Geographical extremes in the glacial history of northern Eurasia: post-QUEEN considerations

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Abstract

This paper summarizes the principal results produced by the European Science Foundation's programme, Quaternary Environment of the Eurasian North (QUEEN). These results concern the distribution of late Quaternary glaciers of different ages across northern Eurasia. The pattern of glaciation is compared with the west–east climatic gradient of the continent. Of particular significance is the coincidence of the Late Weichselian ice margin with the modern 30°C difference between the July and January mean air temperatures. The difference between west and east in the annual amplitude of air temperature did not decrease during the Pleniglacial. The asymmetry of the glacial history suggests a progressive aridification of the Eurasian North, with the result that by marine isotope stage 2 significant ice volumes could only accumulate along the Atlantic seaboard. The different climatic signals of thermochrons and cryochrons of the extreme west and east of the continent are discussed. The growth of continentality eastwards restrains the applicability of pollen proxies for climatic reconstructions.

At present, the huge Eurasian landmass displays a wide variety of environments along its northern margin. The geographical extremes of the modern situation are evident by a comparison of the west with the east along the same latitude: the mild and rainy climate of western Norway contrasts sharply with the frosty and dry climate of Yakutia, close to the northern cold pole. However, the response of this climatic asymmetry to Pleistocene global cooling and warming periods, especially to the inception and development of glaciation, has been debated. The problem has been discussed in Russian literature since the 19th century (Voejkov 1881; Gerasimov & Markov 1939; Veličko 1980). Western European textbooks focussed, as a rule, on Atlantic palaeoenvironments, and hardly ever mentioned the notable west–east climatic gradient that is distinctive of Eurasia. This is understandable as the western European peninsula of Eurasia is too small for studies of long-distance changes.

The climatic gradient has persistently been held responsible for various geographical and palaeogeographical phenomena. For example, Gerasimov & Markov (1939) believed in the decisive importance of the west–east gradient, and elaborated Voejkov's ideas into a theory of the asynchronous development of Quaternary glaciers across Eurasia. They suggested that: (1) warmer intervals of the Quaternary period in East Siberia were more beneficial for glaciation than cold intervals, (2) former West Siberian ice sheets did not exceed 500–700 m in thickness and (3) the main sources of glacial ice were mountainous areas. In the 1970s it became clear that large continental ice masses were basically contemporaneous throughout the Northern Hemisphere. Hence, the initial idea of asynchronous ice advances at two extreme flanks of the Eurasian continent was transformed into the concept of glacial asymmetry, with an eastward reduction of Pleistocene ice volume (Veličko 1980). The latter version of palaeogeographical extremes in glacial history, did not, however, question the previous conclusions about mountains as the main source of glacial ice east of the Fennoscandian ice sheet. There have been persistent attempts to theoretically reconstruct a large Weichselian ice cap over the Urals (e.g., Veličko et al. 1987), despite clear geological indications to the contrary (Astakhov 1979; Astakhov et al. 1999).

The discovery of the Kara shelf ice dispersal centre, and much thicker Pleistocene ice in Siberia than had previously been assumed (Astakhov 1976, 1979), stimulated another extreme in palaeogeographic thinking. The "continental theory" was challenged by palaeoglaciologists who disregarded the fundamental difference of oceanic versus inland environments, and simply transferred the glacial model of the smaller North American continent to the huge Eurasian continent. The resulting reconstructions suggested improbably large and contiguous circumarctic Late Weichselian ice sheets (Grosswald 1998). The maximalist model enjoyed support from geophysicists whose models needed plenty of continental ice to balance the sea level change, whereas only a few geologists were charmed by the idea.

The problem re-emerged after years of study of the Eurasian northern margin by the international research teams assembled under the European Science Foundation umbrella programme, Quaternary Environment of the Eurasian North (QUEEN), which terminated in 2004. These basically European–Russian collaborative projects, supplemented by several ventures with American participation, have, since 1993, attended to the Late Pleistocene geological history of the northern Eurasian landmass from Scandinavia to the Lena delta, and the adjacent Arctic islands and deep seas. The geochronological, sedimentological and geomorphic data that were obtained shed new light on the old palaeogeographical problem of reconstructing former ice sheets (Svendsen et al. 2004). New information on the interglacial intervals during the Pleistocene has been less spectacular.

This paper discusses the principal events in Eurasian glacial history, as demonstrated by QUEEN research, in relation to popular theoretical models and possible palaeogeographic inferences. The purpose of the paper is to draw the attention of western European geologists working in Russia to the peculiar mode in which the extremely continental environment may respond to global climate forcing, and possibly to provoke a discussion of further research themes along the lines embodied in the Arctic Palaeoclimate and Its Extremes (APEX) programme.

Modern and Holocene climatic asymmetry of Eurasia

Continents are known to have climate gradients normal to their coastlines. The huge landmass of Eurasia reveals the most pronounced west–east gradient, reflecting a transition from maritime to continental climates along any given latitude. This natural feature is often described (and taken into account by general circulation models) as an eastward increase in continentality caused by the fading transfer of heat and moisture from the Atlantic. Continentality drops again only very close to the Pacific. It is normally measured by two indirectly linked parameters: annual precipitation per square unit (P) and annual amplitude of mean monthly air temperatures, i.e., the difference between July and January means (J–J index). Maritime climates, typical for western Europe, are characterized by J–J < 25°C and P > 700 mm, whereas in the continental climates of eastern Eurasia J–J may reach 50–60°C (Fig. 1) and P < 400 mm.

Although the size of ice sheets depends first on the availability of moisture, the present-day precipitation pattern does not show a straightforward affinity to the distribution of former glaciers. Annual precipitation, being dependent on seasonal air flows, is a mobile and spatially highly variable parameter, whereas glaciation is a steady feature averaging regional conditions over centuries. The J–J index, governed mostly by radiation balance, also indirectly reflects the level of precipitation. It is a more stable characteristic and gives a pattern easily

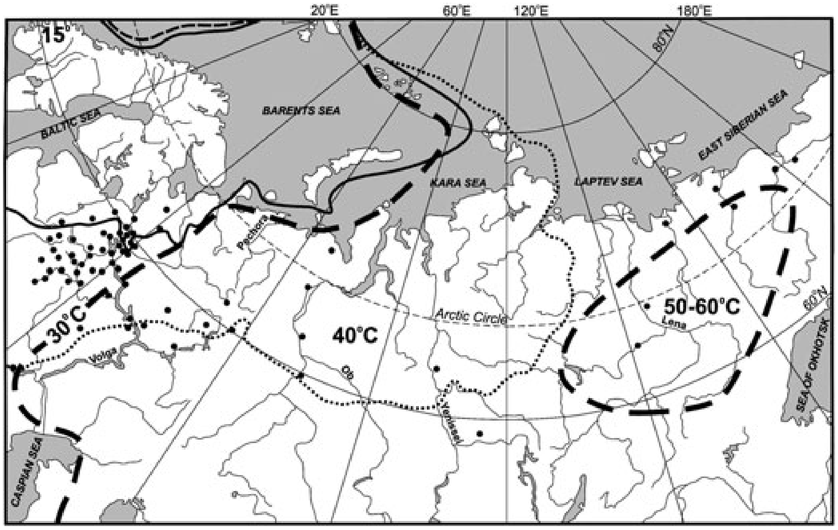

Fig. 1 The spatially changing continentality of northern Eurasia, indicating the limits of ice sheets (see Svendsen et al. 2004). The solid line indicates the extent of the last ice sheet, at about 20 Kya. The dotted line shows the Quaternary glacial maximum. Broken lines are isolines of differences between July and January mean air temperatures (Berg 1938). Black dots are thick peat deposits from the last interglacial, often referred to as "karginsky" in Siberian literature (from numerous Russian publications).

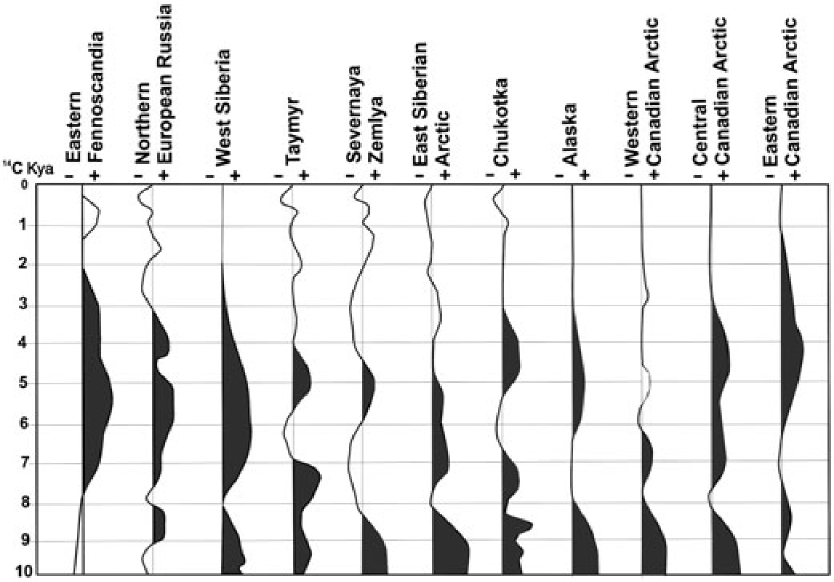

Fig. 2 Circum-Arctic change of Holocene climatic optima inferred from pollen records contained in radicarbon-dated terrestrial sediments. (Modified from Bolšijanov 2000.)

comparable with former glacial phenomena (Fig. 1). The map shows two climatic extremes of northern Eurasia: humid Atlantic coasts, with J–J = 15°C, versus the very continental climate of permafrozen East Siberia, near the cold pole, with J–J = 50–60°C.

The influence of climatic asymmetry on geological history can be more readily perceived from the circum-Arctic change of the Holocene environments. Results of integrated analyses of pollen profiles around the Arctic have provided evidence of temporal shifts of Holocene climatic optima (Bennike et al. 2001). Figure 2 shows that the Holocene optimum gradually shifted westwards from the so-called insolation maximum in East Siberia and Alaska, 9–10 ^{14}C Kya, to West Siberia 6.5 ^{14}C Kya, then shifted further westwards to Europe 5.5 ^{14}C Kya and then finally to eastern Canada around 4 ^{14}C Kya (Bolšijanov 2000). The time-transgressive Holocene altithermal suggests a similar temporal pattern for other palaeoclimatic events.

Glacial asymmetry of Eurasia

The QUEEN results have firmly established the asymmetric configuration of Late Quaternary ice sheets of northern Eurasia. The first Weichselian ice sheet that culminated at about 80–90 Kya was very small in Scandinavia, but occupied the entire Kara Sea shelf, and a good part of the present dry land above the Arctic Circle (Svendsen et al. 2004). The second ice advance at about 60 Kya covered most of Scandinavia and the Baltic Sea, and reached south of the Arctic Circle in western European Russia (Larsen et al. 2006). The early Weichselian expansion of Arctic ice sheets was accompanied by small alpine and piedmont glaciers, mostly along the western slopes of mountain ranges (e.g., Astakhov et al. 1999). The last Late Pleistocene ice sheet, roughly corresponding to marine isotope stage 2 (MIS 2, which is also called the Last Glacial Maximum [LGM] by marine geologists), covered only north-western Europe and most of the Barents shelf, leaving the central and eastern Eurasian Arctic landmass ice-free.

Figure 3 illustrates the reverse succession of the latest glacial events in Siberia versus Europe in terms of ice volume (Svendsen et al. 2004). The same pattern was recorded in the mountains of southern Siberia on the basis of luminescence dating (Sheinkman 2004). The former glaciers seem to have been progressively biased westwards in the course of the Late Pleistocene glacial cycle, i.e., the volume of each successive ice sheet distinctly gravitated further towards the North Atlantic margin. In this respect the Eurasian continent markedly differs from North America, where larger ice sheets were fairly symmetrical in relation to the longitudinal continental axis (Flint 1971). This difference is doubtless a result of the pronounced increase in continentality in eastern Eurasia, whereas in North America, because of the modest size of the landmass, continentality never developed to the same extent, and did not prevent the oceanic influences from the Atlantic and Pacific joining forces to produce the largest ice sheets of the Northern Hemisphere.

The relationship between ice sheet size and the climatic gradient can be seen in Fig. 1, in which the earlier, basically wet-based, Scandinavian glaciations are confined within the present-day J–J isoline of 30°C. The "grey zone" of cold-based glaciations of the West Siberian type

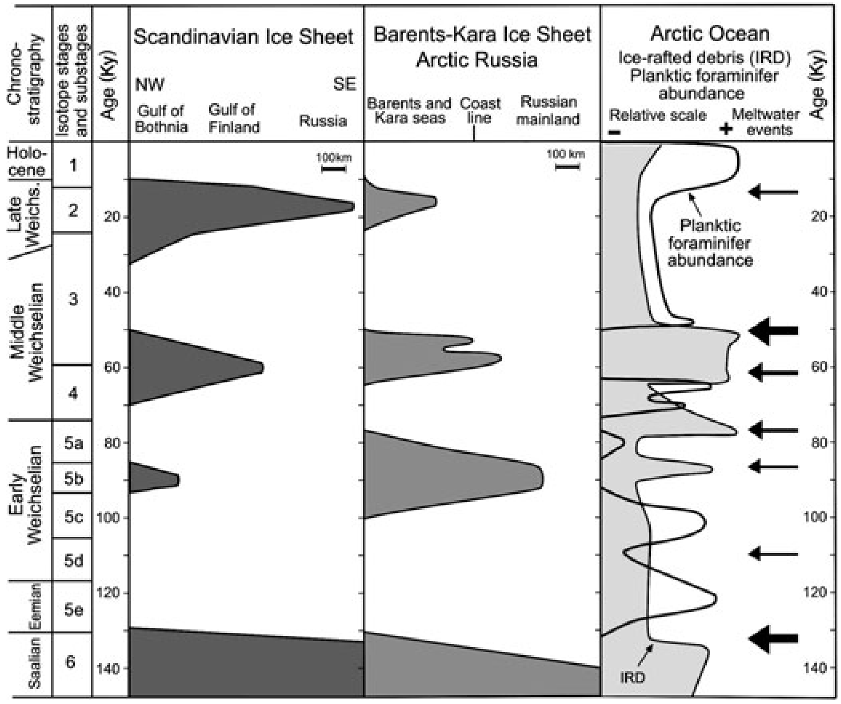

Fig. 3 Time–distance diagram of late Quaternary ice sheets of Eurasia (modified from Svendsen et al. 2004.) The right-hand column shows results of the analysis of bottom sediments from cores of the Arctic Ocean; arrows indicate freshwater fluxes inferred from the isotope composition (Spielhagen et al. 2004).

is located within J–J values of between 30 and 45°C. Further eastwards, where J–J values grow up to 50–60°C, former ice sheets were replaced by thick conservative permafrost, which is virtually underground glaciation without interglacials. The active surficial glaciation of the Atlantic seaboard may be viewed as the extreme versus the passive subterraneous glaciation of East Siberia. Even within the glaciated area there are two extreme cases: predominantly wet-based ice sheets in western Europe versus cold-based Siberian glaciers in the "grey zone" with a J–J of 40–45°C. This does not mean that an ice sheet can form in West Siberia at the present level of precipitation, but the map suggests that this tendency was present throughout the Pleistocene. The extreme modes of the Eurasian glaciation are also evident from a comparison of the fluted and drumlinized subglacial surface of Europe versus the West Siberian glaciated plains, which lack eskers and drumlins, but which are full of glaciotectonic and stagnant ice features (Astakhov et al. 1996).

The climatic gradient is also detected in the deglaciation pattern. The continental climate and thermal inertia of the deeply cooled Siberian lithosphere, with reduced geothermal gradients, led to very slow, retarded deglaciation, and to the preservation of fossil glacial ice in the Arctic for tens of thousands of years (Astakhov et al. 1996). It is significant that the Siberian permafrost persistently grew, irrespective of intermittent glacials and interglacials: even under the present Laptev Sea it is at least 400 Ky old (Romanovskii et al. 2004). Such short retreats from the general Quaternary cooling trend as the Holocene warming were only temporarily able to remove the upper skin of the thick permafrost by oceanic transgression and thermokarst. In contrast, the thin-skinned permafrost in the Atlantic realm was an ephemeral feature that only sporadically affected glacier behaviour. The short-lived marginal permafrost could not impede the fast deglaciation during Atlantic terminations.

Post-QUEEN results

Post-QUEEN results have emphasized the asymmetric distribution of Late Pleistocene ice volume. The change in paradigms is especially evident from the revision of the age of the youngest alpine morainic ensembles, which were traditionally attributed to MIS 2 (the radiocarbon time span of ca. 25–10 Kya), and correlated everywhere with the European Weichselian and the classical Wisconsinan of North America (Kind 1974). During QUEEN research it became obvious that the largest alpine glaciers east of Fennoscandia developed and vanished well before MIS 2. The MIS 2 age of the alpine maximum correlation was refuted by optically stimulated luminescence dating in the Urals (Svendsen et al. 2004), and by bottom sediments cores from deep lakes in the Taymyr Peninsula distally barred by the alpine morainic loops. The pollen data from postglacial sediments in southern Taymyr proved to be incompatible with the idea of the MIS 2 age of the underlying till (Hahne & Melles 1997).

Later on, Mangerud et al. (2006) dated boulders in the glacial troughs of the Polar Urals using the cosmogenic isotope ^{10}Be, and found that values around 20 Ky are confined to moraines not further than 1 km distal from a present-day glacier. Further downstream, boulders were intact for 50–60 Ky. Finally, horseshoe-shaped alpine moraines in the Verkhoyansk Mountains, the stratotypic area for the youngest "Sartan" Siberian glaciation , yielded optically stimulated luminescence ages exceeding 50 Ky (Stauch et al. 2007). It seems that by MIS 2 the climate of the northern margin of the continent became so dry that glaciers could not survive, even in the mountains.

Thus, the latest results stress the insignificant role of mountainous areas as ice sources during the Pleistocene. This conclusion is in harmony with the well-known fact that Middle Pleistocene glaciers overrode the Ural Mountains and the mountains of central Siberia (Astakhov 2004), and with the periglacial evidence of an extremely dry Late Pleistocene climate in East Siberia (Hubberten et al. 2004; Sher et al. 2005).

Asymmetry of non-glacial environments

The west–east gradient is supposed to be less pronounced in periglacial environments governed by a uniform continental climate during sea lowstands. The mammoth tundra-steppe (called a "hyperzone" by Veličko [1973]) extended across all of Eurasia and the dry Arctic shelves. Along the margin of the Late Weichselian ice sheet there is a wide belt of aeolian sand dunes and niveo-aeolian coversands, traced from the Netherlands to central Russia (Zeeberg 1998), and beyond to the south-eastern shores of the Barents Sea (Astakhov et al. 2007). A much wider periglacial zone is marked by sheets of cold loess with ice-wedge casts. These features are very similar along all of the last Scandinavian ice margin. However, Weichselian continental climates with permafrost in western Europe were certainly more humid and less frosty than in East Siberia.

Much drier conditions of the Late Pleistocene periglacial landscapes in East Siberia are recorded by the Yedoma-type subaerial formation of thick silts with long syngenetic ice wedges, which is sometimes called the "Ice Complex". The traditional interpretation of this formation by Russian permafrost scientists as waterlain is hardly applicable, as it conflicts with the monotonous granulometric and mineralogic composition, the mantle-like occurrence and the predominance of xerophilous flora and tundra-steppe fauna. Investigators who specially studied the East Siberian loess-like silts arrived at a more plausible origin of these sediments as mostly aeolian, and deposited in a harsh continental climate (Tomirdiaro 1980; Péwé & Journaux 1983).

Most interesting are the palaeoclimatic indicators recently studied in the Upper Pleistocene icy silts of the Lena delta (the Bykovsky Yedoma). The oxygen isotope composition of long syngenetic ice wedges reveals extremely cold winters: mean January temperatures 7–8°C lower than today for the interval of 60–10 Kya (Hubberten et al. 2004). On the other hand, insect assemblages testify that summers were 6–8°C warmer than today in an arid environment with a precipitation level close to that of Antarctica. The aridity, rather than the summer temperatures, prevented the landscape from being forested during the LGM (Sher et al. 2005). These temperature deviations—winters that were 7–8°C colder and summers that were 6–8°C warmer than today—mean that the Late Pleistocene J–J index for the east Arctic coastlands was about 55–60°C, i.e., 15°C higher than the present continentality. The implication is that the extremely continental climate of mountainous East Siberia (Fig. 1) during the last glaciation spread over the dry Arctic shelf.

The continentality in the Pleniglacial of north-western Europe, measured from former frost cracks and insect assemblages, gave J–J values from 28 to 33°C, decreasing to 20°C during the final arid Pleniglacial after 20 Kya (Huijzer & Vandenberghe 1998). This means that the difference in continentality of about 25–28°C between the Arctic and Atlantic coasts during the coldest phase of the Weichselian Pleniglacial was practically the same as at present. There are not enough data to estimate the LGM J–J value in the East Siberian mountains, where J–J now reaches 60°C. The continentality of the time around 20 Kya probably exceeded this value.

The structure of interglacials is more mysterious, but the strong west–east gradient is also evident in warm intervals. The density of geologically studied peat deposits dating from the last interglacial, west of the J–J 30°C isoline, is spectacular not only in western Europe but also in central Russia (Fig. 1). But, their number decreases eastwards. Between the Urals and Yenisey only three thick (ca. 1 m) peat lenses originating in the last interglacial are known, whereas present-day peat bodies (in places up to 10-m thick) occupy about 400 000 km^2 in West Siberia. According to Smith et al. (2004), the West Siberian peatlands contain 7–26% of all terrestrial carbon stored during the Holocene—indicating a tremendous contrast between the last and present interglacials.

The meagre volume of interglacial peats in Siberia cannot be explained solely by the scarcity of investigators, as there is no lack of marine interglacial sites. The distribution of peat deposits in Fig. 1 can be related to the much drier interglacial climate in Siberia. Despite the well-known fact that Eemian Atlantic water penetrated deep into the Taymyr Peninsula, the interglacial assemblage of small mammals in Transuralia is patently from an arid environment (Maleeva 1982). Also, the lack of forest fauna in East Siberian warm intervals has been intriguing for a long time (Sher 1991). Several interglacial peat deposits are recorded in the maritime lowlands of East Siberia (Fig. 1). Still, the latest palaeobotanic data from the New Siberian Islands indicate an Eemian climate significantly drier when compared with the present day (Kienast et al. 2006). This looks like another extreme versus humid climate of the classical Eemian interglacial of western Europe (e.g., Zagwijn 1996).

In general, the west–east climate gradient appears to have been more pronounced during the last interglacial than in glacial and present-day environments. This conclusion does not fit with the estimates, based on pollen analyses, of Eemian climate in Siberia as having been more humid (Velichko et al. 1991). Local palynologists are, however, more cautious about estimating precipitation based on pollen spectra. They note that computerized general circulation models agree better with a diminished precipitation in the last interglaciation of East Siberia (Lozhkin & Anderson 1995). East of the Urals, the diversity of plant taxa decreases, further limiting the applicability of palaeobotanic data for palaeoclimatic reconstructions. In addition, chronological control of warmer intervals of the Late Pleistocene in Siberia, based on spurious “finite” radiocarbon dates, is very poor (Sher 1991; Sher et al. 2005), as is evident from other geochronometric data (Astakhov 2006).

Extending the Late Pleistocene phenomenon of increasing aridity in Siberia back through geological history calls for caution. The wet climate of the Likhvin interglacial (the Holsteinian of central Russia) with Singil flora and forest elephants is well known, and is readily traceable to West Siberia, where huge alluvial plains with remnants of Pacific-type vegetation reflect a climate more humid than the present one. No reliable climate indicators are known from interglacial terrestrial sequences in East Siberia.

Palaeogeographic and stratigraphic inferences

After the QUEEN studies of the last glacial cycle in northern Eurasia (Svendsen et al. 2004), it became evident that the northeastern shelves and coastlands of the Arctic Ocean were the first to experience the cooling impact of the ice age and to form extensive ice sheets. With the continentality increasing through a glacial cycle, i.e., precipitation and temperature progressively diminishing, Arctic and Siberian ice sheets were waning, but subterraneous glaciation was growing. In western Europe this trend is perceived to be a result of progressive cooling. In terms of the entire continent, the leading trend of glacial history looks like a progressive aridification of the northern margin (which was previously suggested by Velichko for the Late Pleistocene). The Late Weichselian ice sheet may be considered as a byproduct of such development, which eventually resulted in a lopsided glaciation that was restricted to the westernmost Eurasian margin. The ice barrier growing in Scandinavia and on the western Barents Sea shelf probably amplified the aridification of the rest of the continent.

In discussing the problem, it is necessary to take into account the quality of palaeoclimatic signals for distinguishing cryochrons and thermochrons, which in the Siberian Arctic differ from the simple relation “cold–warm”, as has been accepted in Europe. The climate of Arctic Siberia has always been cold, even during the thermochrons when the treeline could reach the coast. However, during global interglacials the Arctic Ocean encroached far onto the low Eurasian margin, thereby changing the extremely continental climate of Siberia into a less continental one. The higher annual temperatures were mostly to the result of milder winters, whereas the increased precipitation and cloudiness could lead to even colder summers during interglacials, thereby decreasing the J–J value. The growth of bogs and arboreal communities was accompanied by more active thermokarst. In contrast, cryochrons were manifested by greater amplitudes of annual temperatures, a replacement of limnic/palustrine and fluvial sedimentation by aeolian processes, a decreasing number of hygrophilous species, and a growing diversity of cryoarid flora and fauna. In such an environment the principal signature of a thermochron is not temperature. It is basically indicated by decreased aridity and a greater organic content in the mineral mass. Summer temperatures, being predetermined by cloudiness rather than by the annual temperature background, can hardly indicate thermochrons in Siberia. Palaeontological evidence for Siberian cryochrons suggests drier and better heated soils than those found in present-day cloudy summers (Sher et al. 2005).

In simplified terms, we conclude that whereas in the extreme west of Eurasia a change from interglacial to full glacial meant changing a warm and wet climate to a cold and dry one, in the extreme east it was instead a cold and dry climate that became doubly cold and dry.

The west–east change of climatic parameters influences other environmental elements, such as vegetation, as exemplified by the pollen diagrams in Fig. 2. The westward temporal shift of Holocene pollen optima shows unequivocally that pollen-based environmental chronotaxons of north-western Europe, such as Boreal, Atlantic, etc., not to mention regional Pleistocene subdivisions, are not applicable to the east of the continent. Their use (or rather misuse) by pollen analysts for Siberia introduces unnecessary noise into the discussion, and may confuse geologists.

The asymmetric pattern of late Pleistocene glacial history means that the upper glacial sedimentary complex of different regions fits into different chronostratigraphic brackets. It is late MIS 5 in the north-east, dominated by the Kara Sea ice dispersal centre, late MIS 4 in the Russian European north-west, where the Barents Sea ice had an influence, and is MIS 2 in the realm of the Fennoscandian glaciation. This pattern, taken as a model for earlier glacial cycles, may help to resolve some stratigraphic problems. The available geological data suggest that the ultimate drift limit (the margin of the Pleistocene maximum glaciation) is spatially diachronous. There is some evidence that this limit is pre-Holsteinian in central Siberia, and is younger (i.e., it corresponds to MIS 8) in West Siberia (Astakhov 2004). The Saalian ice maximum of Kara Sea origin, which is MIS 8 in western Siberia, is naturally replaced by the Fennoscandian Moscow glaciation in European Russia, which happened during MIS 6. The pattern repeats throughout glaciated Europe: the Dnieper ice advance of MIS 8 in the Ukraine is replaced by the classical Saalian MIS 6 of western Germany and the Netherlands (Ehlers & Gibbard 2004).

The drift limit in European Russia coincides with the margin of the oldest Don ice sheet (MIS 16), which advanced to the 50th parallel, i.e., 1500 km from the south-eastern edge of the Baltic Shield (Velichko et al. 2004). However, in western Europe pre-Elsterian tills appear only in Denmark at 56.5°N, just 200 km south of the Scandinavian Mountains (Houmark-Nielsen 2004). The very asymmetric position of the Don lobe margin, more than 2000 km from the centre of the Fennoscandian ice dome, can be explained by an influx of additional glacial ice from the north-east (Veličko et al. 1987), i.e., from the Arctic ice dome located on the Kara shelf and adjacent plains. In post-Holsteinian times a similar mighty ice invasion from the north-east over half of the Russian Plain probably occurred during MIS 8, whereas the next ice advance of MIS 6 was plainly dominated by the Scandinavian source (Astakhov 2004; Velichko et al. 2004).

Perspectives for future research

The results obtained so far still have far to go for a final solution. Even the best studied Pleistocene in the extreme west (Great Britain) poses a number of riddles, such as the location of the Middle Pleistocene ice limits. We certainly need much more data on the extreme eastern flank of glaciated Eurasia. For example, the mechanism of inception of glaciation in the High Arctic during Pleistocene ice ages is not known because of a lack of geological data. It is not clear whether the Kara Sea shelf was first covered by inland ice resulting from the eastward shift of precipitation, or whether the ice-cover of the shelf originated from saline water as a result of the extreme cold. The MIS 2 and MIS 4 ice limits in the QUEEN reconstruction (Svendsen et al. 2004) seem too speculative for the Kara Sea shelf, and need further investigation. Any fresh data from the floor of the Kara Sea would be welcome.

There is hardly any doubt that in East Siberia the amplitude of Pleistocene climatic swings was considerably smaller than on the Atlantic seaboard. However, if the mode of ice sheets shrinking to the east is more or less clear, the fading biotic signal of interglacials still awaits proper study and measurement, especially as these relate to the transition from thermochrons to cryochrons. Although the new drilling results from deep East Siberian lakes are spectacular, they are not enough. To better understand peculiar environments of the interglacials in the extreme east we need more detailed sedimentological and palaeontological descriptions from both lake cores and natural sections throughout the Russian Arctic.

The diminished amplitude of Pleistocene environmental changes in the east poses a serious problem in terms of employing appropriate climatic indicators. For example, the discrepancy between the pollen record and magnetic and luminescence age models in the best-studied sequence of Lake Elgygytgyn in Chukotka is puzzling. The boundaries between palynological "warm" and "cold" stages seem to deviate far from the prescribed chronostratigraphic brackets (Brigham-Grette et al. 2007). It is possible that conventional palynological approaches to palaeoclimate reconstructions are not adequate for East Siberia. As climatic reconstructions from scarce remains of monotonous Siberian vegetation are often ambiguous, looking at other proxies, such as Arctic palaeosols and insect assemblages, is advisable. Considerable work has already been carried out on the oxygen isotope composition of fossil ice in Siberian permafrost (Vasilčuk & Kotljakov 2000), but this method has not yet exhausted its potential for climatic reconstructions.

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