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Biological proxies recorded in a Belukha ice core, Russian Altai

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Abstract

Different biological proxies such as pollen, cysts, and diatoms were identified and quantified in the upper part of a Belukha ice core from the Russian Altai. The ice core from the Belukha glacier collected in 2001 (4062 m a.s.l., 49°48′ N, 86° 34′ E) was analyzed with annual resolution in the period 1964–2000. We used daily data of the frequency of synoptic patterns observed in the Northern Hemisphere along with daily data of precipitation to identify the main modern sources of biological proxies deposited at the Belukha glacier. Our analyses revealed that main sources of diatoms in the Belukha ice core are water bodies of the Aral, Caspian, and North Kazakhstan basins. Coniferous trees pollen originated from the taiga forest of the boreal zone of West Siberia and pollen of hardwoods and herbs from steppe and forest steppe vegetation in the Northern Altai and East Kazakhstan. Cysts of algae and spores of inferior plants were transported from local water bodies and forests. The identified source regions of the biological species are supported by back trajectory analyses and are in good agreement with emission source regions of the trace species in the ice core.

1 Introduction

The analysis of biological species in ice cores provides a valuable tool for the reconstruction of climate dynamics, regional vegetation, biological productivity, and forest fire history (Eichler et al., 2011; Mitrofanova et al., 2012; Nakazawa and Fujita, 2006). Plants and algae are characterized by specific seasonal growth and pollen production. Diatoms and chrysophycean algae are abundant in different waterbodies during spring and autumn months, coniferous trees flower mainly in late spring to early summer, hardwoods and herbs at the end of spring and in summer. This seasonal occurrence of different species can be used as additional and complementary tool to conventional methods for dating of an ice core (Nakazawa et al., 2004, 2005; Uetake, 2006; Santibanez et al., 2008). The vast majority of biological objects are assumed to be deposited onto the glacier surface mainly with precipitation, but not through dry deposition because of the coincidence of seasonality in precipitation and pollen and algae production. Therefore, atmospheric circulation patterns together with data on precipitation can give insight about sources of biological proxies in the ice layers. The Altai glaciers located at the most continental northern periphery of Central Asia are the most typical inland glaciers (Fig. 1). This region is equidistant from all the oceans and is affected by the major northern Eurasian circulation systems, i.e. the westerly jet stream and the Siberian High. The Altai mountains are located on the boundary between contrasting climatic and vegetation zones, i.e. the boreal forest zone in the north and the vast steppe belt of Kazakhstan to the west and south-west, and Mongolia to the south and south-east.

The Russian part of the Altai mountains in South-West Siberia, the most continental northern periphery of the Central Asian mountain system and the southern periphery of the Asian Arctic basin is an ideal area for the analysis of climatic and environmental records. The Atlantic, Arctic and Pacific Oceans are considered to be the external moisture sources for this territory. Internal moisture sources refer to evaporation from continental sources, such as the closed Aral and Caspian basins, or convection from local basins, subjected to increased continental recycling (Aizen et al., 2005, 2006). Moisture transferred from the Mediterranean and the Black Seas to the Altai mountains, is also considered to be evaporated from the internal moisture source. Thus, the Altai glaciers additionally to climatic and environmental records store information on internal and external hydrological cycles, and proxy records of biological species for the Altai region and northern Eurasia as a whole.

Ice cores from glaciers in the Altai mountains have been proven to be invaluable archives of past Eastern European air pollution (Olivier et al., 2006; Eichler et al., 2012), temperature changes in Siberia (Henderson et al., 2006; Eichler et al., 2009a; Okamoto, 2011) and variations in forest-fire activity and biogenic emissions from Siberian boreal forests (Eichler et al., 2009b, 2011).

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In the Altai region, glaciers are located above the tree line and the zone of alpine vegetation in the nival-glacial belt (Galakhov and Mukhametov, 1999), therefore all biological species found in glacial ice originated in other areas. Thus, atmospheric conditions and atmospheric circulation pattern over the Altai and adjacent areas during the vegetation seasons of biological species are important for interpreting proxy records of biological species in the Altai glaciers.

In this work, we investigate the relationship between concentrations of different biological proxies (pollen, cysts, and diatoms) in an ice core from Belukha glacier in the Russian Altai (4062 m a.s.l., 49°48′ N, 86°34′ E) and types of dominant atmospheric circulation, providing the highest amount of precipitation in the Altai Region. In a previous study pollen was already investigated in this ice core covering the time period 1250–2001 (Eichler et al., 2011). The analysis revealed that the most remarkable vegetational shift during the investigated 750 yr in the Altai region was a distinct decline of *Pinus sibirica* forests and a strong expansion of the *Artemisia steppes* around AD 1540–1680, following very dry conditions and a period of exceptionally high forest-fire activity. However, this previous study was based on low-resolution and discontinuous pollen data only, with one sample covering about 30 yr.

Here, we provide a high-resolution analysis of biological species in the Belukha ice core with annual resolution for the period 1964–2000. Using the classification of circulation mechanisms of the Northern Hemisphere (Dzerdzeevskii, 1968, 1969) and instrumental data of daily precipitation from the Kara-Tyurek weather station located close to Belukha the atmospheric circulation patterns providing the highest amount of precipitation were identified for years with maximum and minimum concentrations of biological proxies in the ice core. The analysis of the obtained results allowed to identify the main sources of biological proxies deposited onto the glacier.

2 Environmental setting and data sources

2.1 Regional settings

The Altai mountain range has a Northwest to Southeast extension of ∼ 2100 km and is located on the boundary between Russia, Kazakhstan, China, and Mongolia. This region exhibits the highest degree of continentality in the world. The high-mountain part of the Altai (Belukha glacier, Katunsky ridge, Fig. 1) investigated in this study is characterized by a decrease of the mean annual precipitation near the snowline along the W-E axis from 2000 mm to less than 500 mm (Naroznyi and Osipov, 1999). As a result, the altitude of the snow line rises from 2400 m a.s.l. in the western part of Katunsky ridge to 3350 m a.s.l. at the Mongolian border. The main precipitation season in the Altai is in summer, whereas winter (December–February) accounts for less than 5 % of the annual precipitation (Henderson et al., 2006). This is due to the prevailing stable Siberian High in winter and the predominance of cold and dry arctic air masses. In summer humid air masses from the Atlantic Ocean and recycled moisture from Central Asian sources are the main sources of precipitation (Aizen et al., 2005). In spite of the arid climate, the high altitudes of the ridges (up to 4506 m a.s.l., Belukha east summit) are favorable to glacier formation (Revyakin et al., 1979).

2.2 Sources of the meteorological data

For climatic analysis, we used 70 yr long-term meteorological daily data on precipitation from the Kara-Tyurek (49°57′ N, 86°29′ E; 2600 m a.s.l.) weather station located 15 km northwest of the Belukha (RIHMI-WDC, 2012). Meteorological data from this station agree well with data of the Ak-kem weather station located 10 km north of the Belukha, but in contrast to the Ak-kem station the Kara-Tyurek instrumental data are continuous for the period 1940–2001. Among all Altai weather stations, the data from these two stations have the highest correlation with air temperature and precipitation at Altai glaciers (Revyakin et al., 1979; Galakhov and Mukhametov, 1999).

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3 Methods

3.1 Methods

The drilling site is located on the Belukha glacier in the Russian Altai Mountains. In July 2001 a 139 m long ice core was retrieved from the glacier saddle between the Belukha east and west summit (4062 m a.s.l., 49°48′26″ N, 86°34′43″ E) (Olivier et al., 2003). The ice core was transported frozen to the Paul Scherrer Institute (PSI), Switzerland, for sampling and glaciochemical, diatom, spore, and pollen analyses. Each ice-core section with a length up to 70 cm (diameter 7.8 cm) was processed in the cold room at −20 °C. For cutting and decontamination a band-saw with stainless-steel blades and Teflon-covered tabletops and saw guides were used. Outer core parts (0.5–1 cm) were used for $\delta^{18}O$, ^{210}Pb, ^{3}H, diatom, spore, and pollen analyzes. Inner sections were taken for analysis of the major ions and trace elements.

3.2 Dating

Applying a combination of different dating methods the ice core was found to cover the period AD 1250–2001 (Eichler et al., 2009). The time scale was derived using the ^{210}Pb record, a three-parameter annual layer-counting methodology, and a nonlinear regression (Haefeli, 1961) through the reference horizons related to the maximum of nuclear weapons testing (1963 – ^{3}H maximum) and different volcanic eruptions (Henderson et al., 2006; Olivier et al., 2006; Eichler et al., 2009). Volcanic horizons are marked by non-dust SO_4^{2-} ($exSO_4^{2-}$) concentration maxima and corresponding minima in the temperature record. The dating uncertainty is one year for the period 1964–2000 investigated in this study.

3.3 Analyses of diatoms, spores, and pollen

31 ice-core samples were prepared for the analyses of diatoms, spores, and pollen. Sample processing was carried out using standard hydrobiological methods (Wetzel

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and Likens, 2000). About 0.3–0.5 kg ice was melted in a pre-cleaned glass container and subsequently the melt water was filtered (membrane filter, pore size 1 µm). The filter was rinsed with approximately 5 mL ultra-pure water (Milli Q, 18 MΩ cm quality). The biological objects in the suspended sample were counted using the counting chamber "Nazhotta" with a volume 0.085 mL and a light microscope (Laboval 4) at a 600× magnification. The results were expressed as unit or cell abundance using the formula:

$$N = n \cdot V_1 \cdot (V_2 \cdot V_3)^{-1} \times 1000^{-1} \quad (1)$$

where N – number of biological objects, units l^{-1}; n – number of biological objects in the counting chamber; V_1 – volume of the concentrated sample, mL; V_2 – volume of the sample, mL; V_3 – volume of the counting chamber, mL.

Subsamples of biological material were dried on coverslips, coated with Au–Pd, and observed in a HITACHI S-3400 N scanning electron microscope for species identification.

3.4 Classification of circulation mechanisms in the Northern Hemisphere (outside of tropics)

To describe the atmospheric circulation patterns over the Altai region we used daily data on the frequency of synoptic patterns observed in the Northern Hemisphere (Dzerdzeevskii, 1975) for 6 areal sectors including the Siberian region. This classification was adopted by the World Meteorological Organization (WMO) and described by Barry and Perry (1973). In the framework of this classification, it's assumed that fluctuations in atmospheric circulation are considered as the main component of climate variability and typical location and movement of cyclones and anticyclones occur regularly. Based on the analysis of synoptic daily maps (hPa 500), 41 elementary circulating mechanisms (ECMs) were identified. The important feature of the ECMs is that they are seasonal in nature. Characteristic indicators of the ECM identification were the presence or absence of blocking processes in the hemisphere, their quantity and direction

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as well as the amount and direction of cyclones came from South (from Mediterranean, Black and Aral Sea). The border between the regions of high and low pressure passes along the isoline 1015 hPa. Each ECM has a unique cyclone and anticyclone trajectory scheme and description of fluctuation for period 1899–2008 (Dzerdzeevskii, 1968; Kononova, 2009).

All identified ECMs were split in 13 types and 4 groups (Table 1, Fig. 2). The first group ("zonal") includes two types (types 1 and 2 – anticyclone over the North Pole; "blocking processes" (Arctic invasion) are absent; 2–4 outlets of southern cyclones). The second ("zonal disturbance") group includes five types (type 3, 4, 5, 6, 7 – high pressure on the Pole, one blocking process over the Hemisphere and 1–3 outlets of southern cyclones). The third group ("northern meridional") includes five types (type 8, 9, 10, 11, 12 – high pressure over the Arctic, 2–4 blocking processes and 2–4 southern cyclone outlets). The fourth ("southern meridional") group has only one type (type 13) that is characterized by cyclone circulation over the Arctic as a result of cyclonic activity in the Arctic front associated with the outlets of occluded cyclones from the south to the high latitudes. Such processes occur during all seasons: there are only 3 southern cyclone outlets over the Hemisphere in winter, while 4 outlets happen in summer.

This used classification of atmospheric circulation patterns is the longest one (1899–2008). It takes into account the diversity of the circulation processes during all seasons for the study area, including their rare coming from the east. Therefore, the use of this classification for Altai Region is most preferable relative to other regional classifications of macrocirculation processes developed for Central Asia or for the winter period of Altai (Popova, 1972; Narozhnyi et al., 1993; Subbotina, 1995; Aizen et al., 2004–2006).

4 Results

The different biological species identified in the Belukha ice core, including diatoms, pollen, cysts of algae and spores of inferior plants are summarized in Table 2. The

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flowering and sporulation periods of the identified species between March and November (Fig. 3) correspond with the main precipitation season in the Altai.

To determine the atmospheric processes that contribute to the deposition of biological objects at the Belukha glacier in the period 1964–2000, we compared the changes in the amount of precipitation in the Altai region at different types of ECM for years with maximum and minimum concentrations of biological proxies in the ice core. For this purpose for years with the highest concentration of biological proxies, we identified the types of atmospheric circulation pattern providing the higher amount of precipitation in the period of flowering and sporulation relatively to the average of these types for the corresponding circulation period. It appeared that there was no or significantly less precipitation under selected types of circulation than the average in years with minimum concentration of biological proxies. The studied time period 1964–2000 included two circulation periods for the Siberian region; the first lasted until 1980, and then it was replaced by the second one ("Zonal circulation period") during 1981–2008 (Kononova, 2009). Since the maximum concentration of all identified biological objects in the ice core are within the period 1980–1990s, the calculation of average precipitation values for various types of ECM was performed for the period 1981–2001. A further justification for the use of this period only is that pollen productivity of individual plant species within the same plant communities can vary from year to year depending on the climatic conditions. However, pollen productivity for years within the dominant zonal circulation regime revealing similar climatic conditions (Bezuglova et al., 2012) is assumed to be not significantly different.

4.1 Diatoms

Diatom algae are not abundant in the Belukha ice core and have a weak biodiversity. We identified the following species: *Achnanthidium minutissimum* (Kütz.) Czarnecki, *Pinnularia borealis* Ehr., *Fragilaria ulna* (Nitzsch) Lange-Bertalot var. *ulna, Hantzschia amphioxys* (Ehr.) Grun., *Navicula cryptocephala* Kütz., *Encyonema minutum* (Hilse) Mann. Both *H. amphioxys* and *P. borealis* were most often and best preserved among

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them. The largest number of *P. borealis* and *H. amphioxys* was observed in the layer when diatoms in total had the maximum number (Table 2, Fig. 4). It could be explain by coming more dry periods just after the humid ones, because these species are benthic and can be transported with an air mass from the bare littoral zone of different waterbodies. In other layers mostly *H. amphioxys* was more abundant. We did not find specific (rare or endemic) diatom species. Most of diatom species were pennate forms living in bottom communities (phytoperiphyton or phytobenthos) of littoral zone in lakes and water streams. According to their geographical distribution they belong to the group of cosmopolitic forms. Valves of diatoms from the catchments can be transported by wind over thousands of kilometers. For example, frustules of fossil diatoms from Pleistocene sediments located on the south of Sahara were transported with air mass and fell down with the rains from time to time in London (Ross, 1988).

The ice-core total and different species of diatom record for the period 1964–2000 is shown in Fig. 4. The most pronounced concentration maxima and minima occur during the period 1982–1984 and 1995–1997, respectively. Types of ECMs leading to higher precipitation in 1982–1984 compared to the average (period 1981–2001) are presented in Table 3. Characteristics and trajectories of these ECMs including the example of dynamic scheme of type 10a are given in Table 4 and Fig. 5. The analysis of these data shows that four ECMs (2b, 5a, 8b(s) and 10a) provide major precipitation in the years of maximal concentration of diatoms in the ice core. At the same time these types of circulation showed no or considerable less precipitation in years when diatoms were absent (1995–1997). During the diatom minimum year 1997, precipitation within type 10a was considerably higher than average. However, this precipitation occurred during the winter season, when nearest water bodies (the main source of diatoms) were covered by ice. The correlation coefficient between number of diatom in the all layers of the ice core and total amount of precipitation at four predominant types of ECM (2b + 5a + 8b(s) + 10a) in the period 1980–2000 is quite high ($r^2 = 0.63$, $p < 0.01$)

Thus, for period 1980–2000 most of diatoms were transported to the Belukha glacier by cyclones moved over the Black Sea, the Aral and Caspian basins as well as over

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the southern Ural and northern Kazakhstan. Water bodies of these regions are thus, major sources of diatoms in the Belukha glacier.

4.2 Pollen of coniferous trees

Pollen of coniferous trees are the most abundant biological objects in the Belukha ice core, i.e. Siberian pine (*Pinus sibirica*), Scot's pine (*Pinus sylvestris*), and Spruce (*Picea obovata*). Due to two special air sacs pollen grains of pine can be transported up to 1000 km. Pine pollen of *Pinus sylvestris* and *Pinus sibirica* ripens in June-July. Pollen of spruce (*Picea obovata*) is two times bigger and heavier than pollen of pines, its air sacs are smaller and it can not move so far. Spruce pollen ripens in June. We consider that pollen of spruce origin from local spruce stands, growing in mixed forests in the valley of Chuya River (Ogureeva, 1980). Pollen of birch (*Betula*) was also found in ice samples, but rarer than conifer pollen. The season of birch flowering is May. Its pollen can be transported up to 400 km. and the closest birch forests are located in 200–300 km west.

The concentration record of conifer tree pollen during the period 1964–2000 is presented in Fig. 6. Maximum concentration falls on 1983, whereas a minimum was detected in 1986 and 2000. The analysis of ECM demonstrated that the larger amount of precipitation in 1983 (compared to 1981–2001) was during the predominated types of circulation 8d(s), 11d, and 7b(s) (Table 5). Here, we need to point out that in 1983 more than two thirds of precipitation under types 8d(s), 11d, and the whole precipitation under type 7b(s) was during the flowering season of pines, while in 1986 the major precipitation of 8d(s) occurred in the autumn and winter periods. The correlation coefficient between concentrations of conifer tree pollen in the all layers of the ice core and total amount of precipitation at the predominated types of circulation 8d(s), 11d, and 7b(s) in the period 1980–2000 is 0.61 ($p < 0.01$).

The origin and trajectories of the major circulation processes transporting pollen of conifer trees to the glacier are presented in Table 6. Figure 7 demonstrates the dynamic scheme of the 8d(s) type of atmosphere circulation. The data from Table 6 and

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Fig. 7 show that the major amount of precipitation in spring-summer of 1983 occurred at the Belukha glacier during ultra-polar invasions, when air masses arrived the Altai after passing above the large taiga zone of West Siberia. During this year considerable amount of precipitation fell on the Belukha glacier also due to formation of local cyclones on the periphery of the powerful Asiatic anticyclone (Az). Thus, we can conclude that the main sources of conifer pollen in layers of the Belukha glacier were taiga forests of North-West Siberia and local mountain forests. Since spruce pollen (*Picea obovata*) is too heavy and cannot be transported over longer distances, it originates most likely from local spruce forests growing in the Valley of the Chuya River.

4.3 Cysts of algae and spores of inferior plants

Cyst of chrysophycean algae and spores of ferns and lichens were found to be present in the ice core mainly by forms with a smooth surface. It is known that in eutrophic water bodies as well as in shallow pools smooth forms mostly prevail. This is different in oligotrophic and deep pools, where forms with different elements on the surface dominate, that provides their floating in the water column (Bazhenova et al., 2012). Similar to diatoms cysts of chrysophycean algae and spores of inferior plants can be transported over hundreds to thousands kilometers

The concentration record of chrysophycean algae cysts and inferior plant spores in the Belukha ice core is presented in Fig. 8. Maximum and minimum concentrations were found during 1995–1997 and 1984–1986, respectively. During the maximum years only three types of ECMs occurred (3, 6 and 12a), revealing higher than average precipitation (compared to 1981–2001). However, during types 3 and 6 precipitation was also higher than average in the minimum years (1984–1986 yr). For this reason, these types of ECMs were excluded from the analyses. Thus, the type 12a is most probably the main type of ECM controlling the transport of cysts to the Belukha (Table 7); the correlation coefficient between concentrations of chrysophycean algae cysts and inferior plant spores in the ice core and amount of precipitation at 12a type of circulation is 0.55 ($p < 0.01$) for the period 1980–2000. Under this type of circulation,

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a powerful anticyclone formed above the Asiatic part of Eurasia blocks the movement of western air masses (Fig. 9). As a result, during such periods the main precipitation in the Altai originates from local cyclones (Table 8). The ECMs of this type most often are formed during the transition from the cold to the warm season, when the arctic cyclone reaches its maximal power, and in southern areas the underlying surface is heated enough. Thus, the local water bodies and forests are probably the main sources of chrysophycean algae cysts and inferior plants spores.

4.4 Pollen of hardwoods and herbs

Pollen of hardwoods and herbs (including pollen of *Artemisia*, Cyperaceae, Asteraceae, and Poaceae families) is less abundant in the Belukha core. The pollen maximum in the ice core was observed during 1983–1986, while in the period of dominant zonal circulation (1981–2001), a complete absence of pollen was observed in 1982, 1987, 1990, 1995–1997 (Fig. 10). Table 9 represents the ECMs, leading to higher than average precipitation in 1986 and no precipitation in 1982 and 1987. We excluded the type 5b from the analysis, since in 1986 the precipitation under this type of ECM occurred only in October, when plants did not bloom. Thus, only two summer types of ECMs – 8c(s) and 8d(s) might control the transport of deciduous and herb pollen to the Belukha glacier (Table 10); the correlation coefficient between concentrations of pollen in the ice core and total amount of precipitation at 8c(s) and 8d(s) types of circulation is 0.68 ($p < 0.01$) for the period 1980–2000. Both types of circulation are characterized by powerful ultrapolar invasions from the northern areas of West Siberia to the south, where they hit warm continental air masses (Fig. 11). This leads to the formation of forefronts of collision, when warm air masses uplift intensively (convective uplifting currents), involving aerosols from the underlying surface, including the plant pollen. The uplifting warm air masses replace cold air masses resulting in abundant precipitation and scavenging of bio-aerosols. Taking into account the fact that the distance of herb pollen transport does not exceed 250–400 km (Sladkov, 1967), the major

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sources of deciduous and herb pollen in ice cores are the steppe and forest-steppe areas of northern Altai and eastern Kazakhstan.

5 Conclusions

Biological proxies, i.e. microscopic algae, spores and pollen, can be an additional informative signal of environmental changes along with other proxy data in ice cores from high-mountain continental glaciers. Since the Belukha glacier is located on the boundary of contrast climatic and vegetation zones, and the extinction of plant species and deforestation of vast areas in Siberia were not observed for the last 40 yr (the study time interval), we can interpret the change in pollen concentration of conifer and deciduous trees in annual layers of the Belukha glacier as a reflection of the influence of predominant atmospheric circulation patterns in each flowering season. In other words, the variation of pollen abundance in annual layers of the Belukha ice core together with other studied biological proxies (diatoms, cysts, spores) can be used as a sensitive indicator of the atmospheric circulation dynamics on the global and regional levels. Microscopic algae including frustules of diatoms and cysts of chrysophycean algae grow in water bodies all-the-year-round with their maximums in some seasons in contrast to the plant pollen produced in particular seasonal periods. Their combination in the ice core makes it possible to get outlook about past and future atmosphere circulation changes.

When considering the transport ability of each biological object and the data on precipitation under predominant atmospheric elementary circulating mechanism (ECM) for years of maximum and minimum concentration of biological proxies in the Belukha ice core, we tried to determine the origin of diatoms, cysts, spores and plant pollen. Frustules of diatoms can be brought mostly from the water bodies of the Aral and Caspian, and North Kazakhstan basins, and the cysts of chysophycean algae and spores of inferior plants – from local water bodies and forests surrounding the Belukha glacier. Pollen of coniferous trees prevailing in number in different layers of the ice core

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could be transported from taiga forest of the boreal zone of the West Siberia, whereas the pollen of hardwood and herbs – from the steppe and forest steppe vegetation of the Northern Altai and East Kazakhstan.

The obtained source regions of the biological species are in good agreement with back trajectory analyses and emission source regions of the trace species in the ice core (e.g. Eichler et al., 2009b, 2012).

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Table 1. Characteristics of ECM groups according to the classification of the Northern Hemisphere extra tropical atmospheric processes.

Group of ECM	*Type of ECM	Atmospheric pressure at the Arctic region	Amount of simultaneous blocking processes	Amount of southern cyclones outlets	Example of dynamic scheme (Fig. 2)
Zonal	1a, 1b, 2a, 2b, 2c	High	0	2–3	1a
Disturbance of zonal circulation	3, 4a, 4b, 4c, 5a, 5b, 5c, 5d, 6, 7a(w), 7a(s), 7b(w), 7b(s)	High	1	2–3	5a
Northern meridional	8a, 8b(w), 8b(s), 8c(w), 8c(s), 8d(w), 8d(s), 9a, 9b, 10a, 10b, 11a, 11b, 11c, 11d, 12a, 12b(w), 12b(s), 12c(w), 12 c(s), 12d	High	2–4	2–4	11a
Southern meridional	13(s), 13(w)	Low	0	3–4	13(s)

* Numbers of ECM (from 1 to 13) are labeled by letters "a", "b", "c", "d" according to the geographical locations of blocking processes and southern cyclones outlets; in brackets – letters "s" and "w" indicate summer or winter season

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Table 2. Biological proxies discovered in the Belukha ice core.

Objects	Species	Concentration in the ice core, units/l	Distance of transport	Geographic referencing
Diatoms	*Hantzschia amphioxys*	0–11.1	From some to thousands of kilometers	Cosmopolite, in reservoirs and mosses on the rocks
	Pinnularia borealis	0–18.0		North-alpine, littoral
	Encyinema minutum	0–1.9		Cosmopolite, littoral
Cysts of chrysophycean algae and Spores of inferior plants (ferns and lichens)	Spherical smooth forms (not identified)	6.0–61.9	From some to thousands of kilometers	Mostly in cool-water reservoirs Boreal belt
Pollen of coniferous trees	*Pinus sylvestris* (dominant) *Pinus sibirica* *Picea obovata*	22.2–158.5	500–1700 km 500–1700 km few km	Forest belt Forest belt Forest belt
Pollen of deciduous trees and herbs	*Betula sp.* (dominant) *Artemisia* *Chenopodiacea* *Poaceae*	0–33.3	250–400 km 300–500 km few km few km	Forest-steppe complex Steppe Desert Steppe

Table 3. Amount of precipitation (% of the annual) in the Altai region (according to the meteorological station Kara-Tyurek) at 2b, 5a, 8b(s), and 10a ECM types in years of minimal (1995–1997) and maximal (1982–1984) concentrations of diatoms in the Belukha ice core (months of main precipitation are pointed in brackets).

ECM	Precipitation, %						
	Average for period	maximal concentrations of diatoms			absence of diatoms		
	1981–2001	1982	1983	1984	1995	1996	1997
2b	1.4	10.1 (V, XI)	3.9 (V)	2.8 (VII-VIII)	0	0	0
5a	0.8	4.4 (VIII)	5.9 (VIII)	0	0	0	0.5 (XI)
8b(s)	1.1	3.7 (VI-VIII)	4.8 (VIII)	2.8 (VI-VII)	0	0	0
10a	3.2	6.2 (V, X-XII)	8.9 (IV-V, VII, XI)	3.9 (IV, XII)	1.5 (I)	0	4.1 (II, XI)

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Table 4. Characteristics of atmospheric processes and a description of the trajectories of air masses over Altai region under 2b, 5a, 8bs, and 10a types of ESMs of the Northern Hemisphere.

ECM	Meteorological events over Altai region	Primary season	Trace	Precipitation
2b	Mediterranean cyclone (Zn)	April–November	Over the Black and Caspian Seas towards the south of the Urals and West Siberia, and then to the north-east	intensive
5a	Mediterranean cyclone (Zn)	August–April	Southern cyclones from the eastern Mediterranean Sea move through the Aral-Caspian region to basins of the Ob and the Yenisei rivers.	intensive
8b(s)	Mediterranean cyclone (Zn)	April–September	Through the south of the Urals in the north-east direction	intensive
10a	Cyclonic (Zn) break-through from northern Kazakhstan and Central Asia	During a year	Ultra polar invasions through the Russian Plain closed up with local Zn from the north of Kazakhstan and further to the north east	intensive

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Table 5. Amount of precipitation (% of the annual) in the Altai region (according to the meteorological station Kara-Tyurek) at 7b(s), 8d(s), and 11d types of ECM in years of the minimal (1986 and 2000) and the maximal (1983) concentrations of the coniferous tree pollen in the Belukha ice core (months of main precipitation are pointed in brackets).

ECM	Precipitation, %			
	Average for period	max concentration	min concentration	
	1981–2001	1983	1986	2000
7b(s)	0.9	3.5 (V)	0	0
8d(s)	1.8	13.1 (IV–VI)	4.5 (VII–IX)	0
11d	2.0	12.3 (VI–VII,IX)	1.4 (XII)	1.7 (XI)

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Table 6. Characteristics of atmospheric processes and a description of the trajectories of air masses over the Altai territory at 7b(s), 8d(s), and 11d types of ECMs of the Northern Hemisphere.

ECM	Meteorological events for Altai region	Primary season	Trace	Precipitation
7b(s)	Cyclone-Anticyclone (Zn-Az)	March–September	The formation of local Zn on the northern periphery of the Asian Az	some – intensive
8d(s)	Ultrapolar invasions	March–October	From north to south through the whole territory of the Ob' basin	some – intensive
11d	Ultrapolar invasions	September–April	From northeast to southwest through the whole territory of Eastern Siberia	some – intensive

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Table 7. Amount of precipitation (% of the annual) in the Altai region (according to the meteorological station Kara-Tyurek) at 12a type of ECM in years of the minimal (1984–1986) and the maximal (1995–1997) concentrations of cysts of chrysophycean algae and spores of inferior plants in the Belukha ice core (months of main precipitation are pointed in brackets).

ECM	Precipitation, %						
	Average for period	Minimal concentration			Maximal concentration		
	1981–2001	1984	1985	1986	1995	1996	1997
12a	5.6	0	1.3 (III,IV,XI,X)	0.10 (IV,V, XI)	10.5 (III–VI,X)	8.7 (IV,V,IX)	16.5 (V)

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Table 8. Characteristics of atmospheric processes and a description of the trajectories of air masses over the Altai territory at 12a ECM of the Northern Hemisphere.

ECM	Meteorological events for Altai region	Primary season	Trace	Precipitation
12a	Anticyclone (Az)	All the year round	Az (30–0° N, 45–140° E) blocks the western air mass transport	Some

Table 9. Amount of precipitation (% of the annual) in the Altai region (according to the meteorological station Kara-Tyurek) at 8c(s) and 8d(s) types of ECM in years of the minimal (1982, 1987, 1990, 1995–1997) and the maximal (1983–1986) concentrations of pollen of hardwoods and herbs in the Belukha ice core (months of main precipitation are pointed in brackets).

ECM	Precipitation, %										
	Average for period	Minimal concentration						Maximal concentration			
	1981–2001	1982	1987	1990	1995	1996	1997	1983	1984	1985	1986
8c(s)	1.1	0	0	0	0.7 (IV)	0.5 (IV)	0	4.3 (V, VIII)	3.2 (VI–VII)	1.8 (VI)	3.0 (VIII)
8d(s)	1.8	0	0	0	0	0	0	12.9 (IV–VI, IX)	4.0 (III, VII, XI)	5.2 (VIII)	4.05 (VII–VIII)

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Table 10. Characteristics of atmospheric processes and a description of the trajectories of air masses over the Altai region under 8c(s) and 8d(s) types of ESMs of the Northern Hemisphere.

ECM	Meteorological events for Altai region	Primary season	Trace	Precipitation
8c(s)	Ultra polar invasions	March–October	Ultrapolar invasions through Western Siberia on the background of Az	some – intensive
8d(s)	Ultra polar invasions	March–October	Ultrapolar invasions through Western Siberia on the background of Az	some – intensive

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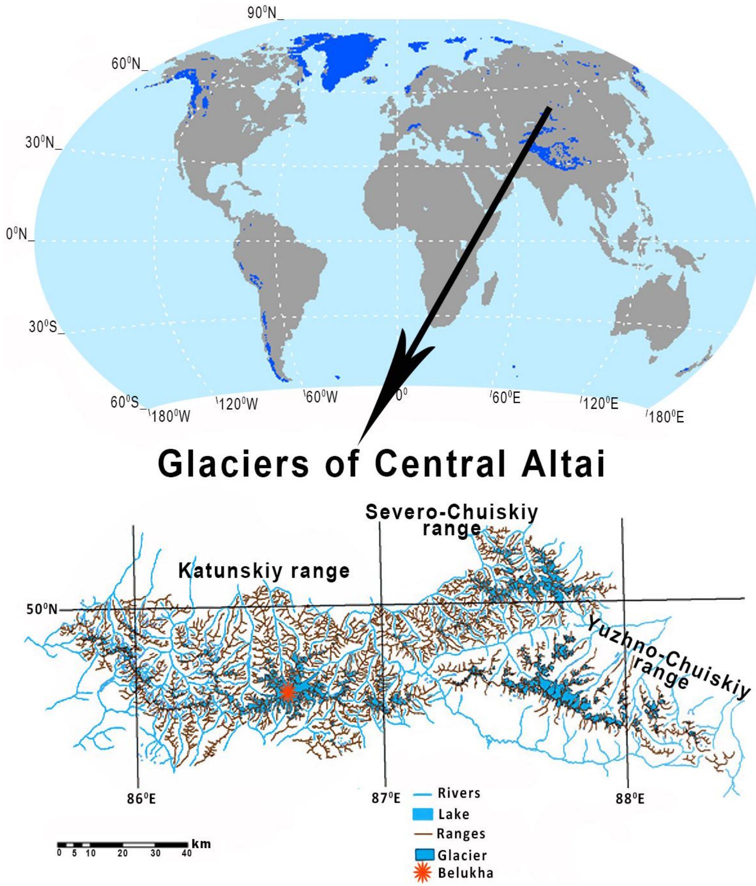

Fig. 1. Distribution of glaciers and ice around the world (except Antarctica) (GLIMS Glacier Database, 2012) and Glaciers of Central Altai (Kobyalko and Ostanin, 2012).

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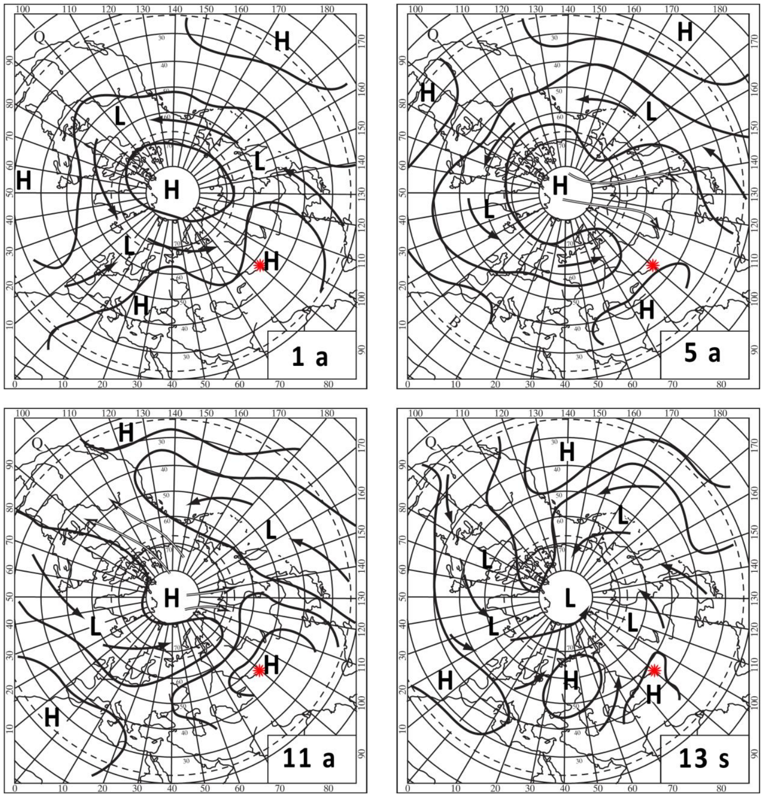

Fig. 2. Dynamic schemes of the ECMs of different circulation groups according to Kononova (2009): zonal (1a); disturbance of zonal circulation (5a); northern meridional (11a); southern meridional (13s). The border between the regions of high and low pressure passes along the isoline 1015 hPa (bold curve). Arrows show the cyclonic (dark) and Arctic invasion (double light) tracks. Letters "H" and "L" denote high atmosphere pressure (anticyclone) and low one (cyclone), respectively; red * – Belukha glacier.

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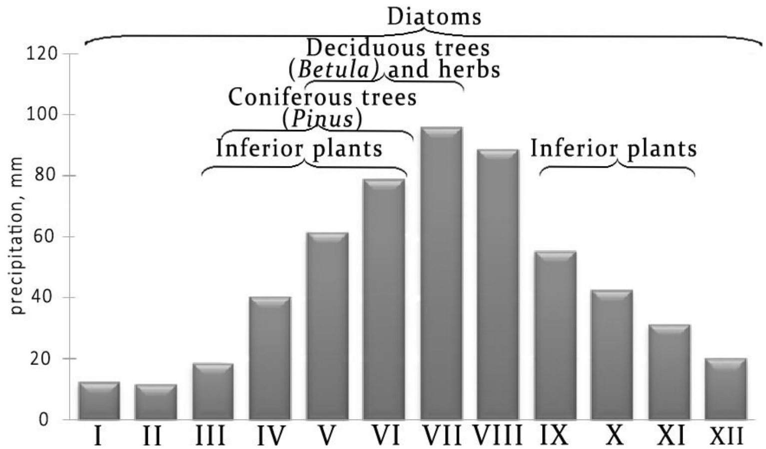

Fig. 3. Monthly precipitation in the Altai Region (data of Kara-Tyurek meteorological station for period 1940–2000) and the time of flowering, sporulation, and cyst formation of biological objects discovered in the Belukha ice core.

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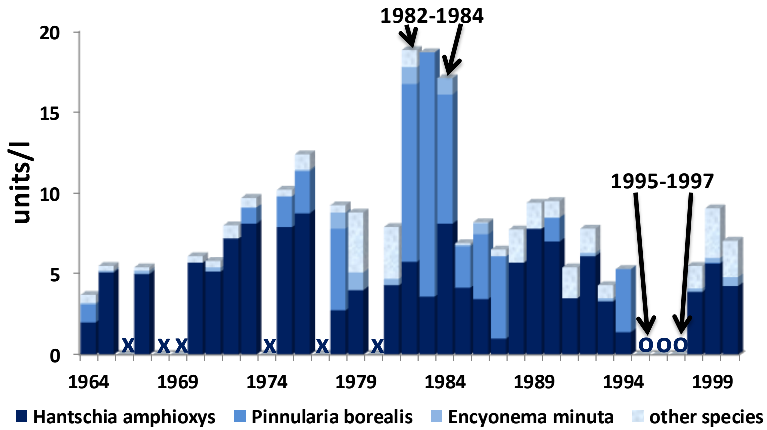

Fig. 4. Ice core records of diatoms (x – sample is missing; 0 – diatoms are not identified).

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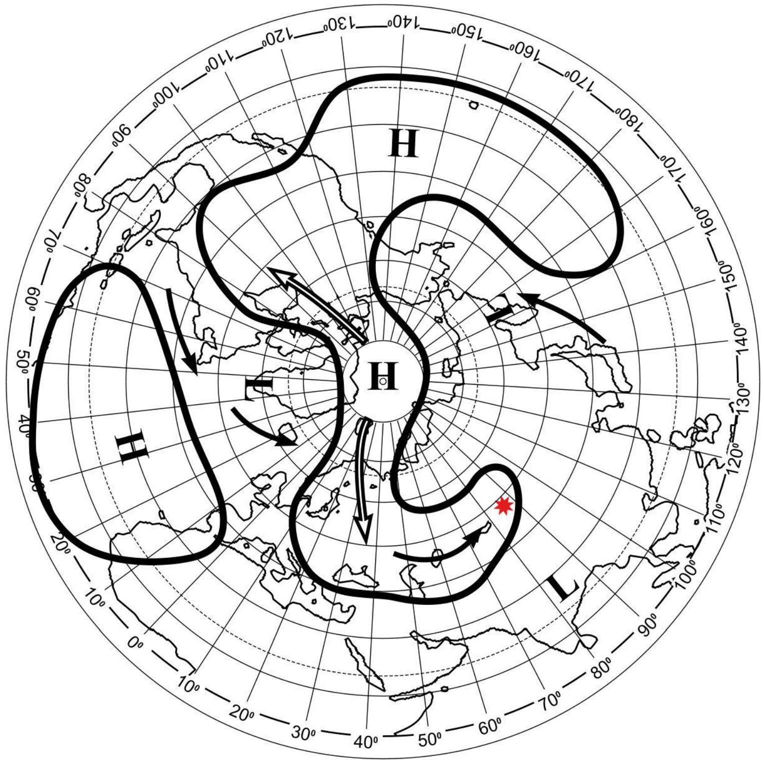

Fig. 5. Dynamic scheme of atmosphere circulation (Type 10a) with significantly higher amount of precipitation in the Altai region during diatom maximum years 1982 and 1983; red * – Belukha glacier.

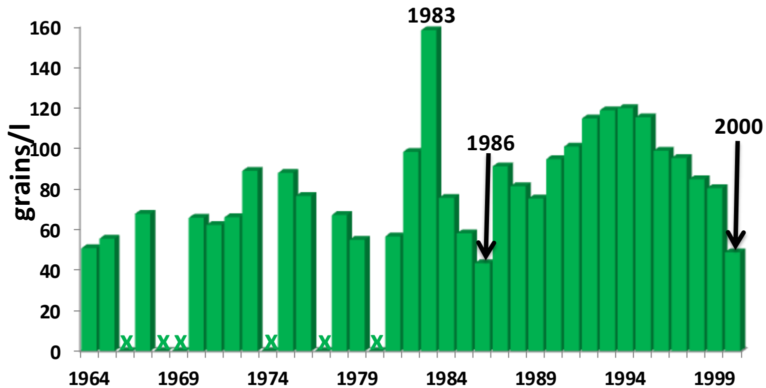

Fig. 6. Ice core records of the coniferous tree pollens (x – sample is missing).

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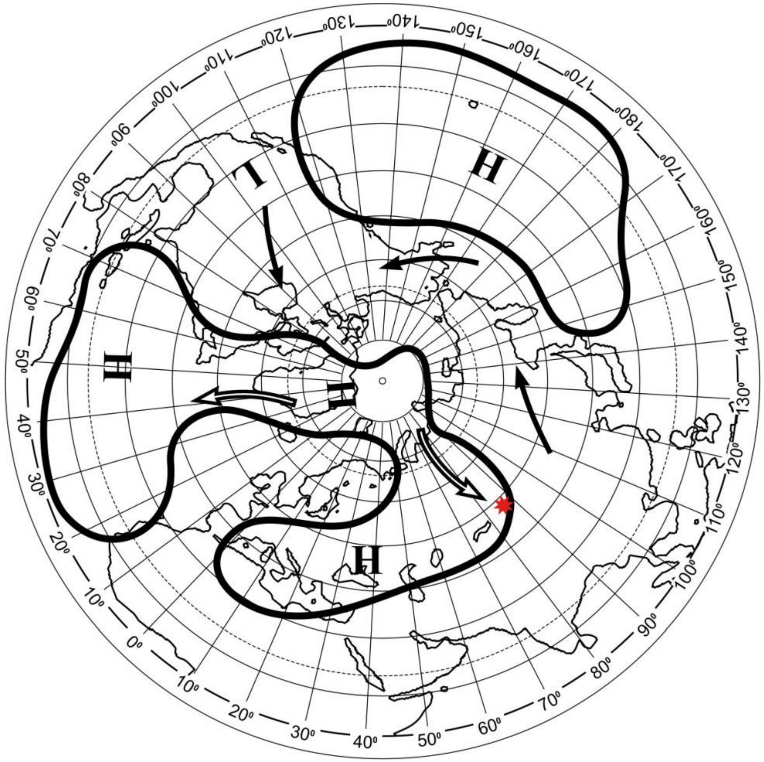

Fig. 7. Dynamic scheme of atmosphere circulation (Type 8d(s)) with significantly higher amount of precipitation in the Altai region during the coniferous tree pollen maximum year 1986; red * – Belukha glacier.

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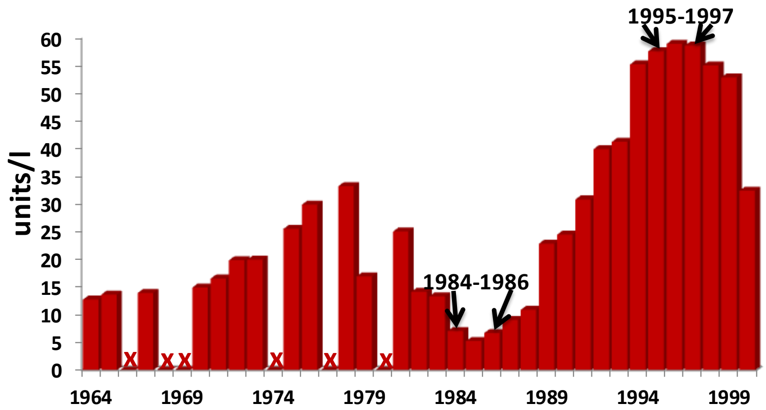

Fig. 8. Ice core records of cysts of chrysophycean algae and spores of inferior plants (x – sample is missing).

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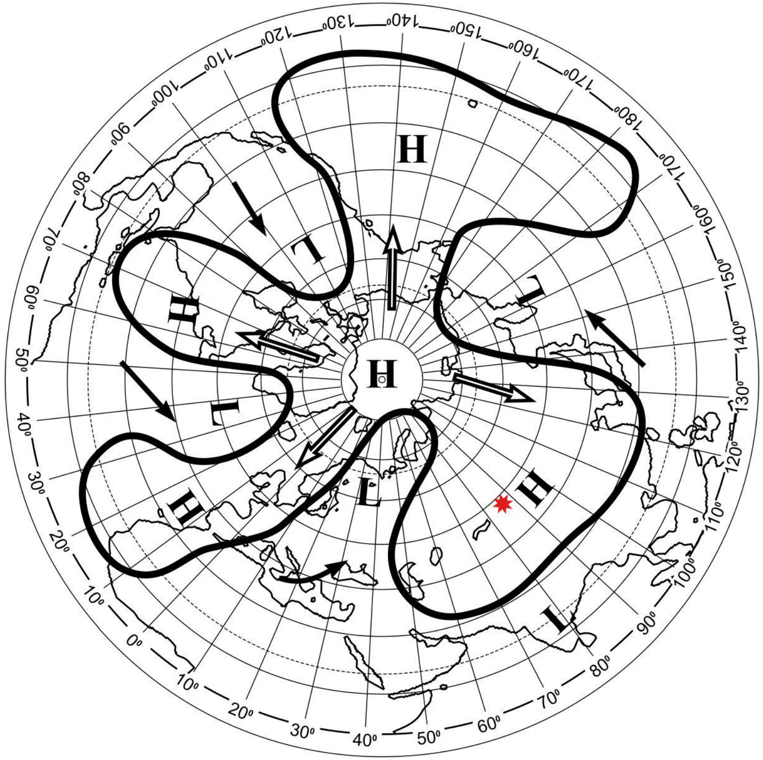

Fig. 9. Dynamic scheme of atmosphere circulation (Type 12a) with significantly higher amount of precipitation in the Altai region during the years 1996 and 1997 (showing maximum concentrations of cysts of chrysophycean algae and spores of inferior plants in ice core); red * – Belukha glacier.

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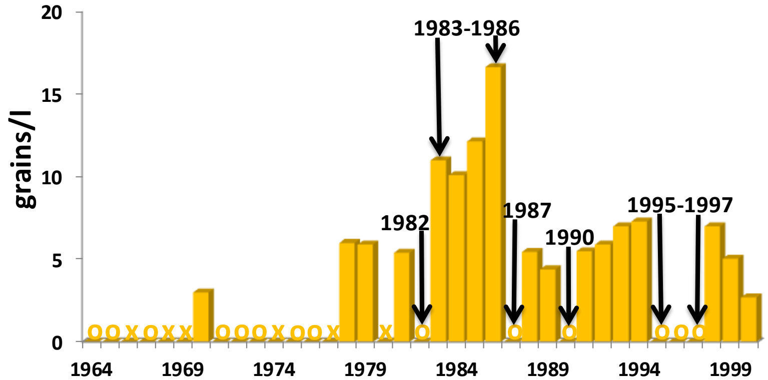

Fig. 10. Ice core records of hardwoods and herbs (x – sample is missing; 0 – pollens are not identified).

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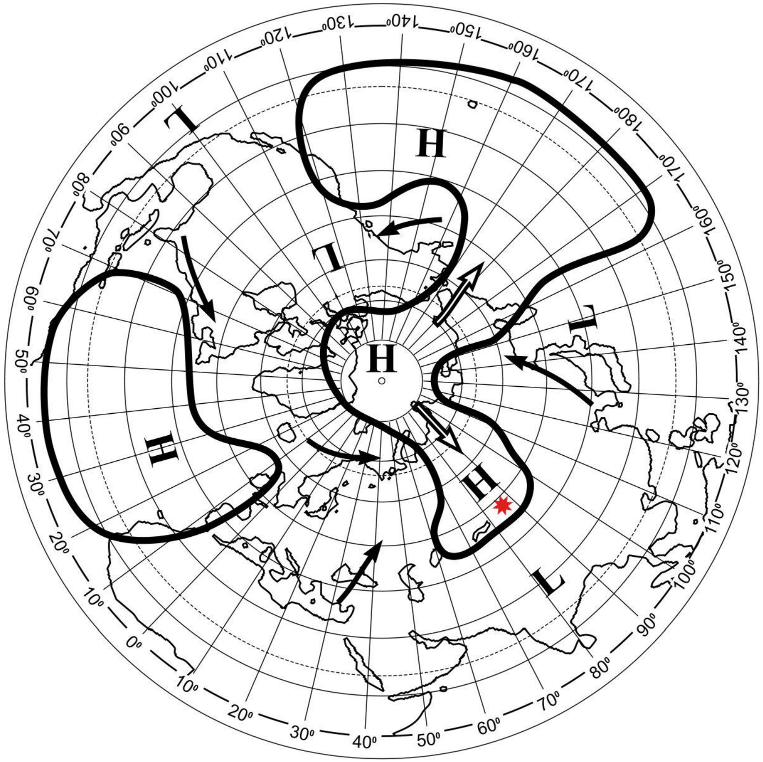

Fig. 11. Dynamic scheme of atmosphere circulation (Type 8c(s)) with significantly higher amount of precipitation in the Altai region during the deciduous and herb pollen maximum in 1986; red * – Belukha glacier.

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