Modelling of Late Pleistocene climatic hazards in the estimation of risk for the future abrupt climatic deterioration

N. Gerasimenko, O. Bonchkovskyi *(Taras Shevchenko National University of Kyiv),* ***I. Kovalchuk*** *(National University of Life and Environmental Sciences of Ukraine)*

SUMMARY

The aim of the study is a quantitative estimation of the scale of changes in palaeoclimatic parameters that occurred at the interface between the short-lived cold and warm events during the Late Pleistocene, and, particularly, at the late phases of the last interglacial. The latter is regarded as an analogue of the modern interglacial, and, thus, the modelling of climatic parameters of short and abrupt events of the past is a useful tool for estimation of possible future climate change. Two independent methodologies for palaeoclimatic reconstructions were applied in the same deposits, corresponding to the thresholds in climatic regimes: the transition from the last interglacial to the early glacial, and the interfaces between warm interstadials and stadials of the last glacial. One methodology is based on pollen data (the climatogram approach) and another reveals climatic indices on the basis of analogy with the modern cryogenic structures distribution. The studied sites are located in N and NE Ukraine, and the results obtained show the existence of climatic hazards (the drop in MAAT, T7, and, particularly, in T1 and precipitation). The quantitative palaeoclimatic parameters demonstrate the necessity for elaboration of future climatic scenarios for assessment of risks and socio-economic adaptations within societies in the modern temperate latitudes.

Introduction

The problem of climate change became most important only during recent decades. Traditionally, studies have been directed at the estimation of the scale of modern climatic warming. Nevertheless, recent research projects within the International Panel of Past Global Changes are focussed on the study of abrupt short-lived climatic changes (*e.g.* Dansgaard-Oeshger cycles during the Late Pleniglacial, the transitions between interstadials and stadials, short-term climatic events at the end of the last interglacial *etc*.). In terrestrial archives, these events are reflected in changes of pedogenic processes, intensity of sedimentation rate, or in drastic alternation of soil formation and loess accumulation followed by vegetational changes recorded by pollen data. Quantitative estimation of the scale of corresponding changes in palaeoclimatic parameters is regarded as being a useful tool for modelling of future climate change amplitude, assessment of risks and elaboration of socio-economic adaptation.

Methodologies for the quantitative reconstruction of palaeoclimatic indices on the basis of pollen data has been elaborated over recent decades (Grichuk, 1989; Guiot *et al*., 1990; Klimanov, 1985; Nakagava *et al*., 2002 *etc.*). Some of them have been applied to the palaeoclimatic interpretation of pollen data from Ukraine (Bolikhovskaya, 1995; Bezus'ko *et al*., 2011; Rohozin *et al*., 2019 *etc*.). The most reliable approach in these methodologies relies on indicator species in the pollen record, *i.e.* plants with known climatic affinities. The other methodology for quantitative climate reconstruction, which is also strongly based on the principle of uniformitarianism, is the revealing of the palaeoclimatic indices of the stadials, with a use of modern cryogenic structures distribution (Romanovskyi, 1993; French, 2007; Vandenberge, 2013; Jin *et al*., 2016; Bertran *et al*., 2017). The idea of this paper is to compare the results of the two independent methodologies for palaeocimatic reconstructions obtained in the same set of deposits, corresponding to the thresholds in climatic regimes, and to mutually verify the results.

Material and methods

The study cases are located in the N and NE Ukraine, where diverse forms of cryostructures opened from the former ground surfaces, which existed at the transition between warm and cold times. The aim of the investigation was to compare palaeoclimatic indices between two consecutive warm/cold phases instead of comparing those of glacial and interglacial maxima. Abundant pollen and cryogenesis proxy-data have been obtained within the same excavation from the sections Vyazivok (Haesaerts *et al*., 2016), Muzychi and Stary Bezradychi (Gerasimenko, 2006), Stayky (Rousseau *et al*., 2011). The new interpretation of cryogenesis is based on the recent re-investigation.

The quantitative reconstruction of palaeoclimates has been obtained with a use of a climatogram methodology firstly developed by Grichuk (1989). The graphs of extreme climatic parameters for growth of each indicative species of the vegetation, represented in the pollen diagram, have been constructed in the Descartes' coordinate system. The indicative species in our case include broad-leaved taxa and bushes, spruce (*Picea alba*), larch, juniper, microthermal plants *(Betula nana, B. fruticosa, Lycopodium dubium, Botrychium boreale*) and xerophytes (*Ephedra distachya, Artemisia* sp.). A superimposition of these graphs allows a revealing of a single climatic area (with a uniquely possible diapason of climatic parameters) in which all the taxa revealed in pollen diagram could grow together.

Concerning the palaeocryogenetic methodology, the modern cryolithozone is subdivided into the regions dependent on continuous, discrete, sporadic and isolated (of 'island' type) permafrost (Romanovskyi, 1993). A particular set of genetic types of cryogenic structures and textures is typical for each of these regions. The boundary between the continuous and discrete permafrost regions corresponds to a zone with an annual temperature between -5° C and -8° C (Romanovskyi, 1993; Smith & Riseborough, 2002; Van-Vliet Lanoe, 2009). A discrete cryolithozone is replaced by isolated (of 'island' type) where there is a mean annual temperature of -3° C (Van-Vliet Lanoe, 2009). The southern boundary of permafrost corresponds to areas with a mean annual temperature of -2..0° C (Романовский, 1993), though in northern China, the permafrost is described as occurring where there is an annual temperature of +1° C (Jin *et al.,* 2016). Formation of frost wedges and solifluction is possible beyond the permafrost boundaries if the mean annual temperatures are 0.. +3° C (Romanovskyi, 1993; French, 2007). It had been proposed (French, 2007) to delimit the extent of the periglacial zone with the annual isotherm of +3° C which would make its area much more extensive than that of the permafrost zone *sensu strictu*. In palaeocryology, the Index of Relative Climatic Severity (Irs) is used to represent the ratio between the mean January temperature and mean July temperature (Nechayev, 2010). V. Nechayev had proved that Irs -1.0 corresponds to the northern boundary of the cryolithozone, and Irs -2.0 and the isotherm +14℃ indicate the southern boundary of continuous cryolithozone (Nechayev, 2010). He also has shown that the July isotherm +16°C corresponds to the southern boundary of the discrete permafrost region. These parameters enable reconstructions of the mean annual, the mean January and July palaeotemperatures. Nevertheless, they cannot be regarded as absolute, being frequently dependent on local lithological and geomorphological factors.

Table 1 *Reconstruction of climatic parameters between two consecutive warm (W) and cold (C) phases of the Late Pleistocene based on pollen proxy-data*

Times	**Loess-palaeosol sequence**	**t_1**	**t_7**	**t annual**	**Precipitation, mm**	**Irs**
bg_1	Stayky	-10..-25℃	+15…+16℃	-3…+1℃	200-500	-0,63…-1,67
vt_3	Stayky	-10…+5℃	+16…+20℃	+5…+8℃	500-800	
ud_1	Stari Bezradychi	-10…-25℃	+15…+16℃	-3…+1℃	200-500	-0,63…-1,67
pl_3	Stari Bezradychi	-7…+3℃	+17…+20℃	+6…+11℃	500-800	
pl_{1b1-b2}	Muzychi	-14…0℃	+16…+18℃	+3…+5℃	400-500	0…-0,88
pl_{1b1}	Muzychi	-7..+3℃	+18…+20℃	+6…+11℃	500-800	
ts	Vyazivok	-10…-17℃	+15…+16℃	-1…+2℃	300-500	-0,63…-1,1
kd_{3b1}	Vyazivok	-4…+3℃	+18…+22℃	+7…11℃	600-1000	

Results

The Late Pleistocene framework (Veklitch *et al*., 1993) is subdivided into short-living cold and warm phases following Matviishina *et al*., 2010. Correlation with MIS is given according to Gerasimenko (2006). Application of the climatogram methodology to the pollen results from the above-mentioned sites allows one to obtain the following data (Table 1).

The cryogenic features of Tyasmyn unit (MIS 5-d), located in palaeodepression, form a generally regular system of bowl-shaped and undulating textures (Fig. 1c). Supposedly, they were primarily formed as thermal contraction cracks under cold and significantly arid climate. Later on, under wetter conditions involution processes occurred caused by saturation of the deposits by moisture. The thermal contraction cracks could have already been weakened zones, and, thus, they were subjected to cryogenic loading. Thermal contraction cracks and involutions caused by small-scale loading are not a reliable indicator of the permafrost (Romanoskyi, 1993; Vandenberghe, 2013; Bertran *et al.,* 2017). However, the cryogenic origin of bowl-shaped and undulating textures had been proved empirically (Murton, French, 1993; Vandenberghe, 2013). Presumably, during the Tyasmyn times, the Vyazivok site was located near the southern boundary of the permafrost belt, perhaps in the area of deep seasonal freezing, with the following climatic parameters (Table 2).

The subunit 'pl_{1b1-b2}' (corresponding to the cool Monteigu event in Europe) includes periglacial structures similar to ground wedges, up to 1 m in depth (Fig. 1b). Such features can be formed both under deep seasonal freezing or sporadic permafrost (Romanovskyi, 1993). Considering the relatively small scale of the thermal contraction cracks in the site, the formation of ground wedges more likely occurred under deep freezing (see palaeoclimatic indices in Table 2).

The periglacial features of the Uday unit (MIS 4) are structures transitional between ground wedges and ice wedge casts (Fig. 1d). Such features occur within the area of isolated and sporadic permafrost, (Van Vliet-Lanoe, 2009). The reconstructed palaeoclimatic indices (see Table 2) clearly correlate with those from pollen data (see Table 1).

The slope location of the Stayky section probably hampered development of large cryogenic features during early Bug times (MIS 2-a), although ice-wedge pseudomorphs of that time were widespread at that time in other sites of northern and, particularly, western Ukraine. At Vyazivok (the Omel'kove site in the palaeodepression), the ice-wedge cast, filled with Vytachiv soil, reaches 2 m in depth (Fig. 1a). Ice-wedge casts formed under continuous permafrost or in the northern part of discontinuous permafrost region where mean annual temperatures are lower than -4° C (Burn, 1990), or even -5° C (Romanovskyi, 1993). Thus, these palaeoclimate reconstructions are proposed (see Table 2).

Table 2 *Reconstruction of climatic parameters during the cold phases of the Late Pleistocene based on palaeocryogenic indicators*

Times	**Loess-palaesol sequence**	**t_1**	**t_7**	**t annual**	**Irs**
bg_1	Vyazivok (Omel'kove)	-25…-30°C	+13…+14°C	-5…-6°C	-2
ud_1	Stari Bezradychi	-20…-25°C	+15…+16°C	-4…-2°C	-1,5
$pl_{1b1-1b2}$	Muzychi	-10…15°C	+16…17°C	-1…+3°C	<-1
ts	Vyasivok (Borysenkove)	-10…15°C	+16…17°C	-1…+2°C	<-1

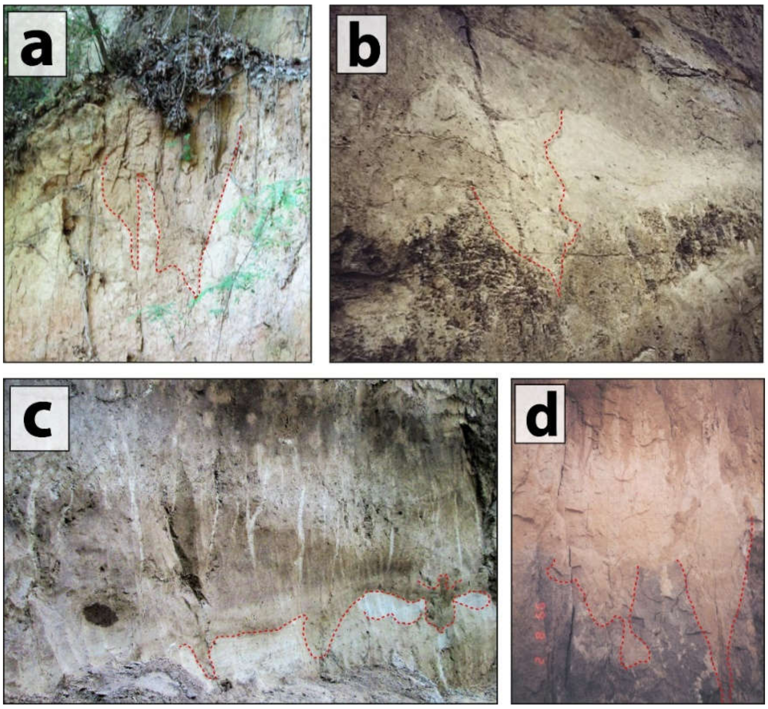

Figure 1 *Palaeocryogenic features in the site studied.* ***a*** *– ice-wedge cast (from Bug times) at Omel'kove;* ***b*** *– ground wedge (from 'pl_{1b1}-pl_{1b2}' cold phase) at Muzychi;* ***c*** *– regular involutions textures (from Tyasmyn times) at Vyazivok;* ***d*** *– ground wedges (from Uday times) at Stari Bezradychi*

Conclusions

The modelling of palaeoclimatic indices for cold phases with two independent methodologies has demonstrated very high similarities in the results obtained. Thus, modelling of palaeoclimatic indices for warm phases can be also trusted. Somewhat lower temperatures and higher indices of climatic severity are shown on the basis of palaeocryogenic modelling. The reason is that the latter reflects only local conditions whereas pollen results represent a wider regional setting (including the existence of refugia for arboreal vegetation). The amplitudes of MAAT at the transition between warm and cold phases reached 8-10°C, and it was even larger for the mean January temperatures (15-18°C colder during the stadials). Despite the amplitude for the mean July temperature not being so high (2-6°C), the obtained data show that most strong climatic hazards occurred at the interface between the short-living cold and warm events during the Late Pleistocene. The transition from the last interglacial (which is widely accepted as an analogue of the modern interglacial) to the beginning of the early glacial was one of the most drastic intervals, followed by a drop in MAAT of 6-9°C, in mean T_1 – of 13°C, mean T_7 − of 3-6°C. The reduction in precipitation was larger than during other studied short-lived events – from 300 to 500 mm. According to calendar varve chronological data, obtained elsewhere from lake deposits, these changes occurred rapidly and abruptly. The existence of such evidence demonstrates a threat of the possible similar events in future, and a necessity to elaborate adequate socio-economic adaptations within societies in the modern temperate latitudes.

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