -25.3°C and between -23.3°C and -26.0°C at cal. AD 1570. The remainder of the record towards the beginning of the 19th century is characterised by highly constrained estimates of T_{MIN} with maxima ranging from -14.9°C to -17.1°C and minima of between -27.1°C to -34.0°C (Table 2). The final samples from the profile produce estimates for T_{MIN} of between -11.3°C and -32.3°C that may equally indicate warming or cooling winters.

5. Discussion

5.1. Comparing the modern and palaeoclimate of the Y-K delta

The earliest and longest instrumental temperature series for the Y-K Delta is from Bethel Airport, with continuous recording of summer (July) temperatures from 1923 and winter (January) temperatures from 1929 (Fig. 2). Summer means for the early 20th century (1923–1952) and mid-20th century (1953–1982) indicate only minor evidence of warming with respective July means of 12.5°C and 12.6°C . In contrast, the modern period mean (1983 to present) is markedly higher at 13.4°C and is neatly illustrated in Fig. 2 as a sharp increase in the cumulative summer temperature departures from the early 20th century mean. On this basis, we calculated both the winter and summer departure of our MCR-derived T_{MAX} and T_{MIN} values from the early 20th century (1923–1952) and modern (1983–2016) means (Fig. 9).

The clearest trend from the dataset is that the summer climate of the Y-K delta from the mid-15th to late 19th century was, in all likelihood, cooler than that of the 20th century. There are no instances where the minimum values of the reconstructed T_{MAX} exceed either the early 20th century or modern means. Indeed, in all instances (with exception of the late 19th/early 20th century), the majority of the range of T_{MAX} is lower than both 20th century reference periods (Fig. 9a, c). There are two points when mean summer temperatures in the Y-K delta were definitively cooler than in the early 20th century. The first of these occurs at the onset of the occupation of the Nunalleq site (c. cal. AD 1570), when T_{MAX} was $\geq 0.3^{\circ}\text{C}$ below the early 20th century mean. Similarly, summer temperatures for the early 19th century (cal. AD 1815) were $\geq 0.4^{\circ}\text{C}$ cooler than the early 20th century (Fig. 9a). A comparison of the same data with the modern mean (Fig. 9c) highlights a further two periods in which past mean summer temperatures were cooler than the present. The earliest occupation at Nunalleq was characterised by a summer climate of $\geq 0.1^{\circ}\text{C}$ cooler at cal. AD 1540, which deteriorated further to $\geq 1.2^{\circ}\text{C}$ cooler by cal. AD 1570. The period immediately prior to abandonment of the site (cal. AD 1735) was also significantly colder ($\geq 0.6^{\circ}\text{C}$) than the modern mean. Although the

majority of the palaeoclimate reconstruction is strongly suggestive of temperatures cooler than those of the 20th century, there is also a hint of climatic warming from the mid-19th century. The T_{MAX} of the final two samples from the profile, dating from cal. AD 1850 and cal. AD 1910, indicate summer temperatures in the respective range of 10.9°C to 15.1°C and 15.5°C (Table 2). These values generally encompass the respective minimal and maximal 20th century summer means (Figs. 2 and 9a, c) of 10.3°C (July 1928) and 16.2°C (July 2004).

Our reconstructed T_{MIN} estimates suggest that the January mean at Nunalleq was consistently lower than both the early 20th century and modern mean July temperatures (Fig. 9b and d), but this is likely to be an artefact of the systematic underestimation of reconstructed T_{MIN} values from beetle subfossil assemblages from coastal Alaska (cf. Elias et al., 1999a). Nevertheless, these data also suggest that there are three periods during which winter temperatures may have been significantly colder than during the rest of the sequence. These periods of possible extreme cold are centred on the onset of occupation (cal. AD 1570), immediately following abandonment (cal. AD 1735) and approximately a century later (cal. AD 1815).

5.2. How does the Nunalleq palaeoclimate compare with elsewhere in Alaska?

Climate changes of the past millennium in Arctic and sub-Arctic Alaska have been examined across a range of geographic locations through lake sediments studies (using a variety of proxy data), dendrochronology and glacial geomorphology (Overpeck et al., 1997; Mann et al., 1998; Hinzman et al., 2005; Wiles et al., 2008). Comparable to elsewhere in the Northern Hemisphere, these studies identify climatic trends of the past 1000 years that can be broadly divided into three periods. First is the relatively warm climate of the MCA (AD 900–1350), which is followed by LIA cooling centred on AD 1350–1900. Recent anthropogenic-driven warming is then traced to the late 19th century, a process which in most places accelerated from the 1970s onwards (Hinzman et al., 2005). This is a simplified picture however, as palaeoclimate records present regional and local responses to global changes in atmospheric and oceanic conditions. The Nunalleq palaeoclimate reconstruction (cal. AD 1460–1910) covers the latter of these two periods: LIA cooling and recent anthropogenic warming, while the occupation of Nunalleq (cal. AD 1570–1670) was centred on the LIA.

Despite an abundance of palaeoclimatic records available from across Alaska, many focus on earlier periods such as the Pleistocene and early Holocene (e.g. Kuzmina et al., 2008; Elias et al., 1999b), or are poorly resolved for the modern period (e.g. Brubaker et al., 2001). Few studies of the past millennium present palaeo-temperature reconstructions – instead the majority make palaeoclimate inferences on the basis of departures from long-term trends within datasets. Examples from a similar latitude to Nunalleq include changes in the diatom flora of Ongoke Lake (c. 150 km east of Nunalleq), which imply LIA cooling between AD 1530 and 1740 (Chipman et al., 2009), and low $\delta^{18}\text{O}$ within diatoms from Mica Lake (c. 750 m east) at AD 1700–1900 (Schiff et al., 2009). Palaeoclimatic inferences derived from geomorphological mapping of moraines are also common, such as in the Akhlun Mountains (c. 150 km east of Nunalleq) where the LIA is placed at AD 1300–1750 (Levy et al., 2004). Further east, around Western Prince William Sound, the LIA is dated to AD 1600–1750 (Wiles et al., 1999), while in south-central Alaska glacial advance linked to the LIA is noted in two phases at AD 1420–1520 and AD 1650–1750 (Wiles et al., 2008). These data are broadly in agreement with the findings from Nunalleq, which identifies three periods, centred on AD 1540–1570, AD 1740 and AD 1810, when summer temperatures were colder than the modern mean. Indeed, it is worthwhile highlighting that the Nunalleq data identify similar trends to those observed at nearby Ongoke Lake by Chipman et al. (2009).

The nearest available palaeo-temperature reconstruction is from Farewell Lake, approximately 540 km northeast of Nunalleq (Fig. 1). Hu

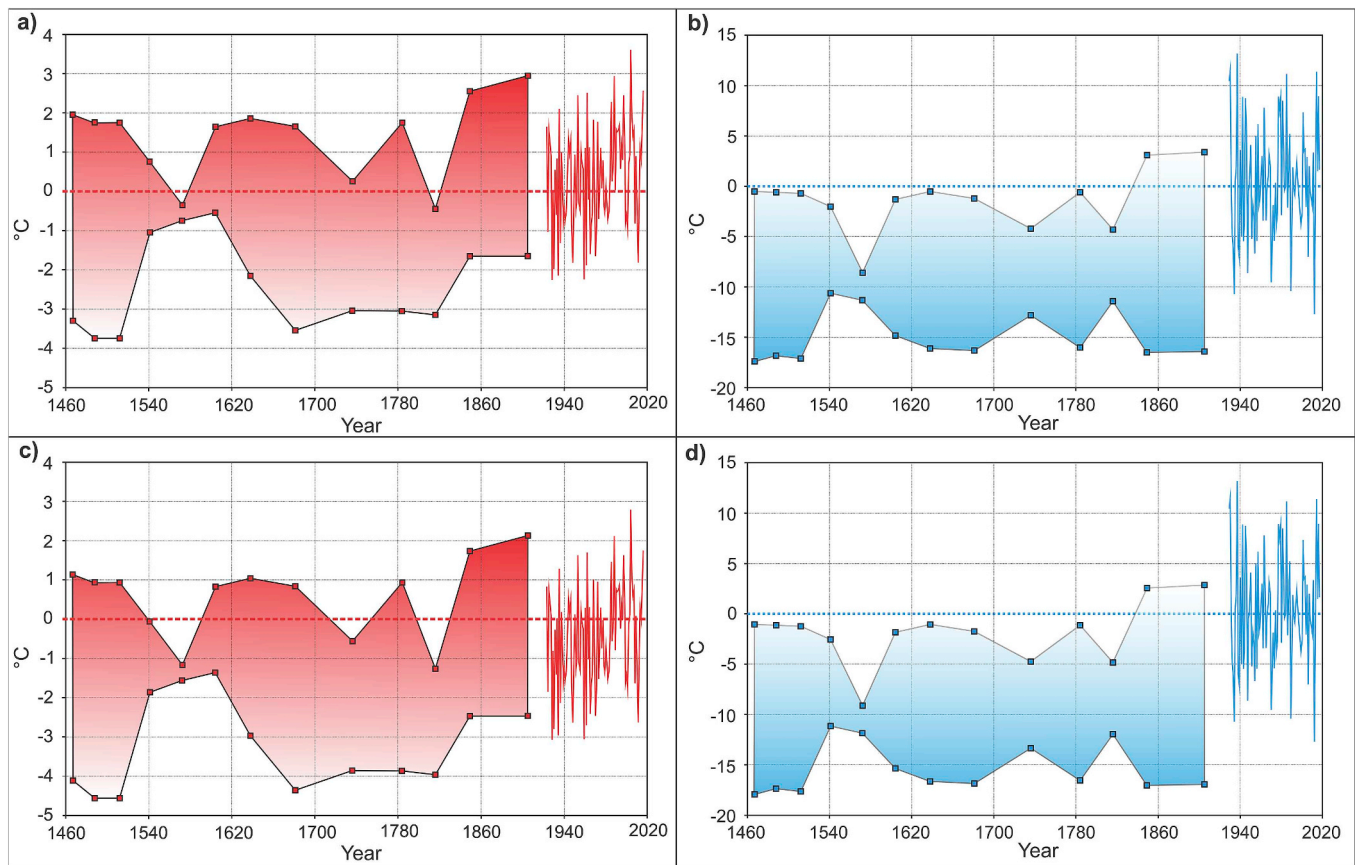


Fig. 9. (a) Summer and (b) winter temperature departures from the early 20th century (1923–1952) July mean. (c) Summer and (d) winter temperature departures from the modern (1983–2016) July mean. The shaded envelopes indicate the mutual climatic range departures from the respective means. Red and blue lines present climatic data from Bethel Weather Station and respectively track July and January departures from the means. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al. (2001) present evidence for significant temperature change from c. AD 1550 that culminated at AD 1700 with temperatures 1.7°C lower than present. Whilst the beginning of LIA cold at Farewell Lake is comparable from observations from Nunalleq, the deepest cold of our record, 1.3°C below the modern mean, is significantly warmer and occurs over a century later at c. AD 1815 (Fig. 9, Table 2). This is perhaps unsurprising given the coastal aspect of Nunalleq relative to the montane continental Farewell Lake. Approximately 1100 km east, varve-based temperature reconstructions from Blue Lake identify the LIA around AD 1620–1720 with mean annual temperatures of 1.0°C below the 1950–2005 annual mean (Bird et al., 2009). Similarly, observations from nearby Iceberg Lake place the coldest part of the LIA around AD 1650 (Loso, 2009). The LIA, as manifested in eastern Alaska, therefore appears to have been shorter and moderately less intense than at Nunalleq. At more northerly latitudes (c. $66\text{--}68^{\circ}\text{N}$), a series of studies (including tree ring record and isotopic studies) present a different story to Nunalleq. At Site 412, Arrigetch Peaks and Dune Lake (Fig. 1), LIA cooling does not really begin until the mid-17th century and persists well into the late 19th century (D'Arrigo and Jacoby, 1989; Overpeck et al., 1997). Conversely at Sheenjek, the period between AD 1675 and 1800 was notable for surface air temperatures of up to 1 standard deviation greater than the early 20th century mean. Evidence for the LIA at this site is not apparent until the beginning of the 19th century (D'Arrigo and Jacoby, 1989).

6. Conclusions

Climatic change associated with the LIA is frequently implicated in interpretative paradigms of the archaeological record of Arctic and sub-

Arctic regions. Yet despite evidence showing that the intensity and occurrence of the LIA is both temporally and spatially transgressive, site-based palaeoclimate data are rare. Typically, palaeoclimatic patterns established at a geographically proximate location are extrapolated to the archaeological site in question to form an interpretative canvas. In instances where the geography (i.e. elevation, latitude, ecology) of an archaeological site is comparable with the source of the extrapolated data, or the site occurs within a region with a dense network of internally coherent palaeoclimate data, this approach is defensible. However, where local, or geographically similar studies are absent, and notwithstanding the chronological uncertainties of transposing datasets, such an approach is problematic. In the case of Nunalleq, the nearest available palaeoclimate data are from a series of interior montane lakes, making local palaeoclimatic data essential.

To this end we undertook a high (contiguous 2 cm) resolution study of the Coleoptera fauna of a peat profile within the immediate vicinity of the archaeological site of Nunalleq. Through the MCR method, we reconstructed palaeo-temperature change at approximately 20–50 year intervals, spanning the period of prehistoric Yup'ik occupation. Precise MCR climate reconstructions rely on the preservation and recovery of the diversity of past beetle faunas in a geographic location. Typically, this is achieved by means of large sample volumes collected using a coarse vertical sampling resolution of c. 4–5 cm, an approach which results in low (> 50 yr) chronological resolution and smooths variation within a dataset. The occupation of Nunalleq likely spanned a century, thus we aimed to maximise chronological resolution through the collection of smaller-volume samples, accepting the potentially reduced precision of the palaeoclimatic reconstruction. Summer temperature estimates for the beginning and end of occupation at Nunalleq, in the

late 16th and early 18th centuries, are relatively well constrained and reconstructed to have been up to 1.3°C cooler than that of the present. The palaeoclimate of the intervening period is less clearly resolved, but in all likelihood was cooler than that of the present. A comparison of these findings with those from elsewhere in Alaska underline the importance of localised palaeoclimate data. In the nearby Akhlun Mountains, the beginning of the LIA is suggested from as early as 14th century, while in parts of eastern and northern Alaska, a mid-18th century date is possible.

Many questions remain regarding the influence of LIA climate change on the human occupational history of the Y-K Delta. Although a deteriorating LIA climate has traditionally been implicated as a causal factor in the Yup'ik Bow and Arrow Wars of the late prehistoric period, the evidence presented here neither supports nor contradicts this conclusion. The beginning of occupation and destruction of Nunalleq were characterised by a similarly cooler summer climate than the present. Therefore, it remains unclear whether the changes in architecture and material culture observed at the site were influenced by colder climatic conditions or not. Similarly, palaeo-temperature may not have been the most limiting climate factor influencing lifeways. For instance, changes in sea ice and/or storm regimes may well have been the true palaeoclimatic drivers at Nunalleq. Therefore, the temperature reconstructions presented here provide the first steps towards a higher resolution understanding of the relationship between LIA climate and human occupational history of Nunalleq and the surrounding Y-K Delta region.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quaint.2019.07.011>.

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