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CLIMATE CHANGE IN EASTERN TAIMYR OVER THE LAST 80 YEARS AND THE WARMING IMPACT ON BIODIVERSITY AND ECOSYSTEM PROCESSES IN ITS TERRITORY

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The analysis of long-term changes of mean annual temperatures and the active temperature sum over 80 years was carried out using data of the Khatanga meteorological station. Since the 1990s, an essential warming was observed, especially after 2000. The warming influence on vegetation takes place immediately (the ecosystem composition changes due to the degradation of cryogenic processes) as well as directly by increasing the time of the vegetation period and the total amount of heat on plants. As a result, in the last few years, the lead of phenological phenomena terms is observed – the time of foliage expansion and efflorescence of plants-indicators, geese arriving, mosquitos appearance, ice thawing. By long term monitoring data, the moving of some north-taiga plant species to forest tundra and tundra is observed, as well as their establishing in vegetation communities. However, at this moment, the character of the vegetation is stable. The occurrence of taiga animals is increased in tundra and forest tundra. An active revival of larch is observed in forest tundra and north sparse forests. A removing forest border to the north is not observed, but in the southern mountains of Taimyr its replacing on higher levels could be seen. A decreasing summer precipitation quantity increases the possibility of forest fires, spring and bog drying. It influences negatively on bog flora and near-water fauna. It is possible, that the main reason of the local climate change at the East of Taimyr is less connected to the global planet change, but much more to pulsations of the strong Siberian anticyclone.

Key words: biodiversity, climate change, duration of the growing season, forest boundary, northward migration of species, phenological phenomena, Taimyr, temperature dynamics

Introduction

In recent time the problem of climate change and the biota response to it became one of the most discussed issues.

There is no doubt that a change in the hydrothermal regime has to result into changes in natural ecosystems. It is manifested in a change of ecosystems' structure and species diversity, in a gradual shift of natural zones' boundaries, primarily at the southern boundary of boreal forests (Olsson, 2009). Undoubtedly, this shift should process very gradually, and only if the climate trends are constant, being expressed in a general warming. A transformation of any ecosystem under climate change because of warming does also process gradually, beginning since the introduction and establishment of more southern thermophilic species, which are not so typical for an ecosystem, and the weakening of the position of the northern species.

Most authors consider the possible consequences of the expected climate change in relation to forests as to communities most prone to catastrophic changes and which play the largest role in the gas composition maintaining in the atmosphere of the whole planet. But, of course, the Arctic region is the most sensitive to climate changes due to a certain seasonal decrease in the ice cover of the Arctic basin and the decline in the thickness of permafrost rocks observed on various places as a result of the increase in mean annual temperatures (Alexeev et al., 2015). It should be noted that during the Pleistocene and Holocene, cyclical global climate changes already occurred. These were accompanied by changes in plant formations: the shift of forests to the north and their subsequent return to the south and the replacement by tundra communities. A comparative analysis of remote sensing data shows an increase in the productivity of tundra vegetation («greening of the tundra»), reflected in an increase in the projective cover of vascular plants and a decrease in the moss-lichen cover (Tishkov & Krenke-jun, 2015). But this is not always confirmed by actual data from terrestrial studies in selected areas.

The Arctic (sensu lato) vegetation is characterised by a high heterogeneity, because species of both warm and cold epochs have established in it at different periods. These plants react differently to climate changes (Telyatnikov, 2005). Based on this, it is possible to draw definite conclusions about the response of the vegetation to specific climate changes based on the analysis of the modern flora and its changes over a certain period of time. However, floristic diversity is likely to be resistant to climate changes. But native species may not withstand competition from southern species extending their range to the north (Callaghan, 2005).

The impact of climatic condition changes on plants can be either direct (an increase in the heat amount due to prolongation of the growing season and an increase of the mean daily temperatures), or indirectly (as a result of habitat changes). The latter has special significance in conditions of the zone with continuous permafrost distribution, where even a low (at a first view) warming leads to an increase in the intensity of the cryogenic processes of degradation series. The microrelief change occurring under their influence (occurrence of thermokarstic subsidence, drainage of small lakes during the thawing of fossil ice veins, formation of the *baydzharakhs* (cemetery mounds / silt pinnacles), slopes erosion, mudflow processes in the mountains) entails the destruction of resistant plant communities and the forming of other plant communities at their place, which correspond more to the changed conditions. On the one hand, there is a waterlogging of the tundra as a result of thermokarst processes, on the other hand there is a formation of meadow and shrubby vegetation on the place of drying basins and exposed scree slopes, an overgrowing of spots in medallion tundra. Apparently exactly this is the possible reason for the aforementioned «greening» of the tundra.

The aim of this work was to identify possible changes in composition and structure of the flora and in the fauna composition of the Taimyr (mainly eastern part) in connection with climatic variations. According to the aim, the tasks were the analysing of long-term climate change in the Taimyr and specific facts of changes in the vegetation cover (phenological indicators, floristic diversity and general character of the vegetation) based on field observations conducted by the authors from 1988 to 2016.

Material and Methods

The data of the meteorological station Khatanga were used as background information. There were continuous observations conducted from 1933 to date with a gap in 1944–1946 (All-Russian Scientific Research Institute – World Data Centre, 2017) – over more than 80 years, until late 2016. During work conducting, a large amount of data was processed in order to identify the character of climate changes in the region during the available period.

Based on these data and the results of our personal observations in field work on key sites, it can be argued that the long-term trends of the climate change in Khatanga closely correlate with the corresponding trends of the adjacent areas (e.g., polar station «Lake Taimyr», according to archival data). They correlate even with such remote area as the meteorological station «Dixon», for which the data of meteorological observations were also analysed over the period of 1936–2016. Thus, the results of the observations in Khatanga can serve as a basis for broader generalisations. The obtained resulting patterns are consistent with the conclusions of the Second assessment report on climate change and its consequences in the Russian Federation (2014).

To identify changes in the composition of flora and vegetation, we used the data of monitoring studies conducted at a series of key sites in the Taimyr Reserve and surrounding areas. A comparative analysis of the ranges of certain plant species and their changes over the past decades has been carried out on the basis of personal relevés on 55 key sites and water routes along the following rivers: Kotuykan, Kotuy, Maymecha, Khatanga, Fomich, Popigay. All sites where herbarium specimens were collected have been pointed by geographical co-ordinates. Also, we used all available literature sources and material of the following two herbaria: Herbarium of the Botanical Institute of RAS (LE) and Herbarium of Moscow State University (MW). The changes in the onset timing of certain phenological phenomena have also been traced since the late 1980s till recent time according to the «Nature Calendars» of the Taimyr Reserve, including the duration and timing of the phenological periods onset, the timing of the flowering of a certain plant species, the arrival of birds, meteorological phenomena, etc.

All plant names are used according to The Plant List (2013).

Results and Discussion

Dynamics of average annual temperatures, sums of active temperatures and changes in phenological parameters

For the north of Central Siberia and, in particular, for Taimyr, linear trends of the change in the mean annual and average seasonal air temperatures (also as – TA) towards warming were recorded in the period of 1976–2012 (Rankova et al., 2014), especially in the summer-autumn and winter periods. Tendencies of winter warming by 2013 are particularly noticeable with respect to the Arctic region from northern Europe to Taimyr and north of Yakutia. In summer, they are most pronounced in the north of Western and Central Siberia. According to the results of the long-term observations in the Arctic and Subarctic, two warming periods were revealed: in 1920–1940, and more recent, which began in the 1990s. Between these periods, there was a period of «deep lowering of surface air temperatures» (Alexeev, 2014).

We considered the distribution of the annual air temperatures of Khatanga with respect to the average annual air temperature, which is -12.6°C (Fig. 1). It is obvious that the change in air temperatures over all these years has the character of alternating colder and warmer periods. We can conditionally assume that the first relatively warm period took place before 1949 (conditionally, because there is a gap in observations), the average air temperature: -12.1°C. This is followed by a relatively long period (1950–1982) which can be considered as a «cold» (average air temperature: -13.4°C), moderately cold (1983–2004) with an average air temperature (AT) of -12.7°C, and the last period (2015–2016), which was significantly warmer than all previous ones with an average air temperature of -10.9°C. It should be noted that these periods fully correspond to the trend of temperature anomalies for the period from 1900 to 2000 for the whole Arctic (McBean, 2005). When the curve is smoothed using a fourth-degree polynomial, it clearly shows a tendency to cool in the middle of the period under review and warming since the mid-1990s. Since 2005, there has not been such a long period with an equally significant excess of the average annual air temperature over the average long-term (2005–2016) air temperature. In those years, only three times the average annual air temperature was lower than the average long-term air temperature. The most significant manifestation of warming was observed in April, May and June.

However, it should be taken into account that winter temperatures, which do not have a significant effect on plants, make the most significant contribution into the average annual air temperatures in conditions of high latitudes. Tolmachev (1939) noted «the primary importance of such factors as the total duration of the warm season and the amount of heat received by the earth surface during this season which should be reflected most vividly by the vegetation of the continental Arctic». From this point of view, it is more appropriate to trace the dynamics of the sum of the active temperatures ($\Sigma AT > 0°C$) over the same period relative to the mean value long-term air temperature, equal to 938.1°C (Fig. 2). The sum of the active temperatures is an indicator, characterising the heat amount and expressed as the sum of the average daily air temperatures exceeding a certain threshold: 0°C, 5°C, 10°C, or the biological minimum of the temperature which is necessary for the plants development in a certain area: e.g., plants in Arctic begin their growing cycle when the air temperature has exceeded 0 °C, and even under the snow.

In this case, the graph shows three periods (Fig. 2). These are moderate (1933–1960) with $\Sigma AT > 0°C = 935.8$; cold (1962–1996) with $\Sigma AT > 0°C = 889.1$ and warm (1997–2016) with $\Sigma AT > 0°C = 1029.2$. During the last 20 years, the values of the sum of active temperatures were below the average long-term ones only in 2004 and 2008.

According to the data of the «Khatanga» meteorological station, we calculated the duration of phenological temperature periods corresponding to stable transitions of average daily temperatures during the growing season: above 0°C is the beginning of spring; above 10°C is the beginning of summer; from the transition below 8°C to the transition below 3°C is the vegetational autumn. These limits are taken for the forest-tundra and in general they correspond to phenomena in the plant world – the beginning of spring: the colouring of *Salix lanata* L. catkins; the beginning of summer: complete deployment of the larch (*Larix gmelinii* (Rupr.) Kuzen.) needles; the beginning of autumn: first yellowing of larch and dwarf birch (*Betula nana* L.) thickets. In general, the duration of the growing seasons in the analysed series varies within 70–105 days, except for the last, «warm», period, where it lasted from 100 to 125 days.

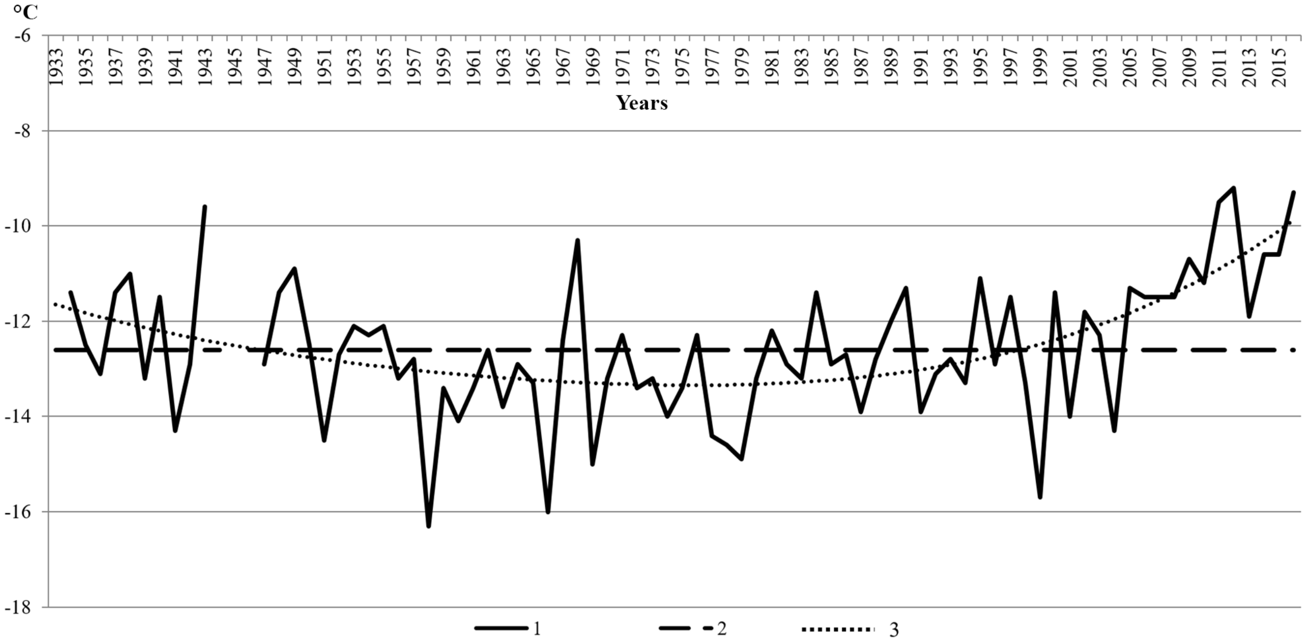

Fig. 1. Change in the average annual air temperature according to the weather station «Khatanga» over the period of 1933–2016: 1 – average annual air temperature; 2 – average long-term air temperature over the entire observation period; 3 – smoothing of average annual air temperatures using a fourth-degree polynomial.

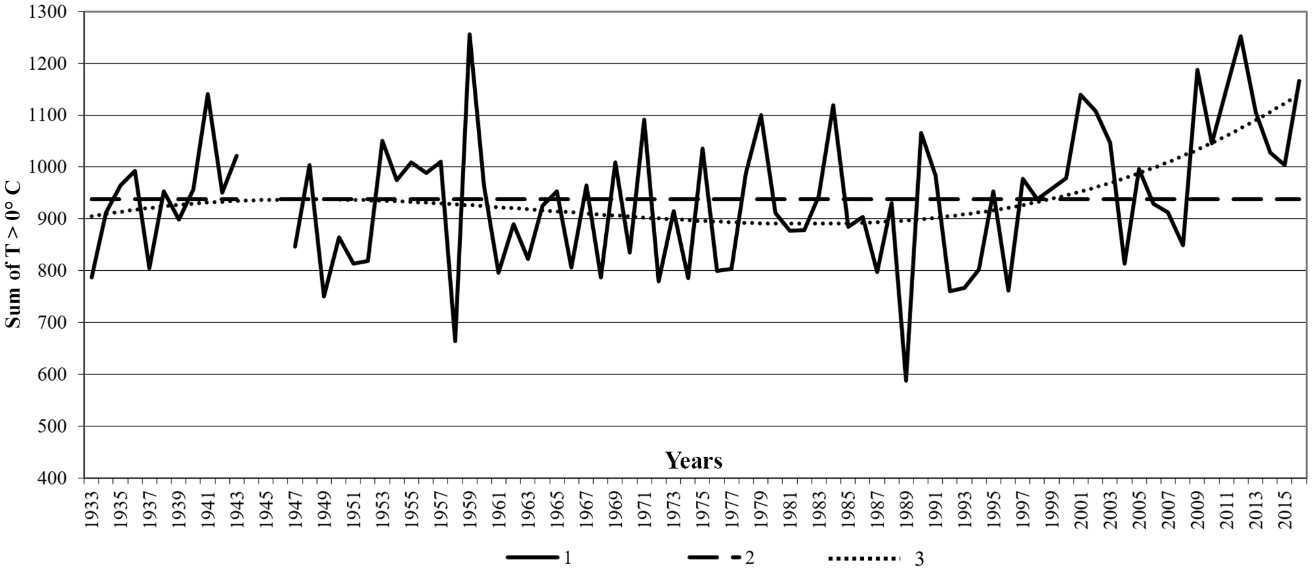

Fig. 2. The change in the sum of the active temperatures (ΣAT> 0 °C) according to the data of the «Khatanga» meteorological station over a period of 1933–2016: 1 – average long-term value; 2 – the values of ΣAT > 0°C by years; 3 – smoothing of annual values of ΣAT >0°C using a fourth-degree polynomial.

An increase in the duration of the growing season promotes the complete passage of the plant seasonal cycle – successful flowering, seed ripening and growth of additional vegetative shoots, which does not always happen under conditions of a short summer and a low average temperature. In recent years, we have often observed a second flowering of a number of not only early-spring plants, but also of early-summer plants (e.g., *Dryas octopetala* L.). On the graph plotted for the entire available data set (Fig. 3), the trend of an earlier beginning of spring and summer and of a later beginning of autumn in the last 10–15 years is clearly visible, especially since the early 2000s. Since that time the observers recorded earlier periods of phenological events compared to the average long-term value dates. For example, the beginning of flowering of *Salix lanata* has shifted to late May (the average long-term date is 8 June); the beginning of flowering of *Dryas octopetala* has shifted almost to ten days: 11–15 June (the average long-term date is 23 June). In recent years mature larch needles are formed during 15–20 June (the average long-term date is 2 July). In recent years the arrival of the first geese (the average long-term date is 24 May) happened during 13–17 May. In recent years, the mass emergence of mosquitoes has been observed at an earlier time – from 21 June to 3 July (the average long-term values date is 7 July). The beginning of leafing of dwarf birch (2–13 June, the average long-term date is 20 June) and the flowering of *Caltha palustris* L. (6–11 June, the average long-term date is 19 June) start earlier as well.

The shift of the vegetational period towards an earlier is also emphasised by a change in the timing of such a fairly stable phenomenon as the breakup of ice in the River Khatanga and the beginning of the ice drift. Fig. 4 shows that in the last 20 years the ice drift began before 10 June, but in earlier years of observations it began at the middle and the end of June (except for three cases). It is peculiar that in this case the dates of freeze-up were very close. Therefore, the duration of open water on the River Khatanga and its tributaries has increased, which provides more favourable conditions to exist for aquatic and near-water plants, birds and mammals. In addition, the earlier ice cover destruction affects the timing of the migration to the north of the wild reindeer (*Rangifer tarandus* (Linnaeus, 1758)), whose herds during spring migration prefer to move before the ice shift, so the rivers do not form an obstacle for them; reindeer do often prefer to move on ice (Makeev et al., 2014). Also, earlier spring migrations allow the animals to migrate timely to the north, before the mass appearance of mosquitoes, which also shifted to an earlier time (Fig. 5).

Fig. 3. Timing of phenological periods over the period of 1947–2016. Transitions of average daily air temperatures: 1 – transition through 0°C, the beginning of the growing season; 2 – transition through +10°C, the summer beginning; 3 – transition through +8°C, the autumn beginning; 4 – below +3°C, the end of the growing season.

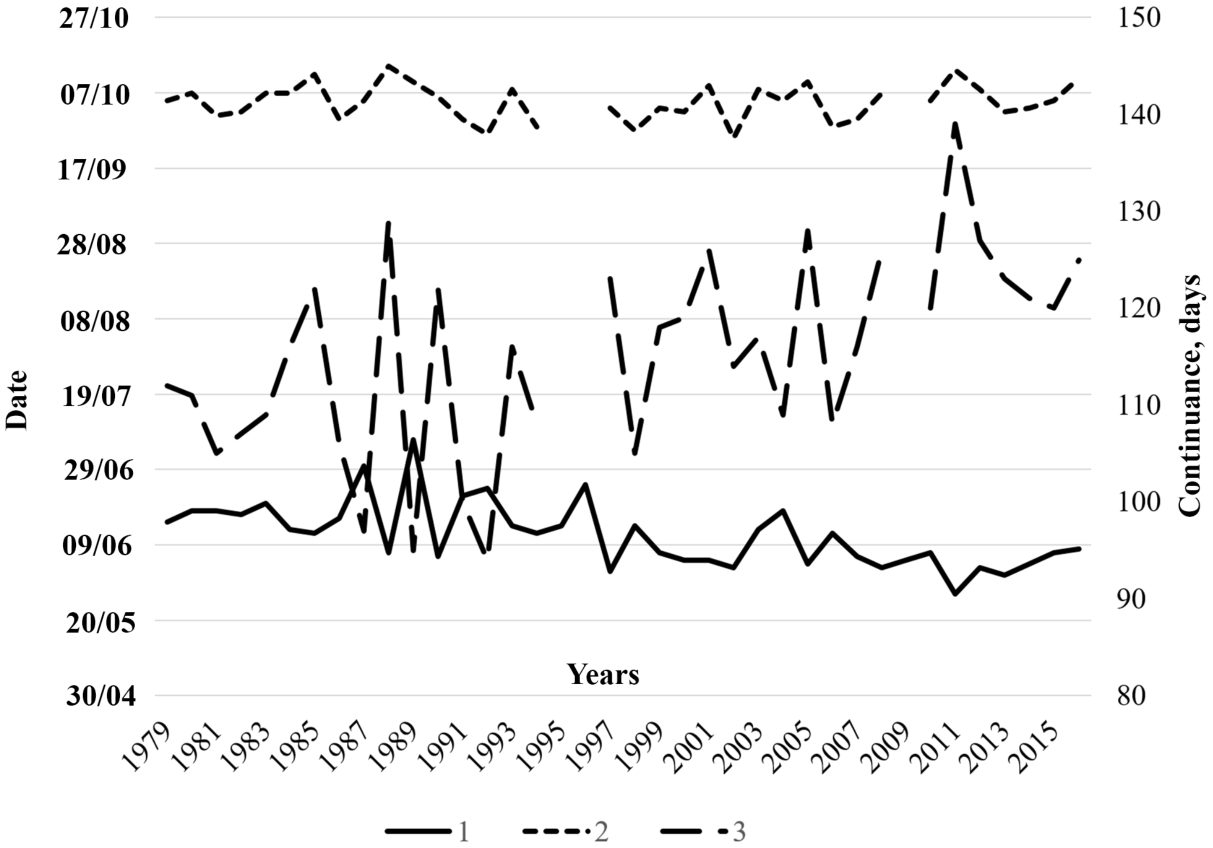

Fig. 4. The timing of the beginning of ice drift on the River Khatanga in 1976–2016: 1 – the beginning of ice drift; 2 – the beginning of freeze-up; 3 – the duration of open water period.

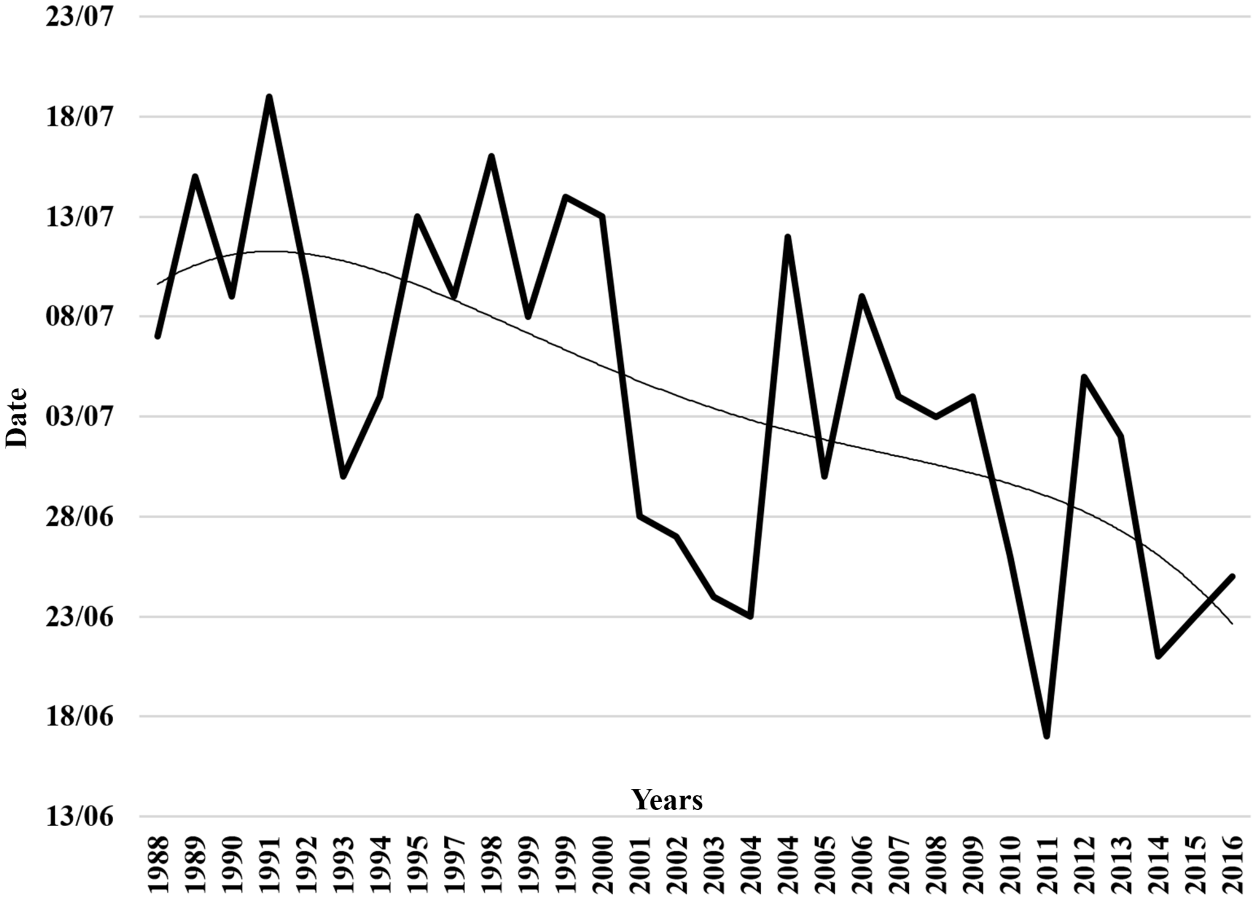

Fig. 5. Timing of mass emergence of mosquitoes in 1988–2016.

The shift of the beginning of the ice drift to earlier times indicates the earlier beginning of the spring temperature in the mountains in the south of Taimyr, from where the tributaries of the River Khatanga (River Kotuy and River Kheta) originate.

The impact of climate fluctuations on biodiversity and species' range limits

It is too early to talk about a significant transformation of the composition and structure of ecosystems as a result of climate warming, because the duration of the last period is still insufficient and it most likely fits within the framework of stable cyclical fluctuations. However, the presence of «warm» and «cold» periods can contribute to migrations of plants and animals that lead to local changes in the composition of the flora and fauna in certain areas. Such changes take place as was shown by the primary monitoring studies conducted by us in 1999–2012 in several key areas.

In the subzone of the typical tundra, a survey of the flora of the «Bikada» site was carried out in 1999, where research was conducted by Tolmachev (1932) in 1928 and by Rapota (1981) in the 1970s. A comparison of their flora lists has been carried out. A significant change in the composition and structure of the flora over periods of 20 and 70 years was noted (Pospelov & Pospelova, 2001). The species richness of the flora had increased by 13% over a period of 70 years, and it had increased by 8% over a period of 20 years, mainly due to more southern species. The ecocoenotic structure of the flora shows that the largest contribution to the increase of the flora diversity was made by the species of meadow, marsh and pioneer-erosiophilous groups, which do additionally become more active; these are *Arctagrostis arundinacea* (Trin.) Beal., *Carex saxatilis* L. subsp. *laxa* (Trautv.) Kalela, *Salix lanata*, *Betula nana*, *Silene taimyrensis* (Tolm.) Bocquet, *Ranunculus pedatifidus* Sm. subsp. *affinis* (R. Br.) Hultén, and *Papaver pulvinatum* Tolm. Apparently, this is connected with the increase in the area of bogs and mass cavings of high banks as a result of intensification of cryogenic degradation processes. Only from 1990 to 1998, three very large landslides, exposing the ice veins, along the river bank happened. A consequence of the development of landslides and cliffs is the appearance of species from the erosiophilous group, previously absent (e.g., *Puccinellia borealis* Swallen, *P. sibirica* Holmb., *Taraxacum platylepium* Dahlst.) or distributed sporadically in the past (e.g., *Phippsia concinna* (Fr.) Lindeb., *Elymus sajanensis* (Nevski) Tzvelev). Both are likely due to climate change. For them three periods are clearly visible, according to data of the Arctic and Antarctic Research Institute (Alexandrov et al., 2005; Alexandrov & Bryasgin, 2012), who calculated the deviations from the average long-term air temperature over a 70-year period in the basins of the seas of the Arctic Ocean. These periods are: 1930–1940s is a warm period, 1950–1970s is a cold period, and subsequent, a warm period, continuing to date. It is very possible that the colonisation of changed landscapes of the region by new plant species was most intensive during these warming periods. That led to an enrichment of the flora, e.g., the draining of a large lake in the late 1970s, in the basin of which a meadow vegetation has appeared.

In the subzone of the southern tundra in the Ary-Mas area, an annotated list of the flora was first compiled by N.E. Vargina in 1971 during work in the complex scientific station of the Botanical Institute of RAS (Vargina, 1978). We have re-studied this site in 2002. Then herbarium specimens were collected at selected fixed plots and through routes in 2012 (Pospelova & Pospelov, 2005, 2014). Thus we were able to compare the changes in the flora over 30 and 10 years. In 2002 40 species not listed in the previous flora list were found. Some striking species among them could not have been missed by previous researchers; e.g., *Castilleja rubra* (Drobow) Rebrist., *Delphinium cheilanthum* Fisch. ex DC., *Astragalus frigidus* (L.) A. Gray, *Epilobium angustifolium* L. All of them were found in the immediate vicinity of the place where the expedition camp was in the 1970s, and nearby of the permanent plots on which at the same time geobotanical descriptions were conducted. In 2012, five species were found on the plots surveyed in 2002. Among them, the bush of *Salix gmelinii* Pall. (= *S. dasyclados* Wimm.), 2 m in height, which was absent at this site earlier; *Eurybia sibirica* (L.) G.L. Nesom (= *Aster sibiricus* L.) quite often occurs in riverine meadows, although it had not been observed on this site before. Besides of the hypoarctic *Astragalus frigidus*, all these species belong to the boreal group and in Taimyr they are located at the northern limit of their range.

Similar trends were also observed according to the results of a re-survey of the «Lukunskiy» site of the Taimyr Reserve (2010), which was first surveyed in 1987–1988 (Zarubin et al., 1991) and visited by Pospelov in 2001. According to the results of specimens' collections in 2010, the flora of the site increased by 82 species, although this can partly be explained by the incompleteness of the original list. Our surveys in 2001 and 2010 together with data of earlier works make it possible to judge on the dynamics of the site's flora which is observed in recent years due to the penetration of a number of species from the south. This is largely due to the significant activity of cryogenic processes. Thermo-erosion leads to landslide processes, drainage of lake basins as a result of erosion of fossil ice. As a result it contributes to the appearance of new species-explerents (ruderals, according to Grime (1979)) on outcropped areas. Due to their stenotopic nature, these species do not penetrate into naturally closed communities. But these are constant and abundant in their typical ecotopes. For example, now *Epilobium angustifolium* grows massively on the eroded areas and shores of drying lakes, although it was unknown in the 1980s, as well as in 2001 (although this survey was superficial). It can be assumed that this species penetrated onto the site in the 1990s, i.e. it has colonised a large area over a very short time. There is the same situation with *Salix viminalis* L. This plant was not known in the 1980s either. In 2001 there were found some isolated bushes. Nowadays this species is quite common in willow-shrubs in floodplains and drained lake basins.

In general, we observed a northward shift of a number of boreal species along the southern bank of the River Khatanga over the last 20 years of work in its basin and in Khatanga settlement. These are *Potamogeton pusillus* L., *Triglochin palustris* L., *Hierochloë odorata* (L.) P. Beauv., *Eleocharis palustris* (L.) Roem. & Schult., *Carex acuta* L., *C. rostrata* Stokes, *Lemna trisulca* L., *Silene repens* Patrin, *Cortusa matthioli* L. subsp. *sibirica* (Andrz. ex Besser) Nyбr., *Campanula stevenii* M. Bieb. subsp. *turczaninovii* (Fed.) Victorov, *Angelica archangelica* L. subsp. *decurrens* (Ledeb.) Kuvaev, *Galium verum* L. (= *G. ruthenicum* Willd.) and some others, which have not been noted previously north of the lower reaches of the River Kotuy and River Kheta (Pospelova & Pospelov, 2016). Plant migrations proceed along the river valleys, with which most of the mentioned species are associated. Only this assumption can explain the unexpected records of the mountain fern *Woodsia glabella* R. Br. which was found on a tussock of a valley swamp in the lower reaches of the River Khatanga near the mouth of the River Malaya Balakhnya as well as on a partially rotten log at the foot of the terrace on the opposite shore (the southern tundra subzone).

Similar phenomena were also noted in the west of Taimyr. The flora of the Taimyr biogeocoenological station at the mouth of the River Tareya has been described sufficiently completely in 1970. A recent survey of this site (Matveeva et al., 2014) showed that this flora has been enriched by some species which had not been recorded here previously. Among these are *Veratrum album* L., *Silene taimyrensis*, *Poa pratensis* L., *Rumex alpestris* Jacq. subsp. *lapponicus* (Hiitonen) Jalas. All of them were found in the floodplain of the River Pyasina. This means that plant migrations take place along the river valley, similar to the situation in the River Khatanga basin.

Thus, the presence of different periods of warming contributes to the penetration of certain boreal species to the north and their establishment in the flora. However, this does not affect the character of vegetation at the present stage. Its structure and composition of dominant species remain generally unchanged. Only the area of certain ecotopes can change slightly, e.g., the change of marshes due to the development of thermokarst. In general, changes in the composition of plant communities may be insignificant in dry habitats. But these are more pronounced in moist and damp ecotopes, e.g., snowfields, marshes and shallow waterbodies. This is probably due to a general drying up of the territory as a result of the earlier snow melting together with a strong warming in the summer (Daniëls et al., 2013).

Besides of the northward migration of boreal plant species, researchers of the Taimyr Reserve and the local citizens observed repeatedly animals of the taiga complex in the tundra zone. The brown bear (*Ursus arctos* Linnaeus, 1758) did not occur outside the forest-tundra zone until the mid-1980s. In 1993–1994, it was seen by geologists in the Byrranga Mountains (the middle reaches of the River Fadyukuda), where it came to the rig. In 2000, the footprints of a young bear were recorded near the southern shore of Lake Taimyr (Baykura-Nehru Bay). In recent years (2014–2016), its meetings have increased on the banks of the River Khatanga (Ary-Mas), River Nizhnyaya, River Lukunskaya and further to the north up to the northern limits of the Khatanga Bay: the Pronchishcheva Bay, the spit of Tsvetkov. At the last location (about 75° N), brown and polar bears (*Ursus maritimus* (Phipps, 1774)) have been observed almost simultaneously by the expedition of NKU «Finval» (Chronicle of Nature, 2015). The elk (*Alces alces* (Linnaeus, 1758)) has been seen repeatedly up to the Novorybnoe settlement. In the 2000s, the sable (*Martes zibellina* (Linnaeus, 1758)) has been noted twice in the sparse forests of Ary-Mas. Being acclimatised in 1930s, the muskrat (*Ondatra zibethicus* (Linnaeus, 1766)) has distributed very widely to the north. To date, this animal is common in the neighbourhood of the Khatanga settlement. It is observed further to the north up to the River Lukunskaya and the Novorybnoe settlement. The muskrat lives permanently in the River Kotuy, River Maymecha and in their tributaries.

The impact of climate change in recent years on the distribution of the wild reindeer in Taimyr has been discussed in detail in a special monograph (Makeev et al., 2014). We note only a few points. We have already indicated above about the shifts in timing of spring migration associated with earlier springs. But the most significant factor is the hot weather during the summer (1999–2003, 2009–2016), which is coupled with an earlier massive emergence of bloodsucking insects. Under these conditions, the reindeer herds migrate to more northern areas, up to the sea coast. They often graze in the intermountain basins of Byrranga and on the plains of the Arctic tundra. Recently wintering of their herds in the tundra are increasingly observed, although in the 1970–1980s only individual herds have been noted.

Dynamics of larch distribution

The transformation of forest vegetation and the changes in boundaries of the boreal zone is one of the most discussed problems associated with the possible consequences of global warming. In this relation, the most vulnerable forests are coniferous and mixed forests of Eurasia, especially pine and spruce forests, while larch forests of Eastern Siberia can be considered as the most stable (Zamolodchikov, 2015). The southern boundary of the forest is less stable, because its aridisation takes place along with climate warming. And it inhibits the growth and resumption of trees (Olsson, 2009). In contrast, in the north of the forest distribution, higher summer temperatures coupled with good moisturising affect the wood vegetation positively because heat is a limiting factor there.

This, probably, explains the fairly rapid, from the geological point of view, movement of the forest boundary into the central part of the North Siberian lowland in the late Pleistocene and in the Holocene during the periods of planetary Karginsky Interglacial and the Holocene Optimum (Belorusova & Ukraintseva, 1980; Ukraintseva, 2002).

It can be assumed that the current warming, which began in the 1990s, and is continuing at the present time, is likely an element of the natural climate cycles, and another period of cooling can replace it sooner or later. Therefore, there were simply no significant changes of the forest boundary during this time. However, there should be noted a marked improvement in the state of forest stands at the northern limit of forests over the past 40 years. For instance, a massive larch resumption on the freed surfaces was repeatedly noted on the Lukunsky site, in particular along the edge zones of the drying up basins of lakes. Dense 30–40-year-old forests were found; the undergrowth is quite abundant in the sparse forests. In addition to sparse forests and open forests, the undergrowth of larch is often presented on slope meadows. Occasionally young trees are being noted in the tundra, in willow thickets on slopes, in dwarf birch communities. A dense undergrowth is sometimes found in climatically and (or) edaphically favourable habitats on the slopes. It is indicated in ACIA (Callaghan, 2005), according to the results of the simulation, that the tundra area will reduce up to half by 2100 due to the movement of the forest to the north. But we are sure that it is very unlikely that during the 21st century the forest boundary can be moved to the north so much.

If we analyse the data of authors who surveyed these territories in the 1920s and 1930s (Alexandrova, 1937; Tyulina, 1937), it can be assumed that over the past 80–90 years there is a certain tendency of movement of the larch to the north in the form of separate trees. For instance, Tyulina (1937) noted the last forms of half-elfin wood (dwarf forest just above the timberline) on the River Zakharova Rassokha, in the estuary, while now we can find separate small trees 15 km to the north. Tyulina's photographs of the same year from Ary-Mas show that only dense alder trees with separate larch individuals were on the ridges of the northern shore of the River Novaya. But now there are small but dense (up to 0.4–0.5) alder-larch forests.

We found separate larch forests along the River Popigay at the mouth of the River Anna (almost 74° N), which is much further to the north than the most northern larches found by Alexandrova in 1934 at the mouth of the River Sopochnaya. This grove still exists. And in some places it can be called even a sparse forest with an immanent species composition. We have observed individual forest islands up to the lower reaches of River Popigay.

An even more interesting phenomenon has been observed in the northern foothills of the Khara-Tas Ridge at altitudes of 250–280 m a.s.l. A young undergrowth of larch (1–5 years) is observed with a very high abundance. Some of the young larch trees (and spruce in Putorana) can be found in good state at altitudes up to 1000 m a.s.l. A very high seed germination is also typical there.

As it is known, the weather of the Central Siberian region from Lake Baikal to the mountains of the north of Siberia is determined by the powerful Siberian (Asian) anticyclone. The result of its impact during winter is the ultra-low temperatures from the east of Yakutia to the northeast of Evenkia. They determine the northern pole of the cold. In summer they determine higher summer temperatures in the region. This anticyclone is relatively stable and constantly occupies the above mentioned areas. But in recent decades, its significant pulsations have been registered. In some years (2003, 2008, 2013) it covered the southern part of the North Siberian lowland, in particular, the Khatanga region. This has caused extremely (for this zone) high temperatures. The duration of the anticyclonic situation and its repeatability for several years, probably, indicate the phenomenon of a blocking anticyclone. For instance, in 2016, an omega-blocking anticyclone has established at the end of June on a large area from Krasnoyarsk to Khatanga and further to the north. The excess of the average daily air temperature in Khatanga was 10°C (In Russia major weather anomalies began in 2016). In 2013, one of the causes of the catastrophic forest wildfires in the northern regions of Siberia was a powerful blocking anticyclone, which caused anomalous heat and drought over a large area (The blocking anticyclone, 2013). In addition, the precipitation amount was minimal in the summer months, which made an increased fire risk. For instance, in July – August 2003, 2013 and 2016 years the precipitation sum was only 54.9, 36.4 and 35.3 mm, respectively, taking into account that an average long-term value is 83.0 mm. Over all previous years of observations, only once (in 1959) the precipitation amount for summer months was less than 50 mm.

A noticeable decrease in summer precipitation over the last 30–40 years in the north of Central Siberia and, particularly, in the Taimyr Peninsula and its southern periphery has been noted in the Second assessment report on climate change and its consequences in the Russian Federation (Bogdanova et al., 2014). The authors have emphasised that trends of decrease in the summer precipitation amount have been recorded exactly in Taimyr, in West Siberia and in a part of Central Siberia. A significant precipitation deficit was registered in 2013 in the north of Central Siberia (in Khatanga – less than 30% of the norm). And it persisted throughout the whole summer season (Report on climate features, 2014). A similar situation in 2016, when a precipitation deficit was observed over all Central Siberia during the summer. And, in autumn, the precipitation deficit reached a historical minimum (66%). At the same time, a continuing increase in the rate of growth of the average annual air temperature was observed: in Taymyr it was 0.8°C per 10 years (Report on climate features, 2017).

Perhaps this is associated with a significant increase in the intensity of forest wildfires in recent years (so far it is only in the southeast of Taimyr and on the Putorana Plateau). If over the past years only one wildfire in the upper reaches of the River Kotuy was registered at the entire area for which the current satellite imagery is available , then in the very dry years of 2013 and 2016, there were more than seven wildfires in the west of Putorana in an area of at least 1000 km^2. And this value is not taking into account the Norilsk sub-urban region, where forests and peatlands burn almost constantly. This is certainly associated with a greater dryness of the climate. For instance, there were two large wildfires in the vicinity of Khatanga after the very dry summer seasons 1975–1979 (the amount of summer precipitation did not exceed 75.0 mm over all these years, except for 1977). Besides, we constantly observed burnt areas along the rivers Kotuy, Kotuykan, Maymecha, and Fomich. The age of some of these burnt areas can be determined at 50–60 years: it is the «dry» period of 1955–1959, when the sum of summer precipitation was almost always below the average long-term values.

Due to this anticyclone the springs in Khatanga became earlier and warmer, the summers became hotter and drier, and the autumns started later. The water content of rivers in the summer time has highly decreased.

Conclusions

It is possible to determine the relatively cold and relatively warm periods in the analysis of the long-term series of average annual air temperatures, according to the data of the Khatanga meteorological station. Since 2005, there has not been a long period with a significant excess of the average annual air temperature over the average long-term air temperature. Since the 7-month winter makes the main contribution to the average annual air temperature, the higher average annual air temperatures indicate first of all about the winters with thaw. However, the summer temperatures have the greatest significance for the plant world and, partially, for the animal world (sum of active AT >0°C). It can be said that the period of climate warming in Taimyr began since the second half of the 1990s. It manifests itself in an increase in both the average annual air temperatures and the sum of positive (active) air temperatures. Particularly distinct increases of the air temperature are observed in April, May (in particular) and in June, starting from 2005–2008. After 2008, the sum of active temperatures constantly exceeds the value of average long-term air temperature, and the duration of the growing season increases.

Accordingly, the recent years are characterised by earlier timing of the beginning of phenological and temperature spring and summer, melting of ice in rivers and lakes. The increase in the duration of the vegetational period affects positively the vegetation. For instance, the number of flowering shoots, annual increment, success of seed ripening have increased considerably, there is an intensive increase in biomass. The increase in the duration of the open water period affects favourably the near-water vegetation. It does also influence positively the nesting conditions of waterbirds (waders, Anseriformes, Gaviiformes), the increase of the coastal-water plants biomass forms the feeding basis for waterfowl and mammals.

Perhaps, the observed warming explains the increased number of records of the brown bear, elk and sable into the tundra zone, as well as the range expansion of the muskrat, although until the 1990s this animal had not been seen in the forest-tundra nor in the tundra zone.

The increase in summer heat and the duration of the season of positive average daily temperatures indirectly affect the change in the landscape structure in the tundra zone. The intensity of cryogenic degradation processes increases. On the one hand, it leads to an increase in the area of tundra-marsh complexes as a result of the increase in thermokarst. On the other hand, it leads to the development of landslide processes and the thawing of fossil ice veins. There are new vacant spaces, being fairly quickly colonised by coenofobic species-explerents, which form solid groupings. These are gradually replaced by more productive meadow and shrub plant communities. There is noted a gradual northward movement of most active meadow-shrub and marsh boreal species that are typical for the northern taiga subzone, with further their establishment in the tundra (at least in the subzone of the southern tundra). However, in this case the zonal vegetation becomes practically unchanged. According to our observations, there is a more intensive overgrowing of medallion spots in the interfluve tundra in recent years.

The considered warming period is still very short. Therefore, there was no significant change in the northern boundary of forest vegetation. Although, a slightly northward movement of the tree line of larch along the banks of the River Khatanga and its tributaries was observed compared with the 1930s. There was also noted an abundance of larch reproduction on the northern border of the forests and in the sub-glacial belt of mountain slopes. According to Ims & Ehrich (2013), the forest boundary can either move to the north or remain stable. Although trees react positively to the air temperature increase, their dispersal may be limited by other factors. Of these are changes in hydrological conditions, droughts and wildfires due to a decrease in the amount of summer precipitation, outbreaks of insect-defoliants, etc. Tikhomirov (1962) also believed that in order to explain the causes of a lack of forest in the tundra, we cannot limit ourselves to any factor, believing that the main causes are wind conditions, limitation of seed germination due to the moss-lichen cover, a lowered seed production of larch.

Simultaneously with the temperature increase, very dry summer seasons are observed increasingly. It leads to an increase in the fire risk in trans-tundra sparse forests, which are protected plantations. The water content in rivers has decreased very much in the summer time. At some years (like in 2013), the usual August flood («black water») could not be recorded in this season. Drying up of marsh complexes adversely affects aquatic and near-water flora and fauna, especially waterfowl. Ultimately, each region of the Arctic has its own set of such factors, which is related to the peculiarities of its climate and landscape structure.

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ИЗМЕНЕНИЯ КЛИМАТА НА ВОСТОЧНОМ ТАЙМЫРЕ ЗА ПОСЛЕДНИЕ 80 ЛЕТ И ВОЗДЕЙСТВИЕ ПОТЕПЛЕНИЯ НА БИОРАЗНООБРАЗИЕ И ЭКОСИСТЕМНЫЕ ПРОЦЕССЫ

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Проведен анализ долгосрочного изменения среднегодовых температур воздуха и суммы активных температур (>0°C) за 80 лет по данным метеостанции «Хатанга». Начиная с конца 1990-х гг. отмечено существенное потепление, особенно заметное в начале 2000-х. Воздействие потепления климата на растительность проявляется как опосредованно (изменение состава биотопов в результате активизации деградационных криогенных процессов), так и напрямую через увеличение длительности вегетационного периода и общей суммы получаемого растениями тепла. В результате в последние годы происходит опережение сроков фенологических явлений – сроки развертывания листвы и зацветания у растений-индикаторов, прилета гусей, массового появления комаров, ледохода и др. По данным многолетних исследований наблюдается продвижение ряда бореальных видов растений, характерных для северотаежных лесов, в лесотундру и в тундровую зону, и закрепление их в составе растительных сообществ. Тем не менее, на данном этапе характер растительности остается неизменным. Увеличилась встречаемость видов животных таежного комплекса в лесотундре и тундре. В настоящее время наблюдается активное возобновление лиственницы в лесотундре и северных редколесьях. Заметное продвижение границы леса на север не отмечено, но в горах юга Таймыра местами отмечается его смещение на более высокие уровни. Снижение летнего количества осадков усиливает возможность возникновения лесных пожаров. Представляется возможным, что причиной изменения локальных погодных условий на востоке Таймыра является не столько планетарное изменение климата, сколько летнее влияние мощного Сибирского антициклона.

Ключевые слова: биоразнообразие, граница леса, динамика температурных условий, длительность вегетационного периода, миграция видов на север, потепление климата, Таймыр, фенологические явления