Quaternary Science Reviews 27 (2008) 1710–1722

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A re-evaluation and spatial analysis of evidence for a Younger Dryas climatic reversal in Beringia

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ARTICLE INFO

Article history:
Received 3 September 2007
Received in revised form 15 March 2008
Accepted 28 June 2008

ABSTRACT

An objective classification of paleoclimatic proxies from 75 lake and peat records is used to re-evaluate data quality and inferred climatic patterns in Beringia during the Younger Dryas. Mapped data reveal coherent but spatially-complex regional patterns, suggesting the Younger Dryas was characterized by: (1) cooling in Southern Alaska, Eastern Siberia, and portions of Northeastern Siberia; and (2) uniform to warmer-than-present conditions through most of Central Alaska, Northeastern Siberia, and possibly the Russian Far East and Northern Alaska. The Beringian patterns correspond to distinctive large-scale climatic forcings, although in some locations further modified by more local influences, such as topography. General circulation models and modern synoptic climatology provide a conceptual framework for exploring possible mechanisms responsible for the observed changes. Forcings and associated climatic responses consistent with the proxy data include: (1) lowered sea-surface temperatures in the North Atlantic and Pacific reducing temperature and precipitation in Eastern Siberia; (2) intensified Aleutian low and lowered sea-surface temperatures causing cooler summers and higher winter precipitation in Southern Alaska; (3) stronger Pacific Subtropical High and an eastward shift of the East Asian Trough reducing summer temperatures in Southern Alaska and causing relative warmth in Northeastern Siberia; and (4) strong high pressure system producing warm, dry conditions in interior Alaska.

1. Introduction

The Younger Dryas (YD), a climatic reversal that occurred ~11,000–10,000 ^{14}C yr BP (~12,900–11,600 cal yr BP) following more than a millennium of post-glacial amelioration, has been the focus of study from a variety of disciplinary perspectives (Broecker et al., 1989; Kudrass et al., 1991; Goslar et al., 1995; Severinghaus et al., 1998; Alley, 2000; Zhou et al., 2001). Characterized by a dramatic and abrupt cooling, the YD was likely triggered by the collapse of North Atlantic Deep Water (NADW) formation, following a massive discharge of freshwater into the North Atlantic Ocean (Broecker and Denton, 1989; Alley et al., 1993). The absence of NADW halted North Atlantic thermohaline circulation (THC), consequently lessening the northward transfer of heat from lower latitudes. Computer model simulations indicate that a diminished North Atlantic THC would have far-reaching effects, including a marked cooling of Pacific sea-surface temperatures (SST; Mikolajewicz et al., 1997; see also Rind et al., 1986; Manabe and Stouffer, 1997). In agreement with the model results, paleo-oceanographic investigations indicate that parallel YD-type cooling was recorded in sediment cores from the northwestern Pacific (Keigwin and Gorbarenko, 1992; Gorbarenko, 1996), the marginal Okhotsk and Bering seas (Gorbarenko, 1996), the tropical Sulu Sea (Linsley and Thunell, 1990; Kudrass et al., 1991), the western equatorial Pacific Ocean (Boltovskoy, 1990), the Japan Sea (Keigwin and Gorbarenko, 1992), the Tsugaru Strait (Itaki et al., 2004; Koizumi et al., 2006), the Gulf of California (Barron et al., 2005), and the Santa Barbara Basin (Keigwin and Jones, 1990; Kennett and Ingram, 1995).

Not surprisingly, the strongest terrestrial evidence for a YD climatic oscillation initially came from lands bordering the North Atlantic Ocean (e.g., Watts, 1977; Mott et al., 1986). Many scientists subsequently argued that YD-related changes in terrestrial ecosystems occurred on global or near-global scales (see Mathewes et al., 1993; Peteet et al., 1993). However, questions lingered about the presence or even logic of universal and uniform ecosystem responses to cooling triggered by a shut-down in North Atlantic THC. Shuman et al. (2002), using a comprehensive analysis of palynological data from eastern North America, demonstrated that spatially-complex paleoclimatic patterns are reasonable and expected characteristics of the YD oscillation. This complexity reflects not only changes in North Atlantic circulation, but also

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0277-3791/$ – see front matter
doi:10.1016/j.quascirev.2008.06.010

effects of variations in insolation, atmospheric circulation, and ice-sheet extent that occurred during this period. Modeling experiments provide additional support for the existence of complex climatic patterns and feedbacks related to a cooling of North Atlantic SST, including significant changes in Northern Hemisphere atmospheric circulation (Mikolajewicz et al., 1997; Peteet et al., 1997; Renssen, 1997; Schiller et al., 1997). For example, a simulated 2 °C decrease in North Pacific SST reduced air temperatures over North America and parts of Eurasia and increased snowfall in northwestern North America (Peteet et al., 1997).

Despite evidence for a YD reversal that affected the Pacific Ocean and Okhotsk and Bering seas, terrestrial records from the North Pacific sector (i.e., north of 50°N) present ambiguous support for widespread cooling over land. YD-related vegetation changes have been reported from sites scattered throughout Alaska (e.g., Hu et al., 1993, 1995; Bigelow and Edwards, 2001; Bigelow and Powers, 2001; Brubaker et al., 2001; Mann et al., 2002), from several lakes in northern Siberia (Anderson et al., 1990; Pisaric et al., 2001), and from Lake Baikal (Prokopenko et al., 1999). In contrast, numerous pollen records from interior and northern Alaska indicate conditions that were warmer and/or wetter than present (Anderson et al., 2003). Palynological data from a majority of sites in Northeastern Siberia suggest a third pattern of no climatic change. The apparent spatially-diverse response of terrestrial ecosystems in Alaska and Northeastern Siberia was noted previously by Anderson et al. (2002). However, no systematic analysis of the YD has been done for Beringia (herein defined as the area stretching westward from the Alaska–Canada border to ~106°E in Eastern Siberia; Fig. 1), despite an abundance of sites that encompass the Lateglacial (LG)-Holocene transition (~13,000–9000 ^{14}C yr BP; Duvall et al., 1999). Reluctance to take on such a project possibly reflects presumptions of inadequate chronological control and/or coarse sampling resolution in existing records, thereby having potential to yield patterns determined more by analytical than paleoenvironmental factors (e.g., Whitlock and Bartlein, 1993; Mock and Bartlein, 1995; Shuman et al., 2002; Whitlock et al., 2007). We conducted a critical reanalysis of published paleo-data from lakes and peats to assess data quality and to determine whether the inferred climatic patterns were reliable. To this end, we qualitatively ranked sites according to chronological control, sampling resolution, and the strength of a YD signal. Sites were mapped using an overall "reliability" index, thereby placing each record in a comprehensive, regional perspective that allows a general evaluation of the coherency in spatial patterns. We finally explored whether the documented patterns are climatologically consistent based on published general circulation models (GCMs) and modern synoptic climatology. Insights about large-scale forcings, in some areas further modified by topography, provide a conceptual framework for determining possible mechanisms responsible for the observed YD patterns in Beringia.

2. Methods

To more systematically assess evidence for and spatial patterns of a response to the YD climatic oscillation in Beringia, we re-examined 75 lake and peat records following well-established procedures for evaluating individual site quality (e.g., Webb et al., 1983, 1993; Gaudreau and Webb, 1985; for Beringia see Brubaker et al., 2005; Edwards et al., 2005). All records included here (Table 1; Fig. 2) possess ages that extend prior to the YD and sampling resolutions that are adequate to detect submillennial climatic responses. Proxy data are primarily palynological, but where available additional geochemical, sedimentological, and macrofossil information was used (Fig. 4B; see also Appendix). Sites were ranked based on the fluctuations in proxy data during the LG to Holocene transition (1: fluctuation; 2: possible fluctuation; or 3: no fluctuation), sampling resolution (1: centennial to bi-centennial; 2: multi-centennial; 3: millennial or greater), and chronological control (1: reliable; 2: questionable; or 3: poor; Appendix). The presence or absence of a fluctuation in proxy data was determined by careful visual examination. If a distinguishable shift occurred during the LG to Holocene transition, the record was deemed to have a "fluctuation." If a minor shift occurred, or the shift occurred in some proxies and not others, the record was deemed to have a "possible fluctuation." If proxy data did not exhibit any discernible changes during the LG to Holocene transition, the record was deemed to have "no fluctuation." Sampling resolution was determined by counting the number of data points spanning the duration of the record, and dividing by the age of the record.

Estimates of sediment ages depend on several factors, including differences between actual and estimated sedimentation rates, analytical errors, and uncertainties related to ^{14}C plateaus (Hadjas et al., 1998; Lotter et al., 2002). Most ^{14}C results in Beringia are from bulk sediments, which can yield dates that are older than those from plant macrofossils. However, consistent patterns of change in Beringia and elsewhere, including studies of the YD (e.g., Mott et al., 1986; Peteet et al., 1990; Shuman et al., 2002), are seen in mapped data that rely predominantly on chronologies using bulk samples (e.g., Huntley and Prentice, 1993; Webb et al., 1993; Anderson and Brubaker, 1994; Brubaker et al., 2005), suggesting that possible discrepancies between bulk and macrofossil dates are not an important source of error in studies that focus on broad spatial patterns. In this analysis, chronological control was considered "reliable" when the record had four or more ^{14}C dates spanning the

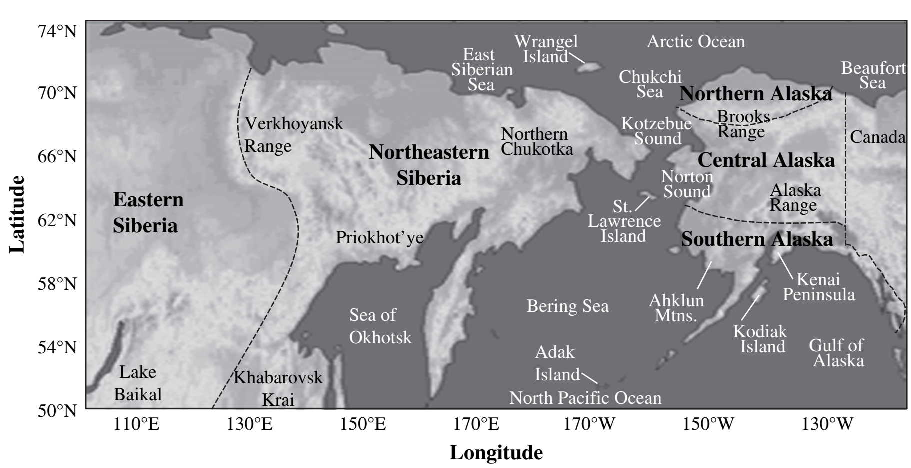

Fig. 1. Topographic map illustrating the locations of features discussed in text.

Table 1
Key to sites in Fig. 3

Site ID[a]	Site name	Location	Elevation (m)	YD signal[b,c]	Citation
1	70 Mile Lake	61.50°N, 145.23°W	565	4	Ager and Brubaker, 1985
2	Adak Island	51.90°N, 176.63°W	60	3	Heusser, 1978
3	Ahaliorak Lake	68.90°N, 151.35°W	~300	3	Eisner and Colinvaux, 1990
4	Alut Lake	60.00°N, 152.08°E	480	3	Anderson and Lozhkin, 2002a; Anderson et al., 2002
5	Angal Lake	67.14°N, 153.88°W	820	4	Brubaker et al., 1983
6	Birch Lake	64.30°N, 146.65°W	275	1	Abbott et al., 2000; Bigelow and Edwards, 2001; Bigelow and Powers, 2001
7	Cape Deceit	66.098°N, 162.748°W	<50	3	Matthews, 1974
8	Circle Lake	59.80°N, 151.15°W	418	2	Ager, 1998
9	Dolgoe Lake	71.87°N, 127.07°E	40	2	Pisaric et al., 2001
10	Dune Lake	64.421°N, 149.894°W	134	4	Bigelow and Powers, 2001; Edwards et al., 2001
11	Eightmile Lake	63.88°N, 149.25°W	646	4	Ager, 1983; Ager and Brubaker, 1985
12	Elgennya Lake	62.13°N, 149.00°E	1040	4	Anderson et al., 1997
13	El'gygytgyn Lake	67.50°N, 172.00°E	492	4	Nowaczyk et al., 2002; Nolan et al., 2003
14	Elikchan 4 Lake	60.73°N, 151.89°E	800	4	Lozhkin and Anderson, 1996; Kokorowski et al., 2008
15	Etivlik Lake	68.13°N, 156.03°W	632	4	Oswald et al., 1999
16	Farewell Lake	62.55°N, 153.63°W	320	4	Hu et al., 1996; Brubaker et al., 2001
17	Flora Lake	63.484°N, 170.121°W	<20	3	Colinvaux, 1967
18	Flounder Flat	58.734°N, 158.390°W	<20–90	3	Short et al., 1992
19	Gek Lake	62.08°N, 147.92°E	969	3	Anderson and Lozhkin, 2002a; Anderson et al., 2002
20	Glukhoye Lake	59.75°N, 149.92°E	3	3	Anderson et al., 1996
21	Goluboye Lake	61.03°N, 152.75°E	810	3	Anderson and Lozhkin, 2002b; Anderson et al., 2002
22	Grandfather Lake	59.80°N, 158.52°W	142	1	Hu et al., 1995; Brubaker et al., 2001; Hu and Shemesh, 2003
23	Gursky peat bog	50.00°N, 137.05°E	35	3	Klimin et al., 2004
24	Harding Lake	64.425°N, 146.854°W	218	4	Ager, 1983; Ager and Brubaker, 1985; Bigelow and Powers, 2001
25	Headwaters Lake	67.93°N, 155.05°W	820	4	Brubaker et al., 1983
26	Hidden Lake	60.485°N, 150.262°W	91	1	Ager, 1983; Ager and Brubaker, 1985
27	Homer Spit peat	59.63°N, 151.51°W	418	4	Ager, 1998
28	Idavain Lake	58.77°N, 155.95°W	223	1	Brubaker et al., 2001
29	Imnavait Creek	68.67°N, 149.33°W	900	3	Eisner, 1991
30	Imuruk Lake	65.58°N, 163.25°W	311	3	Colinvaux, 1964
31	Jack London Lake	62.17°N, 149.50°E	822	3	Lozhkin et al., 1993
32	Jan Lake	63.565°N, 143.916°W	~200	4	Edwards et al., 2001
33	Joe Lake	66.77°N, 157.22°W	183	4	Anderson, 1988; Anderson et al., 1994
34	Juneau peat	58.302°N, 134.420°W	~20–200	3	Heusser, 1952
35	Kaiyak Lake	67.12°N, 161.42°W	190	4	Anderson, 1985
36	Khomutakh Lake	63.72°N, 121.62°E	120	2	Andreev et al., 1997
37	Kodiak Island sites	57.42°N, 154.05°W	30	1	Peteet and Mann, 1994
38	Kollioksak Lake	66.97°N, 156.45°W	213	4	Anderson and Brubaker, 1994
39	Lake Baikal	52.52°N, 106.15°E	various	1	Prokopenko et al., 1999; Horiuchi et al., 2000; Kataoka et al., 2003; Piotrowska et al., 2004; Prokopenko and Williams, 2004; Bezrukova et al., 2005; Boes et al., 2005; Demske et al., 2005; Morley et al., 2005
40	Lake of the Pleistocene	68.60°N, 156.00°W	980	1	Mann et al., 2002
41	Lesnoye Lake	59.55°N, 151.83°E	96	3	Anderson and Lozhkin, 2002a; Anderson et al., 2002
42	Little Swift Lake	60.21°N, 159.77°W	572	2	Axford and Kaufman, 2004
43	Nenana River	63.90°N, 149.10°W	460	1	Bigelow et al., 1990
44	Niliq Lake	67.87°N, 160.43°W	274	4	Anderson, 1988; Anderson et al., 1988
45	Nimgun Lake	59.55°N, 160.77°W	320	1	Hu et al., 2002
46	Noatak River	67.13°N, 162.00°W	unknown	2	Elias, 2000
47	Oil Lake	68.67°N, 150.48°W	745	3	Eisner and Colinvaux, 1992
48	Ongivinuk Lake	59.57°N, 159.37°W	163	2	Hu et al., 1995; Brubaker et al., 2001
49	Ped Pond	67.20°N, 142.00°W	230	4	Edwards and Brubaker, 1986
50	Pleasant Island Lake	58.35°N, 135.67°W	150	1	Engstrom et al., 1990; Peteet and Mann, 1994
51	Puyuk Lake	63.503°N, 162.208°W	25	4	Ager, 1982
52	Ranger Lake	67.15°N, 153.63°W	820	4	Brubaker et al., 1983
53	Ruppert Lake	67.07°N, 154.23°W	210	4	Brubaker et al., 1983
54	Sakana Lake	67.43°N, 147.85°W	640	4	Anderson and Brubaker, 1994
55	Sands of Time Lake	66.03°N, 147.52°W	250	4	Edwards and Brubaker, 1986
56	Screaming Yellowlegs Pond	67.58°N, 151.42°W	660	4	Edwards et al., 1985
57	Sithylemenkat Lake	66.13°N, 151.38°W	227	4	Anderson et al., 1990
58	Smorodinovoye Lake	64.77°N, 141.10°E	800	2	Anderson et al., 2002
59	Snipe Lake	60.63°N, 154.28°W	579	2	Brubaker et al., 2001
60	Sosednee Lake	62.28°N, 149.83°E	822	4	Lozhkin et al., 1993
61	Squirrel Lake	67.10°N, 160.38°W	91	4	Anderson, 1985
62	Suolakh peat-bog	57.03°N, 124.10°E	800	2	Andreev et al., 1997
63	Tangle Lakes and Rock Creek	63.03°N, 146.07°W	860	4	Schweger, 1981; Ager and Brubaker, 1985; Bigelow and Powers, 2001
64	Tenmile Lake	63.07°N, 145.70°W	1000	4	Anderson et al., 1994; Bigelow and Powers, 2001
65	Tiinkdhul Lake	66.57°N, 143.15°W	189	4	Anderson et al., 1988
66	Toolik Lake	68.633°N, 149.605°W	760	4	Eisner and Colinvaux, 1990
67	Tukuto Lake	68.502°N, 157.043°W	541	4	Oswald et al., 1999

Table 1 (*continued*)

Site ID[a]	Site name	Location	Elevation (m)	YD signal[b,c]	Citation
68	Tungak Lake	61.428°N, 164.192°W	60	4	Ager, 1982
69	Ulkhan Chabyda Lake	61.98°N, 129.37°E	200	2	Andreev et al., 1997
70	Wien Lake	64.33°N, 152.27°W	305	1	Hu et al., 1993; Bigelow and Powers, 2001; Brubaker et al., 2001
71	Windmill Lake	63.65°N, 148.80°W	640	1	Bigelow and Edwards, 2001; Bigelow and Powers, 2001
72	Wonder Lake	63.48°N, 151.08°W	610	4	Anderson et al., 1994; Child and Werner, 1999; Bigelow and Powers, 2001
73	Wrangel Island, Exposure WR-12	71.17°N, 179.65°W	204	4	Lozhkin et al., 2001
74	Zagoskin Lake	63.449°N, 162.106°W	120	4	Ager, 2003

[a] Sites used in regional analysis; arranged alphabetically.
[b] YD signal: 1 = YD oscillation; 2 = possible YD oscillation; 3 = YD oscillation probably absent; 4 = YD oscillation absent.
[c] See Appendix for site evaluations that provide the basis for each YD signal ranking.

LG to Holocene and/or dates that bracketed the YD, and no apparent problems with the ages (e.g., no age reversals), "questionable" when the record had two to three ^{14}C dates and/or possible problems with the ages, and "poor" when the record had one or no ^{14}C dates and/or likely problems with the ages.

Based on this evaluation, sites were ranked in the following manner, with (1) and (4) representing the most robust records and (2) and (3) being more ambiguous:

(1) YD oscillation: fluctuation in the proxy data, at least multi-centennial sampling resolution, and reliable chronological control to link the fluctuation with the timing of the YD;
(2) possible YD oscillation: fluctuation in the proxy data, but the record lacks sufficient chronological control to definitively assign the event to the YD, and/or sampling resolution is too coarse to determine if the fluctuation is significant;
(3) YD oscillation probably absent: no fluctuation in the proxy data, dating is adequate to delimit the general period of the YD, but the record lacks sufficient sampling resolution to definitively eliminate a possible climatic reversal;
(4) YD oscillation absent: no fluctuation in the proxy data, at least multi-centennial sampling resolution, and chronological control is adequate to delimit the general period of the YD.

For example, Grandfather Lake in Southwestern Alaska (Fig. 3A,B) is given a ranking of (1) because: (a) palynological and geochemical data exhibit a fluctuation that is contemporaneous with the YD; (b) the record has multi-centennial sampling resolution, with one sample representing ~150–250 years; and (c) the record has six ^{14}C dates spanning the LG to Holocene (Hu et al., 1995; Brubaker et al., 2001) and dates that bracket the YD (Hu and Shemesh, 2003). The Smorodinovoye Lake record from Northeastern Siberia (Fig. 3C) is of lesser quality with a ranking of (2) because: (a) there is a fluctuation in palynological data that might correspond to the YD; (b) sampling resolution is multi-centennial, with each sample representing ~350 years; and (c) the fluctuation is brief and several of the 11 ^{14}C dates are questionable (Anderson et al., 2002). Glukhoye Lake in Northeastern Siberia (Fig. 3D) and Oil Lake in Northern Alaska (Fig. 3E) are given a ranking of (3) because they: (a) exhibit no fluctuation in palynological data; (b) have multi-centennial to millennial sampling resolution, with each sample representing ~500 and 1800–2100 years, respectively; and (c) they have "poor" (Glukhoye; zero ^{14}C dates) to "questionable" (Oil; three ^{14}C dates) chronologies (Eisner and Colinvaux, 1992; Anderson et al., 1996). A ranking of (4) is given to Elikchan 4 Lake in Northeastern Siberia (Fig. 3F) because: (a) no fluctuation exists in any of the palynological, sedimentological, or geochemical data; (b) the record has centennial to bi-centennial sampling resolution (<100–230 years/sample); and (c) the record has four ^{14}C dates spanning the LG to Holocene (Kokorowski et al., 2008).

3. Results

Paleoecological data (Fig. 4; Appendix) from the YD interval are discussed by region (Fig. 1): (1) Eastern Siberia (west of Verkhoyansk Range, extending to ~106° E); (2) Northeastern Siberia/Russian Far East (east of the Verkhoyansk Range, extending eastward to Bering Strait and southward to Khabarovsk Krai); (3) Southern Alaska (south of the Alaska Range); (4) Central Alaska (between the Alaska Range and the crest of the Brooks Range); and

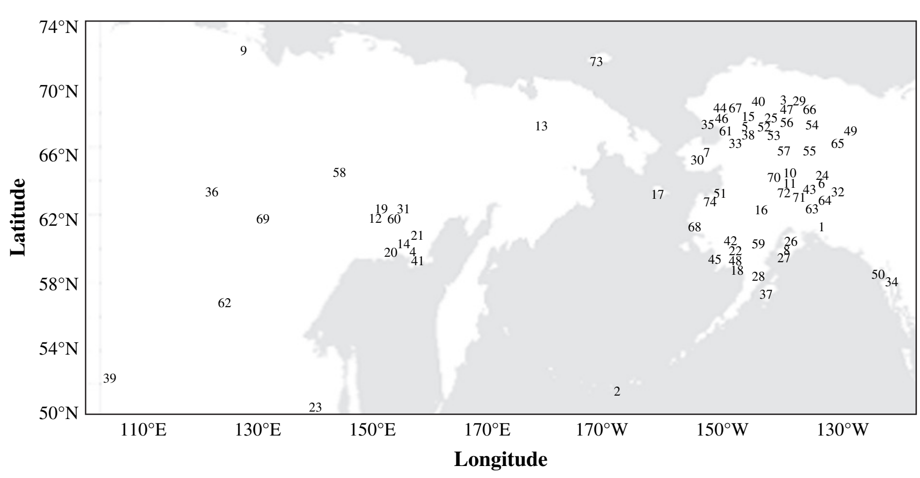

Fig. 2. Map showing the locations of sites used in analysis of YD chronozone. See Table 1 for site identification.

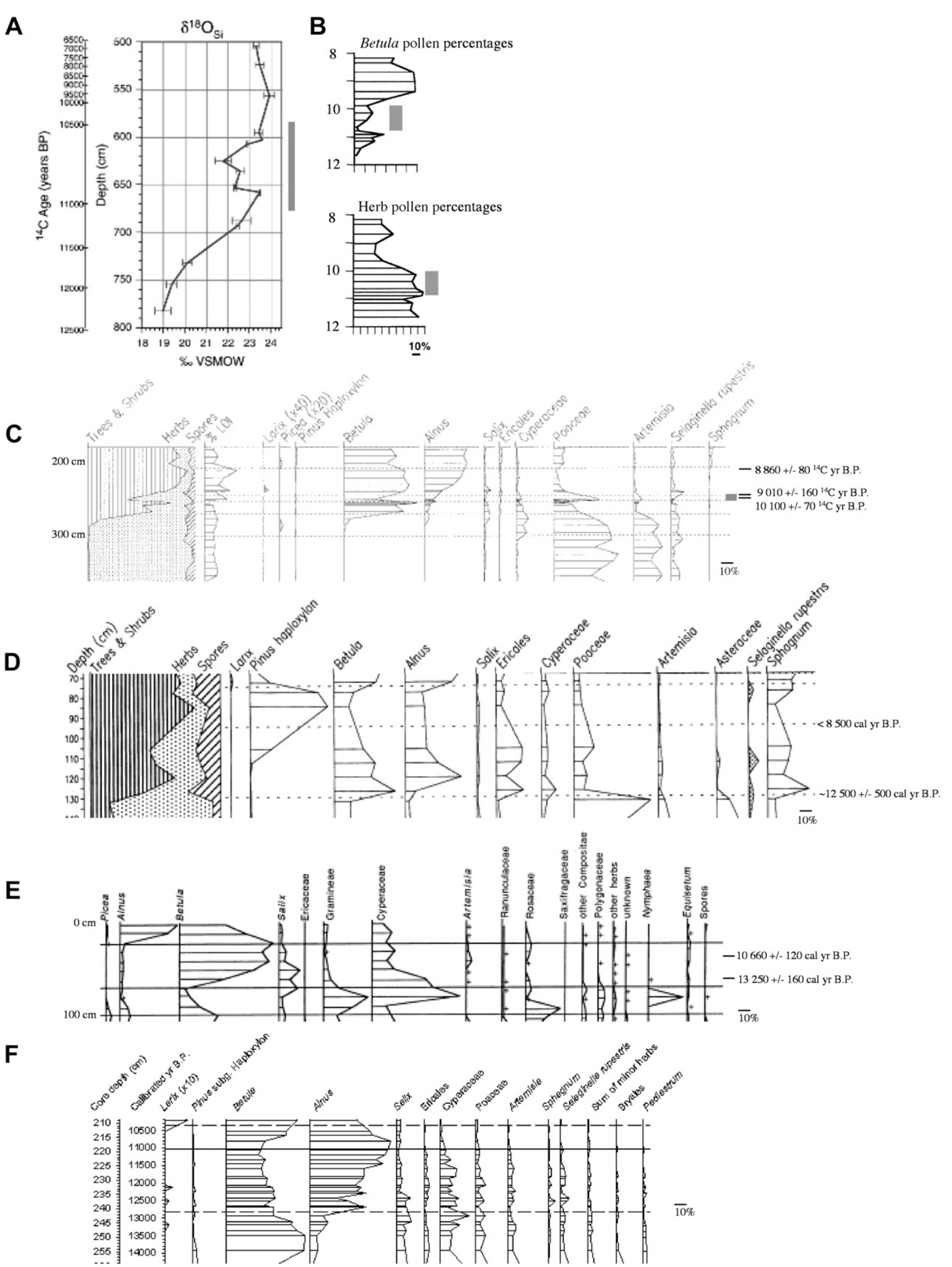

Fig. 3. Examples of YD ranking: (A, B) Rank 1 (Grandfather Lake, gray bar indicates YD oscillation; Brubaker et al., 2001; Hu and Shemesh, 2003); (C) Rank 2 (Smorodinovoye Lake, gray bar indicates possible YD oscillation; Anderson et al., 2002); (D) Rank 3 (Glukhoye Lake; Anderson et al., 1996); (E) Rank 3 (Oil Lake; Eisner and Colinvaux, 1992); (F) Rank 4 (Elikchan 4 Lake; Kokorowski et al., 2008).

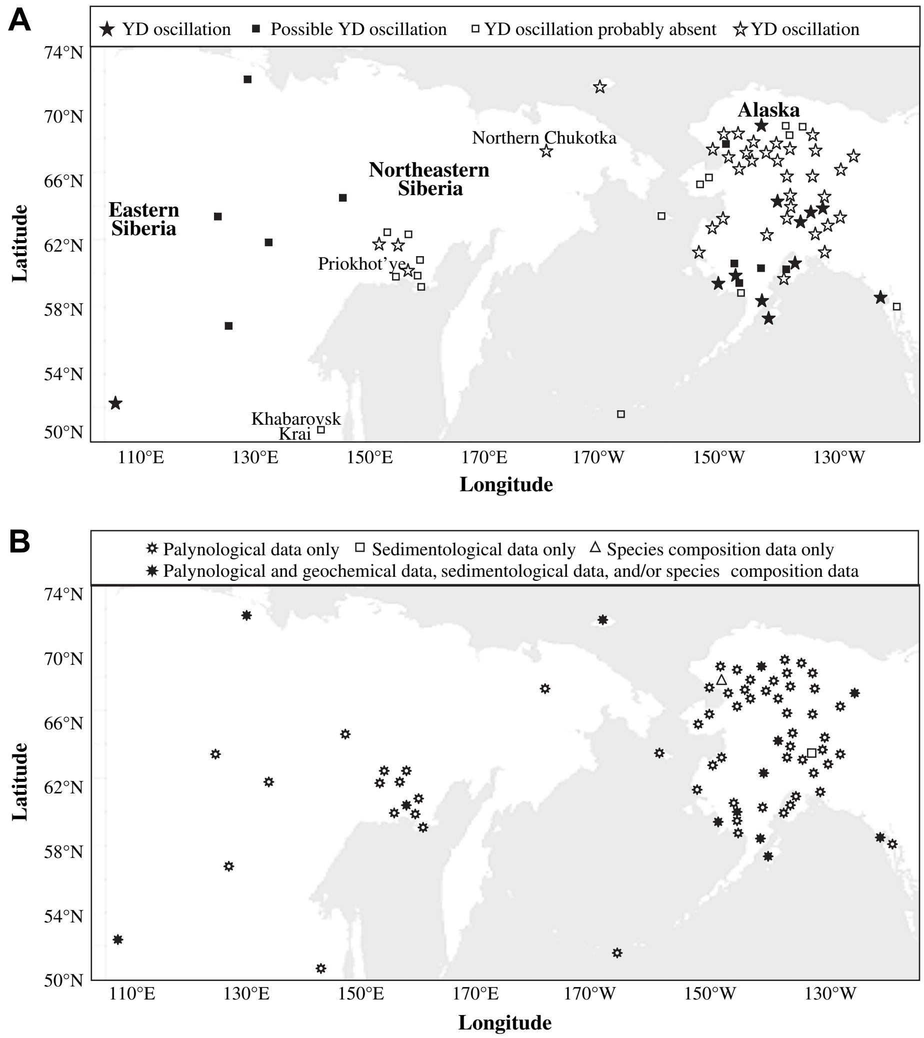

Fig. 4. A: Site map showing results of site evaluations; see Fig. 3 for site identification and Appendix for site evaluations; B: site map showing proxy type at each site (palynological data: pollen percentage and accumulation rate; geochemical data: carbon and biogenic silica content, δ^{13}C, δ^{18}O; sedimentological data: sediment color and composition, magnetic susceptibility, grain size, accumulation rate; species composition data: aquatic diatoms and mollusks, terrestrial beetles); see Appendix for greater detail.

(5) Northern Alaska (north of the crest of the Brooks Range). Any evidence for a YD oscillation in each region will be considered first, followed by evidence against a YD event. Ages are presented as originally published in ^{14}C yr BP. Site identification numbers (Table 1; Fig. 2) are listed parenthetically after the first mention of the record. Number of sites per region vary, with the most in Central Alaska (33), followed by Southern Alaska (15), Northeastern Siberia/Russian Far East (13), Northern Alaska (9), and Eastern Siberia (5).

3.1. Eastern Siberia

All records in Eastern Siberia indicate at least the possible presence of a YD oscillation. Sediments from Dolgoe Lake (9), the northernmost site, exhibit a decrease in organic content and an increase in herbaceous pollen from ~11,000 to 10,000 yr BP. Palynological diagrams from Khomutakh (36) and Ulkhan Chabyda (69) lakes and Suolakh (62) peat bog also show an increase in herbaceous pollen that is interpreted as a response to YD cooling. Uncertain chronology in these southern sites, however, prevents the oscillation from being unquestionably classified as the YD. Nonetheless, the abundance of herbaceous taxa implies a period of climatic deterioration, likely characterized by cooler summer temperatures and/or decreased annual precipitation, some time during the late LG. Furthermore, the presence of similar vegetation changes over the broad range of landscapes represented by these four localities suggests that the cause of the LG changes was likely climatic rather than from edaphic factors.

In the southern basin of Lake Baikal, lacustrine records from Vydrino Shoulder (39) indicate cooler temperatures, associated with the expansion of *Betula*, *Artemisia* and Chenopodiaceae, a decline in diatom concentrations, and a steady decrease in diatom and bulk-sediment δ^{18}O, resulting from climate-induced shifts in drainage patterns during the YD. Corroborating data are evident from the Salenga Delta (39), where a positive shift in sedimentary organic δ^{13}C during the YD parallels a decrease in atmospheric methane described elsewhere (Brook et al., 1996). In the northern basin of Lake Baikal, sedimentary sequences from Continent Ridge (39) exhibit a rapid drop in sediment gray-scale, an increase in magnetic susceptibility, and the appearance of massive clays at the onset of the YD, perhaps due to decreased nutrient influx, increased minerogenic input, and limited aquatic productivity. Effects of YD cooling on vegetation and peat accumulation in the Baikal area appear to have been relatively minor. Data from Continent Ridge, Salenga Delta, Posolskoe Bank (39), and Chivyrkui Bay (39) suggest slight variations in plant communities during the YD, whereas Academician Ridge (39) exhibits no changes. The Academician site, however, is characterized by extremely slow sedimentation rates, so it may lack the resolution to determine the presence/absence of a YD oscillation.

3.2. Northeastern Siberia/Russian Far East

In contrast to Eastern Siberia, palynological records, with the exception of Smorodinovoye Lake (58), show little to no evidence of a YD event. At Smorodinovoye Lake, the westernmost site in this second region, an increase in herbaceous pollen occurs between 10,150 and 9875 yr BP, suggesting a brief period of cooler summer temperatures and/or decreased effective moisture. Interestingly, Smorodinovoye Lake is located on the eastern side of the Verkhoyansk Range, which today acts as a major physiographic barrier between Eastern and Northeastern Siberia. Nonetheless, its pollen record is more similar to those of Eastern rather than Northeastern Siberia, perhaps indicating a climatic boundary that was more eastward than at present (see Section 4.3).

Other data from the Upper Kolyma, Priokhot'ye (area bordering the Sea of Okhotsk) and the Russian Far East reflect uniform warming throughout the LG-Holocene transition. Palynological, geochemical and sedimentological data from a recent high-resolution study at Elikchan 4 Lake (14) indicate uninterrupted warming during the LG into the Holocene. Palynological records stretching from the upper Kolyma drainage (Gek (19), Elgennya (12), Jack London (31), Sosednee (60), and Goluboye (21) lakes) southeastward to the Sea of Okhotsk (Glukhoye (20), Lesnoye (41), Alut (4), and Elikchan 4 lakes) and southward to the Khabarovsk region (Gursky peat; 23) corroborate relatively warm conditions. Aside from Elikchan 4, all other records lack reliable chronologies, and each may have a sampling interval that is too coarse to convincingly address the presence or absence of the YD on its own. However, the chronological control is sufficient to delimit the general interval where a YD response would be expected. The consistent lack of evidence for any climatic fluctuation during the LG suggests that concluding an apparent absence of a YD event is probably valid for the Upper Kolyma–Okhotsk region. This conclusion is also supported by biome analysis, which indicates that deciduous broadleaf-needleleaf forests occupied much of Western Beringia throughout the YD (Edwards et al., 2005).

El'gygytgyn Lake (13), northern Chukotka, has two separate chronologies related to its ~250,000 yr old record. In the chronology that was tuned to Northern Hemisphere insolation, a decrease in magnetic susceptibility corresponding to the YD was reported (Nowaczyk et al., 2007; Asikainen et al., 2007). Changes in vegetation suggest a slightly different chronology, one that in the upper portion of the core is more in accordance with radiometric ages (Lozhkin et al., 2007). In this latter age model, squared chord-distance analog analyses of modern and fossil pollen spectra indicate that climate was warmer than present from 10,700 to 8600 yr BP. In our mapped data, we have chosen to use the palynological findings, because vegetation-climate relationships for arctic regions (e.g., Anderson et al., 1991) are more strongly defined than those for paleomagnetism and climate. Warmer and moister-than-present conditions occurred on Wrangel Island, where a well-dated section (Exposure WR-12; 73) reveals the initiation of peat growth during the YD. Changes in the chemical composition of an ice-wedge in the same exposure imply warmer-than-present temperatures from 11,000 to 10,000 yr BP.

3.3. Southern Alaska

Far more continuous LG records are available from Alaska than Siberia, and 10 out of 15 sites in southern Alaska register a YD or YD-like oscillation. Palynological spectra from sites on Kodiak Island (37) and from Idavain (28), Nimgun (45), Grandfather (22), Hidden (26), and Pleasant Island (50) lakes reflect an increase in herbaceous taxa and/or a decrease in Polypodiaceae percentages during YD times. A decline in $\delta^{18}O$ of diatom biogenic silica ($BSiO_2$) at Grandfather Lake supports the inference from the paleovegetation that temperatures decreased substantially at the onset of the YD. Increased sediment grain size (Kodiak Island) and magnetic susceptibility (Idavain and Pleasant Island lakes) and drops in organic carbon (Pleasant Island and Nimgun lakes) and $BSiO_2$ (Nimgun Lake) suggest stronger winds, greater erosion and decreased vegetation cover. Palynological records from other lakes reflect similar vegetation fluctuations, but lack precise chronological control (Ongivinuk (48) and Circle (8) lakes), adequate sampling resolution (Snipe Lake; 59) or sufficient temporal coverage (Little Swift Lake; 42) to decisively link the changes to the YD.

To the east, palynological data from Homer Spit peat (27), 70-Mile Lake (1), Adak Island (2), Flounder Flat (18), and Juneau peat (34) lack evidence of a YD oscillation. However, the event may have been overlooked at Adak Island, Flounder Flat, and Juneau due to coarse sampling intervals. The 70-Mile Lake palynological record indicates continuous warming, with increasing *Betula* shrubs through the LG followed by the establishment of *Populus* woodland ~10,700–8700 yr BP that possibly indicates warmer-than-present summer temperatures. Increases in *Populus* on the landscape may be the result of edaphic factors that are only indirectly related to climate (Brubaker et al., 1983; Bartlein et al., 1995). However, a similar *Populus* zone, dated between ~11,000 and 9000 yr BP, is found in palynological assemblages from South-Central to Northern Alaska, suggesting that vegetation was responding to regional climate as opposed to local ecologies (Anderson et al., 2003). Biome modeling results also suggest that a deciduous broadleaf forest occupied large areas from South-Central to Northern Alaska (Edwards et al., 2005).

3.4. Central Alaska

Only four sites in Central Alaska show strong evidence of a YD event. An increase in herbaceous taxa at Windmill Lake (71) suggests an episode of climatic deterioration and a decrease in growing season temperature from ~10,500 to 10,200 yr BP. A similar shift in herb percentages is seen at Wien Lake (70) between ~11,000 and 10,500 yr BP. At Birch Lake (6), higher percentages of *Artemisia* pollen and a low lake-stand between ~11,600 and 10,600 yr BP indicate a decrease in moisture related to cooler and/or drier conditions. A prominent sand layer found in exposures of eolian sediment along the Nenana River (43) implies stronger wind intensity and perhaps greater storminess from ~11,100 to 10,700 yr BP.

Other LG records from Central Alaska reflect continuous warming and/or a period of warmer-than-present temperatures. At Wonder (72) and Ten Mile (64) lakes, higher elevation sites that should be sensitive to climatic changes, pollen accumulation rates are at a maximum during YD times, suggesting that conditions were perhaps optimal for the vegetation. Pollen and lake-level records from Jan (32) and Dune (10) lakes indicate moist and relatively warm climates from 12,000 to 10,000 yr BP. A subsequent rise in *Populus* pollen supports the presence of relatively warm temperatures throughout the LG.

Palynological data from numerous sites stretching from the Alaska Range to the crest of the Brooks Range (Tangle lakes (63), Rock Creek (63), Farewell (16), Eightmile (11), Harding (24), Sithylemenkat (57), Sands of Time (55), Tiinkdhul (65), Ped (49), Ruppert (53), Sakana (54), Joe (33), Kollioksak (38), Ranger (52), Screaming Yellowlegs (56), and Angal (5) lakes) exhibit high *Populus* percentages from ~11,000 to 9000 yr BP, which are thought to indicate warmer-than-present summer temperatures. Although many of these sites lack definitive chronologies, the *Populus* interval, which occurs after the establishment of *Betula* shrub tundra following initial post-glacial amelioration, shows no sign of a YD climatic reversal. At Farewell Lake, a low lake-stand, high aquatic productivity indicated by mollusk assemblages dominated by shallow-water species, pollen assemblages dominated by *Betula* and *Populus* and relatively high percentages of $BSiO_2$ provide more direct evidence for warm, dry conditions from 11,000 to 8500 yr BP. Additionally, the increased abundance of charcoal in the lake sediments suggests greater fire activity, as might be expected with warm, dry summers. At Ped Pond (49), pollen concentrations and organic carbon content increased markedly at 11,000 yr BP, indicating the establishment of a warmer and more productive environment, and indirectly a more moderate climate.

In the Norton Sound region, palynological records from Puyuk (51) and Tungak (68) lakes document the expansion of a mesic *Betula* shrub tundra between 14,000 and 6000 yr BP. Although the presence of this vegetation community implies moister and warmer summers than during the full-glaciation, the latter characterized by herb-dominated pollen assemblages representing severely cold, dry conditions, there are no indications of either a thermal maximum or a YD cooling in the pollen data. However, nearby Zagoskin Lake (74) contains high *Populus* pollen percentages between 11,000 and 9500 yr BP, suggestive of warm conditions. A drop in lake level during this interval is inferred from an increase in *Isoetes* spores and possibly demonstrates an increase in dryness but not necessarily warmth (Ager, 2003).

Pollen spectra from St. Lawrence Island (Flora Lake; 17) and the Seward Peninsula (Cape Deceit exposures (7) and Imuruk (30) Lake) are characterized by coarse sampling intervals and extremely poor chronological control. Nonetheless, these records suggest no changes in vegetation that would be associated with a cold reversal within the *Betula* period. East of Kotzebue Sound, palynological data from Squirrel (61), Kaiyak (35), and Headwaters (25) lakes reflect a transition from full-glacial herb to LG *Betula* shrub tundra, with no evidence for a climatic reversal.

3.5. Northern Alaska

This region has only two records that hint at climatic cooling during the YD. In the northwestern Arctic Foothills, evidence from the Lake of the Pleistocene (40) indicates cooling and drying between 10,900 and 10,200 yr BP, with short-term changes in palynological spectra (including the temporary disappearance of *Populus* pollen) and a decrease in organic content. Immediately after 10,000 yr BP, lake levels rose, streams aggraded, and *Populus* re-invaded the area, suggesting warming and moistening. Lower seasonal temperatures during YD times are inferred from fossil beetle assemblages from the Noatak River (46), although reconstructions of mean summer temperature never were lower than modern. Unlike other data used in this study, the beetles provide a more limited spatial resolution and are more likely than pollen to represent microclimatic conditions.

Palynological data from other northwestern Alaskan sites (Etivlik (15), Niliq (44), and Tukuto (67) lakes) document high percentages of *Populus* pollen from ~11,000 to 9000 yr BP, similar to diagrams from central Alaska. These records suggest relatively warm conditions, although chronological control is questionable. In the north-central Brooks Range and the northeastern foothills, palynological records from Oil (47), Ahaliorak (3), and Toolik (66) lakes and from Imnavait Creek (29) indicate *Betula* shrub tundra on the landscape throughout the LG, suggestive of cool but constant conditions. Unfortunately, sampling resolution is coarse and chronologies are poor for these sites.

4. Paleoclimate synthesis for Beringia

4.1. Patterns in the paleo-data

Distinctive spatial patterns during the YD emerge when sites are viewed in a regional context. Records from Eastern Siberia to the Upper Indigirka drainage are sparse with problematic chronologies. However, proxy data consistently suggest the presence of a LG climatic oscillation that not unreasonably can be inferred to be of YD age. In southern Alaska, 10 out of 15 sites reflect a clear YD event or a YD-like oscillation. The five remaining sites, all located in the eastern portion of southern Alaska, have coarse sampling intervals and/or poor chronologies. In contrast, sites in Northeastern Siberia and the single site in the Russian Far East show no evidence of cooling. Generally, the terrestrial paleo-data from these regions indicate an interval of steady climatic conditions. The apparent absence of a YD in many records from this region may be due to their relatively coarse sampling interval. Nevertheless, the density of sites, particularly in the Upper Kolyma and Priokhot'ye, and their consistent lack of evidence for a YD cooling suggest the likelihood that no climatic reversal occurred. Additionally, the high-resolution study from Elikchan 4 Lake, which shows uniform conditions throughout the LG, supports the conclusion that Northeastern Siberia did not experience a climatic reversal. Although more heterogeneous, records from Northern (seven out of nine) and Central (29 out of 33) Alaska predominantly indicate a period of uniform climate through the LG or include an interval of warmer-than-present temperatures. Some of the observed heterogeneity can be explained by local topography (see Section 4.3). Many of the records in Northern and Central Alaska have coarse sampling resolution and/or weak chronologies, but as in Northeastern Siberia, the density of records suggests a YD event as improbable.

The above patterns support the idea that the YD had a climatic complexity that goes far beyond universal cooling forced directly by changes to North Atlantic THC. The shifts in vegetation also mirror general characteristics noted for Eastern North America (ENA; Shuman et al., 2002). In non-coastal ENA, YD conditions resulted in a broad synchronicity of "non-reversing" vegetational changes and in pollen assemblages that lack modern analogs. Non-coastal areas of Beringia also display similar paleobotanical patterns with widespread and nearly synchronous establishment of deciduous trees at the beginning of the YD, a vegetation type that persisted until the Early Holocene (Anderson et al., 2003). Furthermore, no-analog pollen spectra typify YD records of Eastern Beringian (Anderson et al., 1989), and analyses of plant functional types across Beringia indicate the presence of a novel biome during YD times (Edwards et al., 2005). In contrast, coastal and near-coastal areas in both Beringia and ENA show a reversal to cooler vegetation communities. Although the specifics of the plant communities vary between Beringia and ENA, the broad features are similar, adding support to the conclusion of Shuman et al. (2002) that the YD probably is more accurately viewed as an interval of unique climatic characteristics in areas (such as interior portions of Eastern North America and Beringia) where insolation, ice sheets, and other regional influences dominated the effects of lowered SST. The following two sections explore possible mechanisms and boundary conditions that might account for the paleoclimatic patterns inferred from the Beringian data.

4.2. GCM simulations and implications for YD patterns in Beringia

Various GCM simulations, which provide explanations of physically-viable atmospheric processes and responses to large-scale forcings, indicate that the paleoclimatic variability reflected by the Beringia paleo-data is quite reasonable, and suggest that climatic changes associated with the YD may have been transmitted to the westernmost regions of Beringia via changes in westerly atmospheric flow caused by cooling of North Atlantic SST. Cooler North Atlantic SST created sea-level pressure anomalies over Eurasia that strengthen winter and weaken summer monsoonal circulation. The net result produced negative water-balance anomalies in Asia (Hostetler et al., 1999), and colder land-surface temperatures

(Cohen et al., 2001). Cooler North Atlantic SST would have restricted the transport of moisture across Eurasia (Karabanov et al., 1998). A weaker monsoonal circulation, associated with stronger mid-latitudinal upper-level flow, would have enhanced drier conditions and negative surface temperature anomalies most prominently in the warm season. Model simulations examining the effects of a shutdown of NADW and a lowering of North Atlantic and Northern Pacific SST illustrate that cooler Northern Pacific SST result in greater southerly flow on to the Southern Alaskan coast, cooler summer temperatures, and increased winter precipitation (Mikolajewicz et al., 1997; Peteet et al., 1997; Renssen, 1997).

4.3. Modern synoptic climatology, smaller-scale controls and implications for YD patterns in Beringia

Information from modern synoptic-scale climatic studies complement output from the various GCMs and provides further insight into large-scale atmospheric circulation patterns that may drive more detailed, heterogeneous paleoclimatic responses at smaller subregional spatial scales (Mock et al., 1998; Edwards et al., 2001). Different combinations of synoptic controls (e.g., Aleutian low, Siberian high) can create variable spatial patterns of climatic responses that may help explain the heterogeneous response of Beringia to climatic changes associated with the YD (Fig. 5). With the cooling of North Pacific SST, a stronger and more prevalent Aleutian low likely developed during most of the cold season, resulting in greater winter (and likely parts of spring and fall) precipitation in Southern Alaska. Interestingly, the spatial pattern of prominent YD evidence in Alaska corresponds closely with coastal areas that presently experience a prominent winter precipitation maxima, largely due to the alignment of several large mountain ranges (>3500 m a.s.l.; Mock and Anderson, 1997; Mock et al., 1998). In contrast to records south of the Alaska Range, most sites north of the range do not exhibit a YD oscillation, suggesting that the mountains played a direct role in preventing the climatic signal from extending further northward. During the YD, a stronger and expanded Pacific subtropical high was prominent in summer (Bartlein et al., 1998), which would have brought cooler summer temperatures to coastal Southern Alaska through enhanced marine onshore windflow from the southwest.

The modern climatic record illustrates the importance of smaller-scale controls for influencing climatic heterogeneity. These controls include variations in elevation, complex topography that channels windflow and convergence zones and localized mountain/valley breezes. Some of these controls may account for the heterogeneity seen in Central and Northern Alaskan records. For example, evidence for the YD is prominent at Windmill Lake in

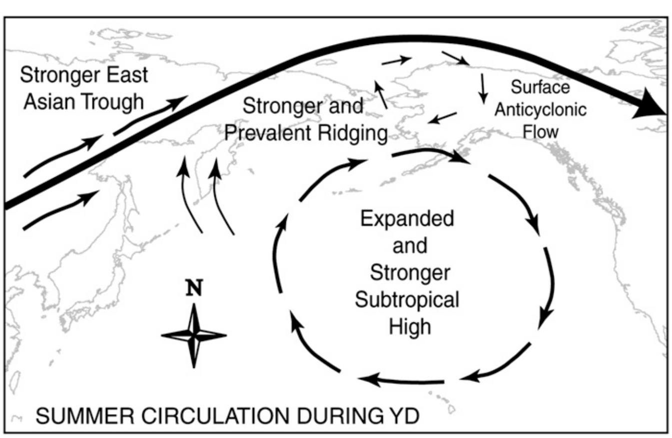

Fig. 5. Predominant synoptic-scale atmospheric circulation patterns for summers during the YD as inferred from regional patterns in Beringian paleo-data.

Central Alaska. Although Windmill Lake is inland, it is situated in a valley bisecting the Alaska Range and therefore remains sensitive to any changes being transmitted from the ocean (Bigelow and Edwards, 2001). Ocean-related influences that would cool summer temperatures were likely much weaker in the interior, with many sites experiencing somewhat warmer temperatures due to the effects of higher insolation from orbital forcing (Bartlein et al., 1991). Additionally, a strong high pressure system centered north of Alaska during summer would have created warmer and drier conditions for much of the Alaskan interior (Edwards et al., 2001) and Northeastern Siberia, and could help explain the absence of YD signals in these areas.

Northeastern Siberia is also topographically diverse and thus the potential exists that like in Alaska, coastal mountains could play a role in preventing climatic effects associated with cool North Pacific SST from extending inland during the YD. However, the Siberian topography (generally 1000–2000 m a.s.l.) is lower than in Alaska and otherwise seems to have had little direct impact on climatic variations. Farther in the Western Beringian interior, the Verkhoyansk Range, which divides Eastern and Northeastern Siberia, does not appear to have been a barrier to the YD oscillation, because evidence for the fluctuation is found on both sides of the range. Summer temperatures must have been cold enough during the YD for cooling to occur over a larger area. Modern climatic data clearly reveal an absence of secondary winter precipitation in Western Beringia, mostly due to low temperatures and the distance of the area from prominent storm tracks and moisture sources (Mock et al., 1998; Mock, 2002). Thus, enhancing the YD through a large increase in winter precipitation is unlikely. However, colder-than-present summer temperatures could account for the strong YD signal found in the westernmost sites. This interpretation is supported by palynological data from Smorodinovoye Lake that indicate the absence of *Pinus pumila* during the YD. *P. pumila* requires deep snow cover to survive the winter, and would likely have colonized the area had winter precipitation increased (Andreev, 1980; Lozhkin et al., 1993). Within modern Beringia, the contrast of cold/warm summer temperature anomalies from west to east, due to shifts in the East Asian trough, are related to the region's most prevalent synoptic climatic patterns (Mock et al., 1998). A slightly westward shift of the East Asian trough, normally situated and centered off the Eastern Beringian coast, could cause a reduction in summer temperature (Bartlein et al., 1998).

5. Conclusions

Spatially heterogeneous responses to past climatic changes as preserved in proxy data can be the result of: (1) uncertainties in the paleo-records themselves, particularly as related to chronology and sampling resolution; (2) local non-climatic factors, such as substrate and disturbance; and/or (3) climatic controls that exert influences at different spatial scales (Mock and Bartlein, 1995). In the case of Beringia, the systematic reassessment of the published lake and peat records suggests that while site quality may vary within or between regions, overall the records are sufficiently robust to ensure patterns of change are not an artifact of poor proxy data. The coherency in the mapped data and the close examination of individual records indicate non-climatic factors are not an important element in the Beringian data set, when examined as a whole. Having confidence that any patterns are not artifacts of site characteristics or data quality, we can then focus on the third factor, proposing possible mechanisms that determined YD climates in Beringia (see Sections 4.2 and 4.3).

Looking at model simulations and modern synoptic climatology, changes in SST, atmospheric circulation, and insolation appear to be the key causal elements determining the inferred Beringian paleoclimatic patterns. The overall pattern, however, is modified in some areas by topography. For example, Central Alaskan sites with evidence of a YD cooling are located to the north of valleys that bisect the Alaska Range, and apparently reflect exposure to cooler air moving from the passes into the interior. Our interpretive framework suggests Southern Alaska is most sensitive to changes in Northern Pacific SST and to the consequent shifts in atmospheric circulation. Central and Northern Alaska respond more heterogeneously to YD changes, but in general do not appear to be as sensitive to changes in SST or related atmospheric changes as are areas to the south (e.g., British Columbia and Pacific Northwest, Mathewes et al., 1993; Grigg and Whitlock, 1998; Briles et al., 2005) and east (e.g., Canadian Rockies, Reasoner et al., 1994; Gosse et al., 1995). Increases in orbitally-induced summer insolation and the presence of a strong high pressure system north of Alaska apparently caused summer conditions in much of Central and Northern Alaska and Northeastern Siberia to be warmer than present. Cool, dry conditions in Eastern Siberia likely reflect shifts in atmospheric circulation, with a prevalent East Asian trough enhancing northwesterly flow into the region (Fig. 5).

The reanalysis of Beringian paleo-data provides quality assurances that permit first steps towards determining mechanisms responsible for the observed YD paleoclimatic patterns, and as such provides a set of working hypotheses that can help focus future research. The proposed framework further supports the idea that climatic changes, especially in regions where SST influence is minimal, are spatially complex, reflecting the unique set of boundary conditions that characterized YD times. Investigations into submillennial paleoclimatic changes, even purported coolings such as the YD, may ultimately prove useful as aids for understanding thresholds, feedbacks and non-linearities within the climatic system (e.g., Alley, 2000; Mayewski et al., 2004; Rial, 2004) that will ultimately help determine regional responses to anthropogenic-induced climatic changes of the future.

Acknowledgements

This work was funded by a research grant to the University of Washington by the National Science Foundation (Grant ATM-00-117406) and grants to the Northeast Interdisciplinary Science Research Institute by the Russian Foundation for Fundamental Research (Grants 06-05-64129 and 07-05-00610a). We thank two anonymous reviewers for their comments and insights which helped strengthen this paper.

Appendix

Detailed results of site evaluations for the presence or absence of the YD oscillation

Site ID[a]	Site name	Fluctuation[b]	Sampling resolution[c]	Chronological control[d]	YD signal[e]	Proxy type[f]
1	70 Mile Lake[1]	3	2	3	4	p
2	Adak Island[2]	3	2	2	3	p
3	Ahaliorak Lake[1]	3	3	2	3	p
4	Alut Lake[1]	3	2	2	3	p
5	Angal Lake[1]	3	2	2	4	p
6	Birch Lake[1]	1	2	1	1	p
7	Cape Deceit[2]	3	3	3	3	p
8	Circle Lake[1]	1	2	2	2	p
9	Dolgoe Lake[1]	1	1	2	2	p, g
10	Dune Lake[1]	3	2	2	4	p
11	Eightmile Lake[1]	3	2	1	4	p
12	Elgennya Lake[1]	3	2	1	4	p
13	El'gygytgyn Lake[1]	3	2	1	4	p
14	Elikchan 4 Lake[1]	3	1	1	3	p, g, s
15	Etivlik Lake[1]	3	2	3	4	p
16	Farewell Lake[1]	3	2	2	4	p, g, s, d
17	Flora Lake[1]	3	3	3	3	p
18	Flounder Flat[2]	3	3	3	3	p
19	Gek Lake[1]	3	2	2	3	p
20	Glukhoye Lake[1]	3	2	3	3	p
21	Goluboye Lake[1]	3	2	2	3	p
22	Grandfather Lake[1]	1	1	1	1	p, g
23	Gursky peat bog[2]	3	2	1	3	p
24	Harding Lake[1]	3	2	1	4	p
25	Headwaters Lake[1]	3	2	2	4	p
26	Hidden Lake[1]	1	2	1	1	p
27	Homer Spit peat[2]	3	2	2	4	p
28	Idavain Lake[1]	1	2	1	1	p, s
29	Imnavait Creek[2]	3	3	2	3	p
30	Imuruk Lake[1]	3	3	3	3	p
31	Jack London Lake[1]	3	2	3	3	p
32	Jan Lake[1]	3	2	2	4	p
33	Joe Lake[1]	3	2	1	4	p
34	Juneau sites[2]	3	2	3	3	p
35	Kaiyak Lake[1]	3	2	2	4	p
36	Khomutakh Lake[1]	2	2	1	2	p
37	Kodiak Island sites[1,2]	1	2	1	1	p, s
38	Kollioksak Lake[1]	3	2	1	4	p
39	Lake Baika[1]					
	Academician Ridge[1]	3	2	3	3	p, s
	Chivyrkui Bay[1]	2	1	1	2	p
	Continent Ridge[1]	1	1	1	1	p, s
	Posolskoe Bank[1]	2	1	2	2	p

(continued on next page)

Appendix (*continued*)

Site ID[a]	Site name	Fluctuation[b]	Sampling resolution[c]	Chronological control[d]	YD signal[e]	Proxy type[f]
	Salenga Delta[1]	1	1	1	1	p, g
	Vydrino Shoulder[1]	1	1	1	1	p, d, g
40	Lake of the Pleistocene[1]	1	2	1	1	p, g
41	Lesnoye Lake[1]	3	2	2	3	p
42	Little Swift Lake[1]	2	1	1	2	p
43	Nenana River[2]	1	2	1	1	s
44	Niliq Lake[1]	3	2	2	4	p
45	Nimgun Lake[1]	1	1	1	1	p, g
46	Noatak River[2]	2	3	1	2	d
47	Oil Lake[1]	3	3	2	3	p
48	Ongivinuk Lake[1]	1	2	2	2	p
49	Ped Pond[1]	3	2	1	4	p, g
50	Pleasant Island Lake[1]	1	2	1	1	p, s, g
51	Puyuk Lake[1]	3	2	2	4	p
52	Ranger Lake[1]	3	2	1	4	p
53	Ruppert Lake[1]	3	2	1	4	p
54	Sakana Lake[1]	3	2	1	4	p
55	Sands of Time Lake[1]	3	2	1	4	p
56	Screaming Yellowlegs Pond[1]	3	2	1	4	p
57	Sithylemenkat Lake[1]	3	2	1	4	p
58	Smorodinovoye Lake[1]	1	2	2	2	p
59	Snipe Lake[1]	2	2	1	2	p
60	Sosednee Lake[1]	3	2	1	3	p
61	Squirrel Lake[1]	3	2	2	4	p
62	Suolakh peat-bog[2]	2	2	2	2	p
63	Tangle Lakes[1]and Rock Creek[2]	3	2	1	4	p
64	Tenmile Lake[1]	3	2	1	4	p
65	Tiinkdhul Lake[1]	3	2	1	4	p
66	Toolik Lake[1]	3	2	2	4	p
67	Tukuto Lake[1]	3	2	2	4	p
68	Tungak Lake[1]	3	2	1	4	p
69	Ulkhan Chabyda Lake[1]	2	2	3	2	p
70	Wien Lake[1]	1	2	1	1	p, g
71	Windmill Lake[1]	1	2	1	1	p
72	Wonder Lake[1]	3	2	1	4	p
73	Wrangel Island, Exposure WR-12[2]	3	2	1	4	p, g
74	Zagoskin Lake[1]	3	1	1	4	p

[a] Sites arranged alphabetically.
[b] Presence or absence of any fluctuation in proxy data: 1: fluctuation present; 2: possible fluctuation; 3: fluctuation absent.
[c] Sampling resolution: 1: centennial to bi-centennial; 2: multi-centennial; 3: millennial or greater.
[d] Chronological control: 1: reliable; 2: questionable; 3: poor.
[e] YD signal: 1: YD oscillation; 2: possible YD oscillation; 3: YD oscillation probably absent; 4: YD oscillation absent.
[f] Proxy type: p: palynological data (pollen percentage and accumulation rate); g: geochemical data (percent carbon and biogenic silica, $\delta^{13}C$, $\delta^{18}O$); s: sedimentological data (sediment color and composition, magnetic susceptibility, grain size, accumulation rate); d: species composition (aquatic diatoms and mollusks, terrestrial beetles).
[1] Lacustrine sediment core.
[2] Peat and/or organic silt deposit.

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