FREQUENCY DISTRIBUTION OF ^{14}C AGES FOR CHRONOSTRATIGRAPHIC RECONSTRUCTIONS: ALASKA REGION STUDY CASE

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ABSTRACT. In this study, we test the possibility of using databases of radiocarbon ages to estimate boundaries of climatic chronozones. The Alaska region was chosen and compared with chronozones of 2 European countries: Poland and the Netherlands. The study included setting up a database of ^{14}C ages published for climatic records from Alaska. Some 974 ^{14}C determinations on organic samples were selected and used to establish chronozones for the Late Glacial and the Holocene for the Alaska region. The selected data were calibrated and a summed probability density function (PDF) was calculated. The shape analysis of the constructed frequency distribution of ^{14}C dates on calendar timescales together with the assumption about preferential sampling seems to be a useful tool for establishing calendar ages for boundaries of climatic periods, i.e. chronozones.

INTRODUCTION

Commonly used chronostratigraphical boundaries proposed by Mangerud et al. (1974) are typically expressed in radiocarbon years. During the last 20 yr, the use of chronozones became less common because of the discrepancy between ^{14}C and calendar ages, and the common practice of correlation to Greenland ice records. In 1995, the INTIMATE project was initiated as a core project of the INQUA Paleoclimate Commission, which has a primary goal to establish timing of paleoenvironmental events in the North Atlantic region during the Last Termination. A protocol for time-stratigraphic correlation over the time interval 30–8 ka BP was recently published (Hoek 2008; Lowe et al. 2008). The INTIMATE Event Stratigraphy scheme was proposed as a standard against which regional stratigraphies should be compared to look for synchrony (or asynchrony) of comparable events. It is based on the new NGRIP isotopic record and associated Greenland Ice-Core Chronology 2005 (GICC05) (Rasmussen et al. 2006).

Most of the records from terrestrial and marine environments are typically dated by ^{14}C. Using the OxCal or BCal programs (Bronk Ramsey 1995, 2001, 2008; Buck et al. 1996, 1999), which provide appropriate statistical tools, it is possible to build an age-depth model and date the boundaries for single investigated sites.

In the last few years, Michczyńska and coworkers pioneered a method to establish the calendar ages for the boundaries of regional chronozones. The focus of these earlier studies was set on the territory of Poland (Michczyńska and Pazdur 2004; Michczyńska et al. 2007; Macklin et al. 2006; Starkel et al. 2006).

Michczyńska and Pazdur (2004) and Michczyńska et al. (2007) used shape analysis of probability density functions (PDFs) calculated for large sets of ^{14}C dates to reconstruct past environmental changes in Poland. Although this method was initially used to reconstruct paleohydrological conditions in Poland, they observed a general tendency of collecting samples from specific horizons, i.e. where changes in sedimentation or changes in pollen diagram are observed. Such a procedure results in high and narrow peaks in the PDF near the Late Glacial and Holocene subdivision boundaries. An extensive data set of ^{14}C dates (785 dates for peat samples and ~330 for fluvial sediments) was used

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to establish calendar ages of chronostratigraphical boundaries of climatic changes that took place during the last 16,000 cal BP in Poland (see Table 3) (Michczyńska et al. 2008).

Having developed this tool, we would like to apply it to data from various regions to see if there are any similarities in climate change patterns that can be observed between distant regions of the Northern Hemisphere. The calendar ages of regional climatic changes from part of Alaska were established and compared with the timing of changes that occurred in selected regions of Europe (Poland and the Netherlands). Alaska was chosen as a focus of this study because ecosystems of this high-latitude region are highly sensitive to climatic change.

INVESTIGATED AREA AND TIME INTERVAL

Alaska is situated in the northwest extremity of the North American continent. It can be divided into several regions characterized by different patterns of temperature, precipitation, permafrost, amount of daylight, and topographic relief. The boundaries of each of these regions should not be thought of as sharp lines of contrast but as gradual zones (Daly 2002; Shulski and Wendler 2007; http://akclimate.org/; http://www.wrcc.dri.edu/summary/Climsmak.html; http://esp.cr.usgs.gov/research/alaska/):

Arctic. The northern part of Alaska, encompassing the area north of the Brooks Range, is known as the Arctic. The local climate is severe with long, very cold winters and short, cool summers. It is influenced by the Arctic Ocean. Even in July, the average temperature in Barrow (the northernmost settlement) is 1 °C. The ground is permanently frozen (continuous permafrost) and during the summer, the soil thaws only a few inches. Precipitation is light, with many places averaging <250 mm/yr, mostly in the form of snow that stays on the ground almost the entire year. For all areas in this zone, the sun remains below the horizon from late November until mid-January, and is continuously visible from the middle of May through the end of July.

Interior. This region is isolated by the Alaska Range to the south and the Brooks Range to the north. Due to its isolation from the coast, Interior Alaska's climate is strongly continental, with high seasonal extremes. This region has the warmest summers in the state, as well as the lowest recorded winter temperatures. Average temperatures range from 22 ºC in high summer to –28 ºC in winter. The mountain ranges also limit the amount of precipitation that falls in the Interior by limiting the advection of moisture. The average annual precipitation in Fairbanks (main city of this region) is 287 mm/yr. Most of this comes in the form of snow during the winter. The permafrost is discontinuous. In the midsummer, the time between sunrise and sunset is around 22 hr, and in midwinter, 4 hr.

West Coast. The climate is maritime, influenced by Bering Sea. In this zone, summer temperatures are moderated by the open waters of the Bering Sea, but winter temperatures are more continental in nature due to the presence of sea ice during the coldest months of the year. There is no natural topographic barrier to separate this region from the Interior. The region is generally underlain by discontinuous permafrost. Annual average precipitation varies between 250 and 500 mm/yr. The mean annual temperature is below the freezing point. The daylight amount is similar to the Interior.

South-Western Alaska includes the Aleutian Islands. There are more than 200 islands in this chain of islands. They separate the Bering Sea from the North Pacific Ocean. They are generally free of permafrost. Due to the moderating effects of the ocean, it is difficult to define any seasonal periods. Precipitation ranges between 250 (Seaward Peninsula) and 2500 mm/yr (some locations between Dillingham and Bethel). The climate is maritime with mean annual temperatures above the freezing point. In June, the day length is near 22 hr and in December, 4 hr.

South-Central Alaska. This area is under a strong maritime influence and is characterized by high annual precipitation and moderate temperatures. Regional precipitation ranges from 430 mm/yr in drier areas to more than 5000 mm/yr in the coastal mountains. The first snowfall usually comes in October or November. The average annual temperature is ~5 °C. Ground near the coast is free of permafrost, and other areas of this zone are underlain by isolated masses of permafrost. In June, the day length is near 18 hr and in December, 6 hr.

South-Eastern Alaska. The climate of southeast Alaska is primarily influenced by the adjacent Pacific Ocean, and occasionally modified by dry continental air from Canada. This is the only region in Alaska in which the average daytime high temperature is above freezing during the winter months. The mean annual precipitation is 1560 mm. The zone is generally free of permafrost. Daylight hours reach 17 hr/day in June and fall to 7 hr/day in December.

Division of Analyzed Time Interval

In the paper, the following terms are used: Wisconsin, Late Glacial, Bølling, Allerød, Younger Dryas, Preboreal, Boreal, Atlantic, Subboreal, and Subatlantic.

The period from ~20 kyr until the end of Pleistocene was characterized by a great expansion of glaciers. It has been given a series of local names: Pinedale or Wisconsin (in North America), Devensian (in the British Isles), Würm (in the Alps), Weichselian (in Scandinavia and northern Europe), Vistulian (in northern central Europe), and Valdai in eastern Europe. The location of the analyzed area determined the term "Wisconsin" as most appropriate.

The term "Late Glacial" is used according to the definition from *A Dictionary of Earth Sciences* (Allaby and Allaby 1999): "the term 'late glacial' is usually applied to the time between the first rise of the temperature curve after the last minimum of the Devensian/Wisconsin/Vistulian/Würm glaciation, and the very rapid rise of temperature that marks the beginning of the post-glacial, or Holocene period."

For the Late Glacial, names of climatic zones proposed in 1935 by Jessen (see Hoek 2008)—Bølling, Allerød, Younger Dryas—and for the Holocene—Preboreal, Boreal, Atlantic, Subboreal, and Subatlantic—proposed by Blytt and Sernander (see Mangerud et al. 1974) are used. Although these zones were proposed for Scandinavia and for the British Isles, they are commonly accepted and applied more widely than originally intended. This terminology was originally developed for biostratigraphy zones, but it is frequently used in a chronostratigraphic sense, which is also the case in this study.

Environmental Changes during Analyzed Time Period

This project focused upon the last 16,000 cal BP. During the analyzed time period, one of the most important environmental changes was the global sea-level change. During the Late Wisconsin, the global sea level was about 120 m below its present position and a natural land bridge, called the Bering Land Bridge (BLB) or Beringia, linked present-day Siberia and Alaska. At its greatest extent, the land bridge was roughly 1600 km wide. Melting of glacier ice caused the sea levels to rise, gradually flooding the land bridge. During the Late Wisconsin (Late Glacial), the climate of the BLB was arid and cold. The land was not glaciated because snowfall was extremely light, and predominant vegetation was graminoid-herb-willow tundra (Ager 2003; Ager and Philips 2008). Rising sea levels had began to flood the BLB about 13,500 cal BP (http://www.ncdc.noaa.gov/paleo/parcs/atlas/beringia/lbridge.html) and climate became wetter with deeper winter snows, and moist, cool summers with dwarf birch-heath-willow-herb tundra vegetation (Ager and Philips 2008).

The abrupt climatic change—the transition from glacial to interglacial conditions—was recorded clearly for many investigated sites in the Alaskan territory. On the whole, Alaskan climate became warmer and moister than climate of the Late Wisconsin, and an almost synchronous change from a herb-dominated to shrub-dominated tundra took place (Anderson and Brubaker 1993). The later climate changes were more complex in spatial and temporal patterns. Axford and Kaufman (2004) pointed to the role of local- and regional-scale factors, especially moisture availability. These local and regional factors acted as modulators of global-scale climate forcing.

METHODS

Usually, researches choose one or a few sites and, based on results of their studies, try to reconstruct environmental changes concerning the studied region. The majority of these reconstructions are supported by ^{14}C dating; therefore, we propose another approach that is based on ^{14}C ages available from the whole region. Thus, we began by collecting information about ^{14}C dating for the selected region. After rejection of questionable dates, a frequency distribution of the dates on a calendar timescale is constructed. The only assumption in our analysis is that samples are usually taken on purpose. In other words, in the analysis the distinct tendency to collect samples from specific horizons is taken into account. The assumption was testified for Poland (Michczyńska and Pazdur 2004; Michczyńska et al. 2007).

It is a general rule to take samples for ^{14}C dating from places of visible sedimentation changes or changes in a pollen diagram. Thus, in the database for selected region there are ^{14}C dates connected with only local environmental changes, with regional or global environmental changes, as well as random ^{14}C dates, i.e. connected with dating organic material for every few centimeters in some core. If we collect data from many places, then the common signal is increased, and the signals concerning local changes (or connected with random dates) are smoothed. As a result, if there is any common signal in the chosen set, we can expect peaks in the frequency distribution of dates. We expect that dates connected with chronozones occur significantly more frequently, and therefore, they produce peaks on PDFs. Moreover, the faster the environmental changes, a more distinct boundary and a more distinct, narrow peak could be expected. Dates corresponding to such changes encompass a smaller time period.

The methods employed in this study involve construction of a database of ~1000 ^{14}C dates for organic samples collected from records of Alaska, i.e. "data mining." The ^{14}C database was compiled from dates lists published in *Science* and *Radiocarbon* journals, and from scientific papers available via ISI Web of Knowledge (see Appendix) published up to date. The next step after collecting the data was selection of dates. Excluded from the analysis were all dates suspected of contamination by younger or older organic matter (on the base of inconsistency of ^{14}C age and stratigraphy or palynology), connected with dating earthquake, volcano activity, human activity, and also dates for driftwood. In total, the database includes 974 ^{14}C dates from 469 sites (see Figure 1). The number of ^{14}C ages obtained on different types of dated material is given in Table 1.

Our task was to reconstruct chronozones on a calendar timescale; therefore, the set of ^{14}C dates was calibrated and a summed probability density function (PDF) was calculated. The culminations of the PDF represent periods of environmental changes on a regional or global scale and are helpful in identifying the chronostratigraphical boundaries on a calendar timescale. We are looking for coincidence of these peaks and localizations of chronozones (e.g. proposed by Mangerud et al. 1974) after their calibration. This method was used also for estimating calendar dates of chronozones for Poland.

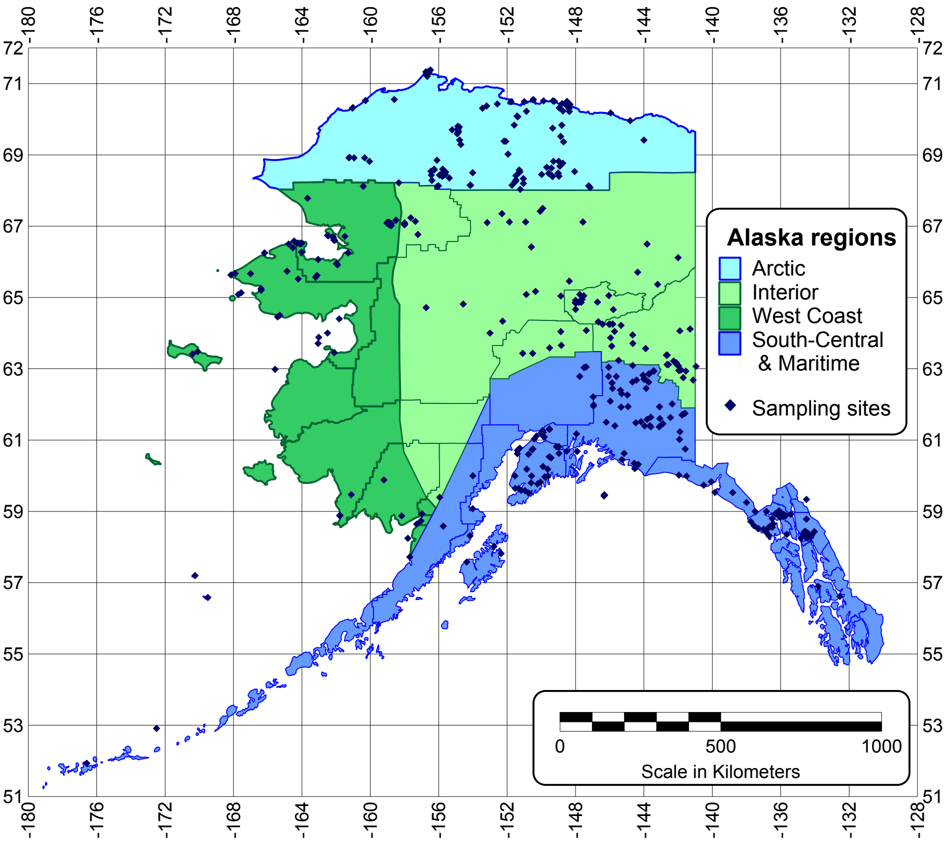

Figure 1 Alaska regions and sampling sites. South-Western, South-Central, and Maritime regions were joined together for simplification.

Table 1 Number of samples vs. dated material in analyzed set of ^{14}C dates.

Dated material	Number of samples
Wood	407
Peat	207
Organic matter	174
Plant remains	89
Bulk sediment	21
Gyttja	17
Charcoal	16
Pollen	15
Macrofossils	8
Moss	5
Seeds	5
Soil	4
Detritus	3
Clay	1
Mud	1
Root	1

Chronozones for Poland

The boundaries of chronozones proposed by Mangerud et al. (1974) were given as rounded numbers on a ^{14}C timescale. Similar chronozones for the Polish territory were proposed by Starkel (1977, 1999), but he proposed the additional divisions of Atlantic, Subboreal, and Subatlantic on 4, 2, and 3 subzones, respectively (see Table 2). Boundaries for Poland were established mainly on the basis on fluctuations in rainfall and runoff regime reflected in fluvial and other facies of continental deposits and also changes in pollen diagrams supported by ^{14}C dating of organic material from the appropriate horizons. Results of calibration of these ^{14}C ages (with an arbitrary chosen uncertainty, i.e. 50 or 100 yr) inform us roughly where chronozones could be located on a calendar timescale. More precise localization can be obtained by combining this information (probability distributions of calendar ages for chronozones) with the shape of the PDF constructed for a large set of ^{14}C dates. Calendar ages for the Late Glacial and Holocene chronozones in Poland were proposed on the basis of analysis of 2 large sets of ^{14}C dates: 785 dates of peat samples and 331 dates of fluvial sediments (Michczyńska et al. 2008) (Table 3).

Table 2 Chronostratigraphical subdivisions of the Holocene according to Mangerud and Starkel.

Name of zones	Mangerud et al. (1974) ^{14}C yr BP	Starkel 1999 ^{14}C yr BP	
Subatlantic		SA2/SA3	500
		SA1/SA2	2000
Subboreal/Subatlantic	2500		2800
Subboreal		SB1/SB2	4200
Atlantic/Subboreal	5000		5000
Atlantic		AT3/AT4	6000
		AT2/AT3	6600
		AT1/AT2	7700
Boreal/Atlantic	8000		8400
Preboreal/Boreal	9000		9300
Younger Dryas/Preboreal	10,000		10,250
Allerød/Younger Dryas	11,000		11,800

Chronostratigraphy for the Netherlands

^{14}C dates connected with dating zone boundaries for 102 pollen diagrams from the Netherlands, northern Belgium, and northwestern Germany were collected by Hoek (1997). We used his data to establish zone boundaries in calibrated years. These zones were established using the *Sequence* function in OxCal (Bronk Ramsey 2008). As values of these boundaries, we proposed to use expected values and dispersions (see Table 3).

RESULTS

The whole large set of chosen ^{14}C dates was calibrated and a probability density function (PDF) was constructed using the function *Sum* in OxCal (Bronk Ramsey 1995, 2001, 2008) and the IntCal09 calibration curve data (Reimer et al. 2009) (see Figure 2A). Similar PDFs for different climatic regions of Alaska were also constructed (Figure 2B–G).

Alaska, the whole area, 974 ^{14}C dates, Figure 2A: The division of the analyzed time period was proposed based on the shape of the constructed PDF. The clearest are the following boundaries: 11,200 cal BP, which is close to the Younger Dryas/Boreal transition (YD/BO); 9500 cal BP, which is close to the Boreal/Atlantic (BO/AT); and 2750 cal BP, which is close to the Subboreal/Subatlantic (SB/

SA). The peak near 12,850 cal BP could possibly correlate with the Allerød/Younger Dryas boundary (AL/YD); however, no distinct boundaries close to the Preboreal/Boreal (PB/BO) and the Atlantic/Subboreal (AT/SB) can be set, although there are visible changes at 10.2 and 6 ka cal BP. It is possible that the gap near 14,000 cal BP could also be connected to the European Older Dryas event.

The following periods are clearly visible as wide peaks: 15,000–13,000, ~1200, and ~400 cal BP, which might reflect the Bølling-Allerød warming, the Medieval Warm Period (MWP,) and the Little Ice Age (LIA), respectively. There are visible differences between particular regions. Due to the influence of local factors, not all changes are recorded in all the regions:

Maritime (South-Eastern Alaska), 156 ^{14}C dates, Figure 2B: The clearest boundaries are at 9500 and 2750 cal BP, which are close to the European BO/AT and SB/SA, respectively. The onset of the Younger Dryas is not distinctly visible. The values of the curve during 0–2 ka cal BP are high due to a large portion of ^{14}C dates obtained for this time period (62 dates). These data reflect changes in the local glaciers' extent.

South-Western Alaska: there were only 8 ^{14}C dates for this region and they were added to the ^{14}C dates set for South-Central region.

South-Central, 213 ^{14}C dates, Figure 2C: There are visible boundaries at: 10,200, 9500, and 2750 cal BP, which might correspond to the PB/BO, BO/AT and SB/SA boundaries, respectively. There are visible peaks at ~1200 and ~400 cal BP, which might show MWP and LIA periods, respectively.

South-Central and Maritime, 369 ^{14}C dates, Figure 2D: The shape of the PDF for the time period 0–2 ka cal BP confirms that peaks for the same period for the Maritime region reflected only local changes. A rather flat part of the curve during the Late Glacial and the beginning of the Holocene is connected with the fact that most of the landscape was buried under glacial ice during this time.

Interior, 215 ^{14}C dates, Figure 2E: There are distinct boundaries: at 12,850, 11,200, 10,200, 9500, 6000, 4850, and 2750 cal BP, which might correlate with climatic chronozones as defined for Europe (AL/YD, YD/PB, PB/BO, BO/AT, AT/SB1, SB1/SB2, and SB2/SA). There are clearly visible warming events before 13,000 and at ~1200 cal BP that can be correlated to the Bølling-Allerød and the MWP, respectively. The peak at ~400 cal BP can be correlated with the LIA. Clearly, the environmental changes in this region are the most distinct.

West Coast, 158 ^{14}C dates, Figure 2F: There is a visible warming at 16,000–13,000 cal BP that is close to the Bølling-Allerød in Europe. Any boundaries that are near the European AL/YD and YD/PB are hardly visible. The peak near 10.2 ka cal BP seems to be connected to the PB/BO boundary. There are distinct boundaries at 6000, 4850, and 2750 cal BP that might correlate to the AT/SB1, SB1/SB2, and SB2/SA, respectively.

Arctic, 232 ^{14}C dates, Figure 2G: There are distinct peaks at 13,400, 12,850, 11,200, and 9500 cal BP. The 3 latter peaks are close to the European AL/YD and YD/BO transitions and to the BO/AT. There is a visible warming at 15,000–13,000 cal BP close to the Bølling-Allerød timing. The Holocene boundaries at 5600 and 2300 cal BP seem to be shifted in comparison with the other regions and do not closely resemble the AT/SB and SB/SA boundaries from Europe. Because of the presence of continuous permafrost, there is a big risk of contamination of ^{14}C samples by older or younger organic matter for this region. It is difficult to say if the differences between the shape of the PDF for the Arctic and the rest of the regions are connected with different patterns of environmental changes in the past or with contamination.

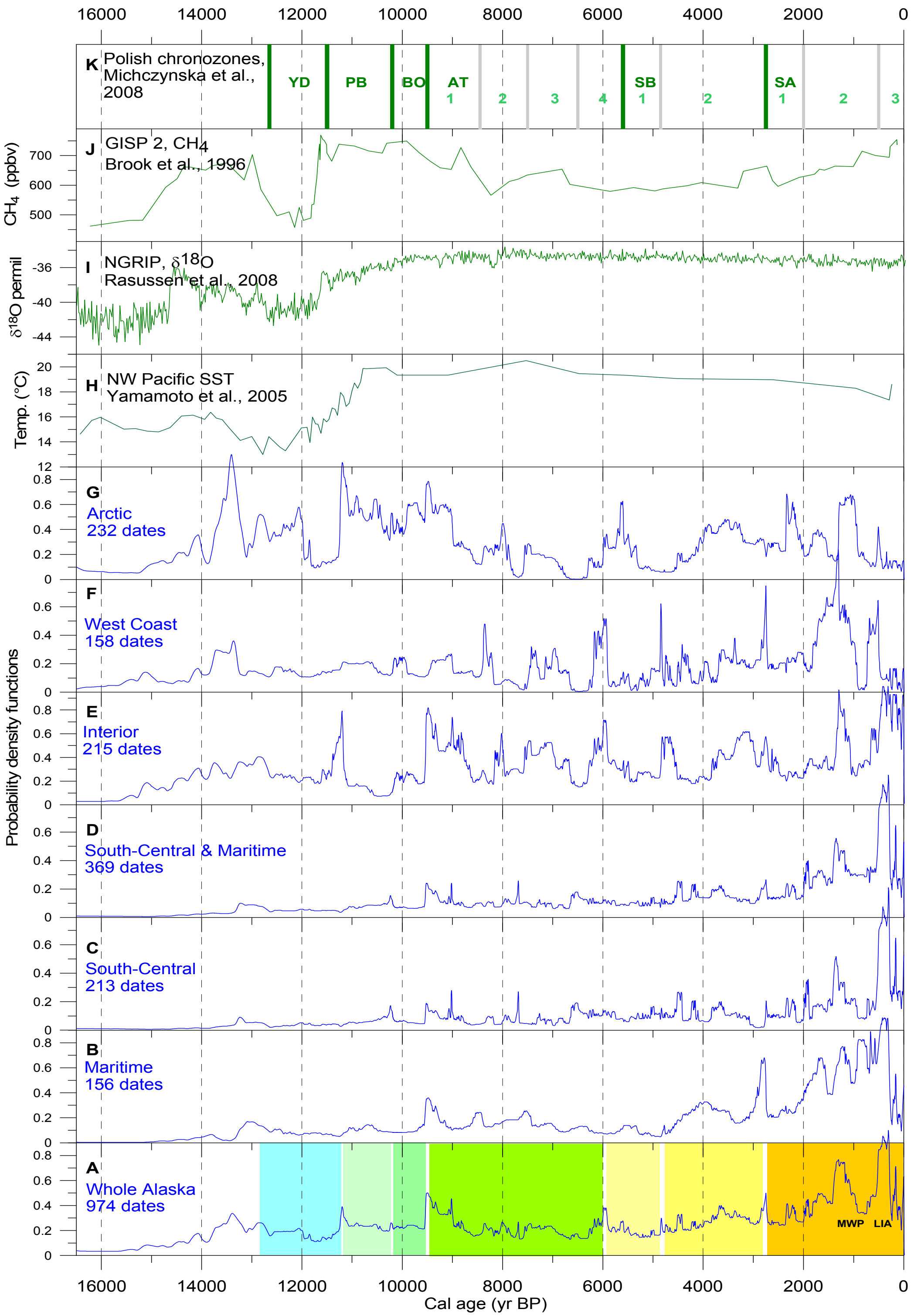

Figure 2 Probability density functions for Alaska and its different regions in comparison with environmental data. The proposed chronozones for Alaska are marked in A.

Data from the northwestern Pacific (reconstruction of SST, Yamamoto et al. 2005, Figure 2H), Greenland ice core (changes of δ^{18}O in NGRIP core and methane concentration in GISP2, Rasmussen et al. 2008; Brook et al. 1996; Figure 2 I–J), and chronozones proposed for Poland (Michczyńska et al. 2008, Figure 2K) were used to compare the division of the Late Glacial and the Holocene period into chronozones with other environmental data.

DISCUSSION

Validity of Used Dates: Possible Influence of Contaminated Samples

Almost half of dates were obtained on samples of wood (407), charcoals (16), and seeds (5), which are considered to be most suitable materials for ^{14}C dating. Although contamination of the samples cannot be excluded, the influence of incorrect dates on the shape of the probability density function (PDF) constructed for a large set of ^{14}C dates is limited. This fact was tested by Michczyńska in her PhD thesis (2003). It was shown that even in the case when 30% of samples are contaminated by younger or older organic matter (e.g. 15% of all dates are younger by 10% and another 15% of all dates are older by 10%), changes of the shape of the PDF are not significant. The experiment was repeated many times and contaminated dates were chosen randomly. Moreover, the only region for which contamination can play a significant role is the Antarctic. Nevertheless, a study based on 1 type of material could be more valid. The authors' forthcoming study in the field of reconstruction of chronozones is planned to focus on regional and interregional comparisons based on the same type of dated material.

Influence of Chosen Divisions into Regions

A great diversity in the precipitation, temperature, topography, and glacial ice cover patterns within a chosen region could result in asynchrony of chronozones from place to place (strong local effect). Such a case takes place for the South-Central and Maritime regions. Consequently, only a few boundaries are recorded in the shape of the PDFs.

Uncertainty of Established Chronozones

An uncertainty for the established chronozones expressed as a width of the peak at half of its height seems to be an acceptable solution. The authors propose to set the value of the uncertainty as 100 yr on average. The boundaries established for different regions of the Northern Hemisphere are presented in Table 3.

Alaska vs. Poland:

For detailed comparison, the frequency distributions of dates from Poland and Alaska are presented in Figure 3. The curves during the Last Glacial-Interglacial Transition (LGIT) are correlated. For both regions, a warming at 15,000–13,000 cal BP (Bølling-Allerød) is clearly visible. The onset of the Younger Dryas is better marked for Poland than for Alaska. It should be stressed that the uncertainty of the calibration curve for ages greater than 12,600 cal BP is significantly higher than for lower ages. By contrast, the onset of the Holocene is more distinct for Alaska. The changes during the YD/PB transition observed in the PDF curve for Poland are more smoothed than for Alaska. It could also be cause by the geographical coordinates: high-latitude regions are more sensitive on climate changes. For Poland, the YD/PB boundary was chosen at the mid-point of the slope of the curve. Such localization is in high concordance with boundaries established for Lake Gościąż (Goslar et al. 2000), one of the representative geo-sites selected for the European Network.

Table 3 Proposed chronozones for Alaska (this study), Poland (Michczyńska et al. 2008), and the Netherlands (Hoek 1997, changed) compared with event stratigraphy for NGRIP (Hoek 2008; Lowe et al. 2008) and Lake Suigetsu (Nakagawa et al. 2005). All boundaries are expressed in yr BP. For NGRIP boundaries, maximum counting errors (MCE) are also given in parentheses.[a]

	Alaska	Poland	the Netherlands		NGRIP event stratigraphy	Suigetsu event stratigraphy	
SA			Holocene			SGPH	
	2750	2750					
SB2							
	4850	4850					
SB1							
	6000	5600					
AT							
	9500	9500					
BO							
	10,200	10,200					
PB							
	11,200	11,500		11,800 ± 180	11,653 (99)		11,250
YD			GS-1			SGPS-1	
	12,850	12,650		12,750 ± 50	12,846 (138)		12,300
AL			GI-1a			SGPI-1a	
				13,100 ± 50	13,049 (143)		13,750
			GI-1b			SGPI-1b	
				13,420 ± 40	13,261 (149)		
			GI-1c				
				13,770 ± 40	13,904 (165)		
OD			GI-1d				
	~14,000			13,910 ± 50	14,025 (169)		13,950
Bø			GI-1e			SGPI-1c	
				14,450 ± 170	14,642 (186)		15,000
			GS-2			SGPS-2	

[a]Bø: Bølling; OD: Older Dryas; GS: Greenland stadial; GI: Greenland interstadial; SGP: Suigetsu pollen (H: Holocene; S: stadial; I: interstadial).

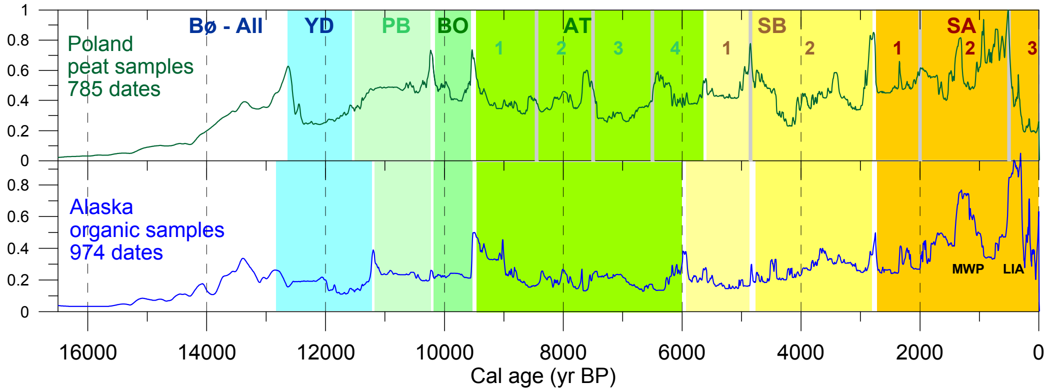

Figure 3 Comparison of the chronozones proposed for Alaska and Poland

The boundaries between the Boreal and Atlantic, and also between the Subboreal and Subatlantic are distinct for both regions (and also Alaska subregions), near 9500 and 2750 cal BP, respectively. It should be noted that the shape of the PDF curve for Alaska is highly influenced by the shape of the PDF for the Interior region; therefore, the observed synchrony between Poland and Alaska concerns mainly 2 areas with continental climate: Poland and the Alaskan Interior.

Alaska vs. the Netherlands

For the Netherlands region, only data concerning LGIT are presented in Table 3. It is interesting that the gap near 13,900–14,000 cal BP, which is visible for the Whole Alaska PDF and the PDFs of 3

Alaskan regions, Arctic, Interior, and West Coast (cf. Figure 2), correlates with the Older Dryas event recorded in the pollen diagrams from the Netherlands (cf. Table 3).

It is difficult to say if there are any offsets between boundaries marking the beginning of the cold event (European AL/YD) for these regions. From a statistical point of view, 2 results (12,850 ± 100 and 12,750 ± 50 cal BP) are in agreement, but the next boundary marking the end of the cold event (European YD/PB) for Alaska is distinctly younger (11,200 ± 100 cal BP) than the appropriate boundary GS-1/Holocene for the Netherlands (11,800 ± 180 cal BP).

Alaska vs. NGRIP

The gap near 13,900–14,000 cal BP visible for the Whole Alaska PDF and the PDFs of 3 Alaska regions, Arctic, Interior, and West Coast (cf. Figure 2), is in correlation with the GI-1d event recorded in the ice core NGRIP (14,025–13,904 cal BP). There is an excellent agreement between the ages for the onset of the cold event (12,850 ± 100 cal BP) and GI-1a/GS-1 (12,846 cal BP with maximum counting error of 138), but the ages for the end of this event in Alaska (11,200 cal BP) and GS-1/Holocene (11,653 cal BP with maximum counting error of 99) are different.

Alaska vs. Suigetsu

There is an agreement between the gap near 13,900–14,000 cal BP visible for the Whole Alaska PDF and the PDFs of 3 Alaska regions, Arctic, Interior and West Coast (cf. Figure 2), and boundary SGPI-1c/SGPI-1b (13,950 vyr BP). There is an excellent agreement between ages of the change at 11,200 ± 100 cal BP and the SGPS-1/SGPH boundary (11,250 vyr BP). There is a distinct shift between the onset of the cold event at 12,850 ± 100 cal BP and the SGPI-1a/SGPS-1 event (12,300 vyr BP).

Influence of Calibration Curve

Changes in the shape and uncertainty of the calibration curve influence the shape of the constructed PDFs. This effect can be seen in Figure 4 where results received for Alaska and Poland are presented for 2 versions of the calibration curve: IntCal04 (Reimer et al. 2004) and IntCal09 (Reimer et al. 2009). Application of the updated version of the calibration curve resulted in a shift of the onset of the cold event of the European Younger Dryas. This boundary is now marked as a lower peak (due to the higher uncertainty of IntCal09 compared to IntCal04 for ages older than 12,600 cal BP).

CONCLUSIONS

Changes in environmental conditions are often recorded as changes in the type of sediment. Preferential sampling from such horizons results in notably greater numbers of ^{14}C dates in the literature that correspond to chronostratigraphical boundaries. Shape analysis of the frequency distribution of ^{14}C dates could be useful in the reconstruction of the environmental changes. On the curve of the probability density function, chronostratigraphical boundaries are marked by peaks. The faster and stronger the environmental change, the more distinct and steeper the peaks observed.

The wide peaks at 15,000–13,000, ~1200, and ~400 cal BP, might correspond to the Allerød-Bølling warming, the Medieval Warm Period, and the Little Ice Age, respectively. The cold event during the LGIT, marked in the PDF curve for Alaska, seems to be correlated with the changes in the concentration of ^{18}O in the NGRIP ice core and with the sea surface temperature in the NW Pacific region.

The peak near 12,850 cal BP in the PDF for Alaska correlates well with the European boundary AL/YD for Poland (12,650 ± 100 cal BP) and the Netherlands (12,750 ± 50 cal BP), as well as with the GI-1a/GS-1 boundary for the NGRIP core (12,846 (138) cal BP). Higher resolution of the calibra-

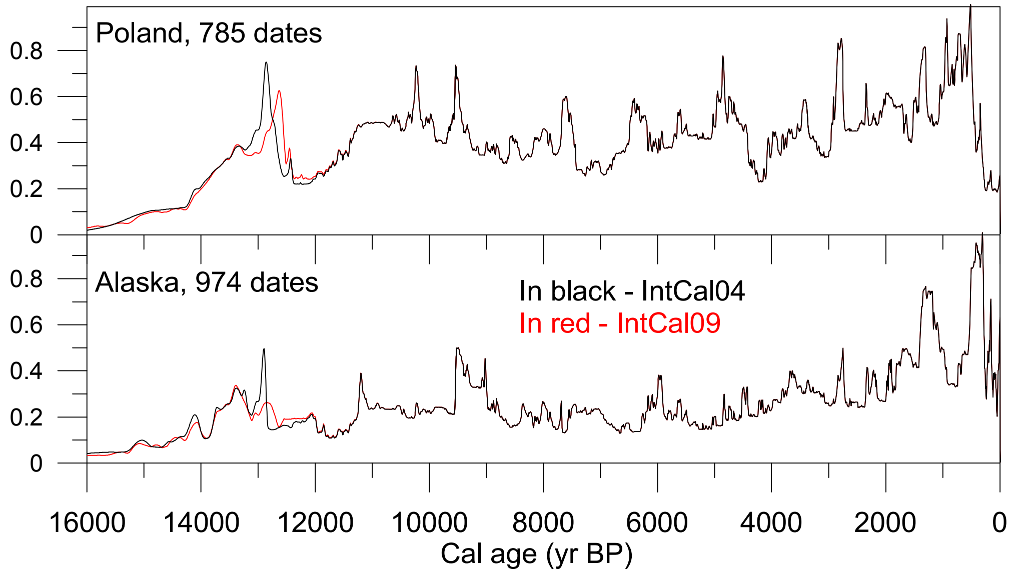

Figure 4 The influence of the calibration curve on the shape of PDFs. Changes in a course of the calibration curve and its higher uncertainty during the interval 12,600–16,000 cal BP resulted in changes of the PDFs constructed for Poland and Alaska. The onset of Younger Drays for Poland and Alaska is now shifted towards younger ages.

tion curve during Last Glacial-Interglacial Transition is needed to set more precise boundaries for this time interval.

The boundaries for the Whole Alaska PDF (11,200, 9500, 6000, 2750 cal BP) are distinctly visible and near the following European boundaries: YD/PB, BO/AT, AT/SB, and SB/SA, respectively. There is a good correlation between the established chronozones for Alaska and Poland, although they are not simultaneous. This means that environmental changes were similar for the whole hemisphere, but some shifts can be observed from region to region. Our results show synchrony and asynchrony of events that could be helpful in the discussion of abrupt climate changes.

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APPENDIX: LIST OF PUBLICATIONS CONTAINING ^{14}C DATES USED IN PDF ANALYSIS

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