EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryosphere, 2017, vol. XXI, No. 5, pp. 89–100 **http://earthcryosphere.ru/**

METHODS OF CRYOSPHERE'S RESEARCHES

DOI: 10.21782/EC1560-7496-2017-5(89-100)

DENDROCHRONOLOGIC RECONSTRUCTION OF GAS-INFLATED MOUND FORMATION AT THE YAMAL CRATER LOCATION

S.P. Arefyev[1,2], A.V. Khomutov[2,3], K.A. Ermokhina[3], M.O. Leibman[2,3]

[1]*Institute of Northern Development, Tyumen Scientific Centre SB RAS, P/O box 2774, Tyumen, 625003, Russia; sp_arefyev@mail.ru*
[2]*Tyumen State University, 6, Volodarskogo str., Tyumen, 625003, Russia*
[3]*Earth Cryosphere Institute, Tyumen Scientific Centre SB RAS, 86, Malygina str., Tyumen, 625026, Russia*

Analyzed are tree-ring width chronologies of willow shrubs from the area of a crater formed in Central Yamal as a result of gas emission in October 2013. The crater was formed in place of a mound, probably formed by gassing. We collected samples from willow shrubs on the ejected blocks of soil, the mound slope *in situ*, and the background shrub tundra. Based on the location of the blocks and their vegetation cover, we reconstructed the original block position on the top and slope of the initial mound. Further analysis of tree-ring width chronologies of the willows demonstrated that formation of the mound lasted for at least 66 years (most likely from the end of the 1940s), during which the mound increased in both diameter and height. We estimated the growth rate of the mound height in 1976–1985 at 8 cm per year. It has been for the first time for the tundra zone that in some loci the relationship has been observed between willow growth and air temperature of not only July but also August. Thus, such relationship can be used as indication of similar mounds. Noted is a recurring inconsistency between tree-ring width of willows on the mound and on the background tundra. Such tree-ring width dissonances have a 6-year periodicity, connected to the planetary tidal effect; identified are the Wolf cycle (10.8 years) and Hale cycle (20–22 years), as well. Gas emission fell into the year of dendrochronological dissonance at the peak of the solar cycle.

Gas-emission crater, gas-inflated mound, tundra shrubs, tree-ring width chronologies, natural cycles

INTRODUCTION

A gas emission crater was discovered in 2014 in the central part of the Yamal Peninsula, immediately to become a matter of close attention on the part of scientists, authorities and general public. It was established during the studies [*Leibman et al., 2014*] that emission occurred in the period from October 9 to November 1, 2013, at the place of a mound recorded in satellite images, the base diameter of which was 45–58 m and the height of which was 5–6 m. In early 2014, the crater depth was more than 50 m, the diameter of its cylindrical part was 15–16 m, that of the funnel was 25–29 m, and that of the parapet formed by the discharged material was about 70 m. Ice constituted the most of the material – 9,260 out of 11,200 m^3 [*Kizyakov et al., 2015*].

Shrubs are present both around the crater and on the blocks of the erupted material, allowing the scientists to use their tree-ring width chronologies to restore the parameters of this natural phenomenon considering the available regional experience [*Arefyev, 1994, 1998, 2015*], in particular, concerning dating permafrost landslides [*Leibman et al., 2000; Gorlanova, 2002; Nikolaev and Samsonova, 2012*], as well as the growing interest of the scientific community to shrub chronologies in evaluating the landscape-climatic changes in the Arctic [*Schweingruber and Poschlod, 2005; Schweingruber and Rump, 2010; Myers-Smith et al., 2011; Alsos et al., 2012; Buchwal et al., 2013; Buchwal, 2014*]. Tree-ring width chronologies are known to have been used in studying permafrost processes in Yakutia, in particular, in assessing the dynamics of forests and aufeis and reconstructing evolvement of thermokarst lakes and depressions [*Nikolaev and Petrov, 2009; Nikolaev, 2010, 2011; Nikolaev and Skachkov, 2012*].

A study of an object of such a kind by using the dendrochronological method has been undertaken for the first time. The objective of the study was to reconstruct the geomorphological processes of forming the gas-inflated mound by applying dendrochronological indicators. Based on the methodology of dendroindication [*Gorchakovsky and Shiyatov, 1985; Methods..., 1990*], the authors believed that the processes of mound formation and destruction were reflected in the parameters of tree rings and could be dated in analyzing tree ring width chronologies (TRWC). As the field works were conducted after the gas emission, in order to interpret the TRWC parameters, it was necessary to reconstruct the location of the studied shrubs in relation to the top and the slopes of the mound based on the materials of satellite images using geomorphological and geobotanical methods. It was also supposed that analysis of the response of TRWC to changes in the position of shrubs in the mesorelief would be able to confirm or correct the original location of the ejected `blocks.

MATERIALS AND METHODS

Selecting shrub samples and making TRWC

Willow samples meant for the study were collected in August 2015. The possibilities of field testing were limited both in terms of time and preservation of the shrubs after the gas emission. We were able to collect five stems of the woolly willow (*Salix lanata*) from the mound in question, with saw cuts made below the tillering node. These shrubs (samples S1–S5) grew in five different loci локусах of the mound surface from its top and slopes to its base (Fig. 1). Sample S6, selected at the distance of 54 m from the crater edge in the background tundra was considered as a control sample which was not exposed to the mound formation process. Loci S5 and S4 were represented by the willow which was preserved *in situ*, respectively, on the flat slope of the mound and, most likely, below its steep part (near the crater edge as in 2015) (Fig. 1). Three more loci were represented by the willow shrubs preserved on the ejected turf-covered blocks.

In order to reconstruct the positions of those blocks on the mound, it was assumed that the fragments most remote from the crater axis were most likely closer to its top in the original state. The study of the distances of rock fragments' emission in volcanic eruptions determined, other conditions being equal, by the distance between the fragment and the axis of the eruption column testified to this [*Carey and Sparks, 1986; Wohletz and Heiken, 1992*]. Judging by the distance between the block and the crater edge and by the photo indicators of its vegetative cover [*Dobrinsky, 1995*], the authors supposed that the block with willow S3, least remote from the crater axis, originally belonged to the upper part of the mound slope, S2 block belonged to the concave surface with a thick moss pad already within the mound top, while S1 belonged to the drained surface of the mound top (Fig. 1).

A shrub stem with its record structures (tree rings) was considered as a surface-located recorder of the state of the mound roof in the locus with the area of about 1–3 m^2, whereas information was read from it by measuring the width of the rings and by analyzing the TRWC. To make TRWC, common methods were used considering the specifics of the accretion of dwarf shrubs [*Methods..., 1990; Arefyev, 2015*]. As there were only single shrubs on the ejected blocks, one stem was taken for each locus, with the tree ring width measured in different sections of the stem at least three times (at its base, normally located under moss, 1/3 and 2/3 of its length, including crutches). The entire surface of the cut was cleared with a blade and contrasted with chalk powder. At each cut, measurements were carried out microscopically with the accuracy up to 0.01 mm using two perpendicular diameters, possibly in four radii. Altogether, in the reconstructed profile, measurements were conducted in 103 radii, from 10 to 31 for different loci.

In switch-back dating of the obtained ring series, the known TRWC from neighboring territories were used [*Arefyev, 1998, 2015; Leibman et al., 2000; Nikolaev and Samsonova, 2012*]. Rings of individual radii of each saw cut were dated, accompanied by tracing down of dubious and missing rings in their entire circumference under a microscope, then switch-back dating of TRWC was performed from different saw cuts and different samples. Then for each locus, series of the average width of annual rings (absolute TRWC) were calculated, in which information about the local factors determining the growth of a shrub was superimposed on the single macroclimatic ground common for the given territory. In addition, for each radius, standard indices of the tree ring width were calculated, with further series of average indices constructed. Such a procedure allowed the influence of local factors to be ruled out and maximum approximation of the individual TRWC to a common series to be achieved.

TRWC standardization was carried out by the method of triple moving average (*TMA*) with equal weights [*Greshilov et al., 1997*]:

$$EMA_1 = (p_1 + EMA_0)/2, \ldots, EMA_t =$$

$$= (p_t + EMA_{t-1})/2, EMA_0 = p_1; I_t = p_t/TMA_t,$$

where p – the absolute width of a ring; t – the position of the time series; EMA – first-order moving average; TMA – third-order moving average; I – the tree ring width index.

This method does not allow centennial climatic trends to be revealed; therefore, it is rarely used in dendrochronology [*Methods..., 1990*]. However, the use of a spline to the lowest window limit is reasonable due to the details of the shrub ring series in question – their small length, the high occurrence rate of anomalous values, and violations of the stationary character against the background of active geomorphological processes. Such standardization of shrubs' TRWC provides a higher and more reliable response to climatic parameters, compared to the widely used method of negative exponential smoothing previously used by the authors [*Arefyev, 2015*].

The parameters of multiple regression of standardized TRWC were found with the STATISTICA (v. 10) by climatic series. To evaluate the response of

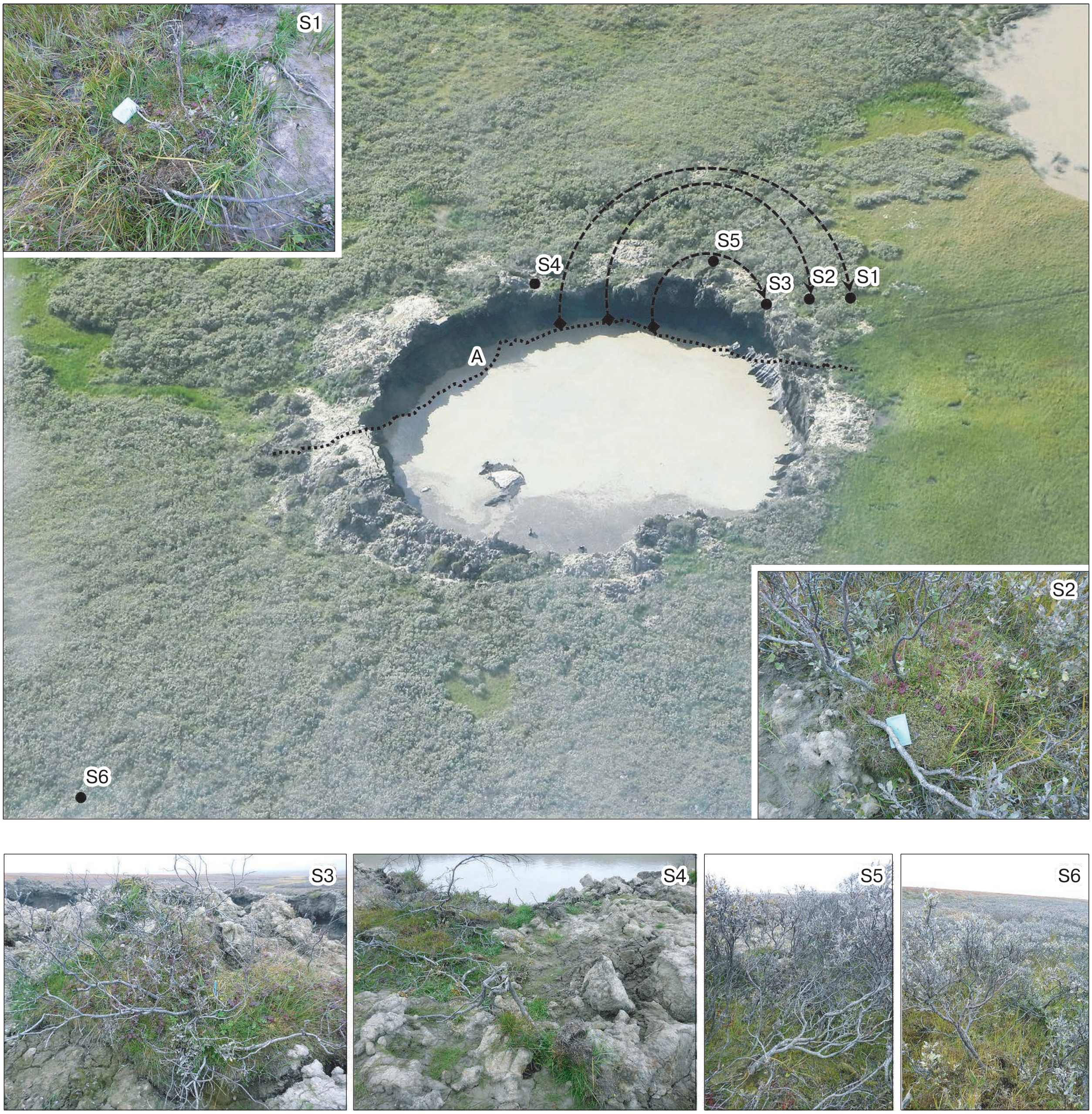

Fig. 1. Locations of willow shrub sampling (S1–S6) in the area of the Yamal gas emission crater (a view from a helicopter, the photo taken by A.V. Khomutov on 15.08.2015 and the condition of the area at the time of sampling (inserts S1–S6, the photo by A.V. Khomutov, 02.09.2015).

A – the reconstructed line of the mound surface [*Kizyakov et al., 2015*]; the arrows demonstrate reconstructed movement of the soil blocks with willow shrubs ejected during the emission.

TRWC to climatic factors, the parameter β was used – normalized regression coefficient, varying from –1 to +1. In the same software program, cluster analysis of TRWC was conducted, with the method of the simple Euclidian distance.

To characterize the local conditions of the shrubs' vegetation in the period of 1977–2013, the following parameters were calculated by absolute measurements: 1) the average width of a ring – the indicator of the quality of the soil and climatic conditions (i.e., the potential height which a shrub may reach under the given conditions); 2) the coefficient of variation of the rig width – the indicator of stability of the given conditions; 3) the sensitivity coeffi-

Table 1. **A characteristic of tree ring width chronologies (TRWC) of the willow shrubs at the place of the crater**

TRWC	Origin	Condition of shrub	Vegetation species	Projective coverage by tiers, %	Growth years	Age (at 2013), years	Number of radii	Shrub growth in 1977–2013			
								Average, mm	Variation, %	Sensitivity	Auto-correlation
S1	A block from the mound top ejected 11.5 m from the crater edge	Mossy turf 4–6(8) cm thick; dead broken willows	*Salix lanata* *Carex* sp. *Rubus arcticus* *Polemonium* sp. *Petasites frigidus* *Poa* sp. *Hylocomium splendens* + *Pleurozium schreberi*	<10 60 <5 <5 1 1 20	1951–2014	63	10	0.20	88.2	0.34	0.56
S2	A block from the mound top ejected 6 m from the crater edge	Mossy turf; dead broken willows 0.8–1.0 m long	*Salix lanata* *Carex* sp. *Rubus arcticus* *Petasites frigidus* *Pleurozium schreberi* *Polytrichum* sp.	50 20 15 1 70 5	1948–2013	66	12	0.16	55.2	0.36	0.29
S3	A block ejected from the steep slope of the mound on the parapet of the crater	Mossy turf; live willows 0.7–0.8 m long	*Salix* sp. *Carex* sp. *Rubus arcticus* *Ranunculus borealis* *Polemonium* sp. *Pleurozium schreberi*	15 25 25 <5 1 30	1976–2015	38	12	0.21	51.2	0.27	0.49
S4	A mound slope near the crater edge, partly buried by the parapet material	Dead broken willows	*Salix* sp. *Carex* sp. *Rubus arcticus* *Polemonium* sp. *Salix nummularia* *Petasites frigidus*	10 30 5 <5 1 1	1965–2014	49	15	0.30	47.5	0.26	0.61
S5	A flat mound slope 6 m from the crater edge	Live willow shrubs 0.6 m high above the surface, with a crutch	*Salix lanata* *Carex* sp. *Rubus arcticus* *Petasites frigidus* *Pleurozium schreberi*	70 40 5 1 80	1924–2015	90	31	0.28	49.8	0.29	0.41
S6	Poorly drained background area 54 m from the crater edge	Live willow shrubs 0.8 m high over the surface, with a crutch	*Salix lanata* *Carex* sp. *Polemonium* sp. *Pleurozium schreberi*	70 60 <5 70	1935–2015	79	23	0.33	41.2	0.25	0.49

cient of TRWC [*Douglass, 1936*] – the indicator of the limiting impact of external factors, proportional to the level of the shrub's physiological stress [*Arefyev, 1998*]; 4) auto-correlation of the first-order TRWC – the indicator of the relation between growth of the current and previous years, biologically characterizing the homeostatic ability of a shrub to preserve the relative sustainability of the internal environment under conditions of unstable external environment of vegetation (Table 1).

Dendrochronological indication of the height of snow cover

Under conditions of a tundra, the absolute growth of shrubs is determined by both climatic factors common for the given territory, primarily, by the summer air temperatures [*Arefyev, 2015*], and local factors, primarily, the depth of the active layer, the wind regime, and the height of the snow cover preventing shrub offshoots from freezing and damage by snow drifting [*Gorchakovsky and Shiyatov, 1985; Dobrinsky, 1995*]. In the subzone of the typical tundras of the Yamal Peninsula, willow offshoots survive only under the cover of snow, while the height and the absolute growth of the willow are normally proportional to the depth of the snow cover. The maximum growth of shrubs was recorded in the valleys of rivers and streams, where the height of the snow cover and the depth of the active layer reached maximum values. The growth curve in the chronologies of the radial growth of shrub willows is practically not observed in typical tundras [*Arefyev, 1998, 2015*]. This allows the use of the willow's absolute growth for indicating the conditions of the external environment without additional transformations ruling out the age-related features of the shrub growth.

The positive relation of the radial growth with the height of the snow cover was established also for the trees growing in the permafrost zone [*Nikolaev and Skachkov, 2011, 2012*], where the height of the snow cover determines the temperature regime of soils [*Nekrasov, 1981*]. When the snow cover height is low, severe freezing of the root layer take place in the winter period, which negatively affects the radial growth of trees in the following year. In this respect, the time of formation and disappearance of the stable snow cover and its maximum height are important [*Pozdnyakov, 1986; Nikolaev and Skachkov, 2012*].

Indication of the snow cover height by shrubs is of primary importance in reconstructing the mound growth, since, as its grows, the zone of its impact on the height of the snow cover increases, and the shrubs growing on the mound may rise from the zone of the high snow cover near the mound base to the zone where the snow is drifted off from the mound by winds.

Calculation of dendrochronological dissonances

Standardized TRWC from the tundra shrubs of the Yamal Peninsula, mainly reflecting the background macroclimatic signal, are normally characterized by high degrees of synchronicity and correlation [*Nikolaev and Samsonova, 2012; Arefyev, 2015*]. In some sections of TRWC, such correlation may be missing due to the impact of disturbing factors [*Arefyev, 2003*]. As the studies conducted by A.N. Nikolaev and V.V. Samsonova on the territory of the Bovanenkovo gas condensate field (GCF) showed, dissonance in the correlation of the TRWC of shrub willows is observed in permafrost landslides [*Nikolaev and Samsonova, 2012*]. In our case, incongruity of the TRWC sections of the willow from the mound, on the one hand, and of the TRWC sections of the willow from the control area, on the other hand, may be considered as evidence of local tensions in forming the mound. We designate such incongruity of TRWC as TRWC-dissonance.

To identify TRWC-dissonances, we used Pearson's sliding coefficient of correlation r_t with the lowest window limit, relating to the window's end date t [*Arefyev, 2003*], which provided a better result compared to rougher non-parametric Spearman's correlation coefficients; the calculation was made in standardized series.

The data from the Marre-Sale meteorological station were used [http://Aisori.meteo.ru/ClimateR], located 50 km south-west of the mound.

RESULTS AND DISCUSSION

Characteristics of tree ring width chronologies

The longest-lasting chronology of the willow was obtained from the flat slope of the mound (S5): it begins with 1924, the willow's age being 90 years at the time of the emission, which is close to the willow's limit age. In the reconstructed profile from the background tundra to the mound top, non-linear but ordered change in the willow's age is observed: in the background tundra and on the adjacent flat slope of the mound (S6 and S5) it is the greatest (79–90 years), followed by the steep slope (S4 and S3) and the least (49 years in the lower part and 38 years in the upper part), finally, on top of the mound (S1 and S2), the age of the shrub was 63–66 years (Fig. 1, Table 1).

Orderliness is observed in the change of the other TRWC parameters of the willow in the profile. In the direction from the background tundra to the mound top, the average width of the annual rings gradually decreases from 0.33 to 0.16–0.20 mm, while its variation, conversely, increases from 41.2 to 88.2 %, being the greatest in the drained locus of the mound top S1. Sensitivity of TRWC also gradually increases from 0.25 in the background tundra up to

0.34–0.36 on top. The greatest auto-correlation of TRWC is noted in the loci of the steep slope of the mound S3 and S4 (0.46 and 0.61), its level is somewhat lower in the low loci S5 and S6 (0.41 and 0.49). On the mound top, auto-correlation varies from the lowest value on the moss pad S2 (0.29) to the comparatively high value in the drained locus S1 (0.56).

The proportion of the missing rings was on average 5.5 % (S1 – 6.0 %; S2 – 9.9; S3 – 5.2; S4 – 8.3; S5 – 3.7; S6 – 6.2 %).

The recorded regularities testify to correctness of the profile reconstruction. Judging by the above TRWC parameters, in the background tundra and on the flat slope of the mound, where the oldest TRWC samples were taken, the conditions for the willow growth were generally most stable and beneficial. In the loci referred to the mound top, the conditions for willow growth were formed (or restored) later, by the end of the 1940s, depressive years for shrubs, with their cold summer seasons (Figs. 2, 3). The conditions for the willow in the loci of the mound top were least beneficial from the very beginning of its growth, from which we could conclude that by the end of the 1940s, the mound already rose above the plain, with snow drifting causing the depressed state of the shrub.

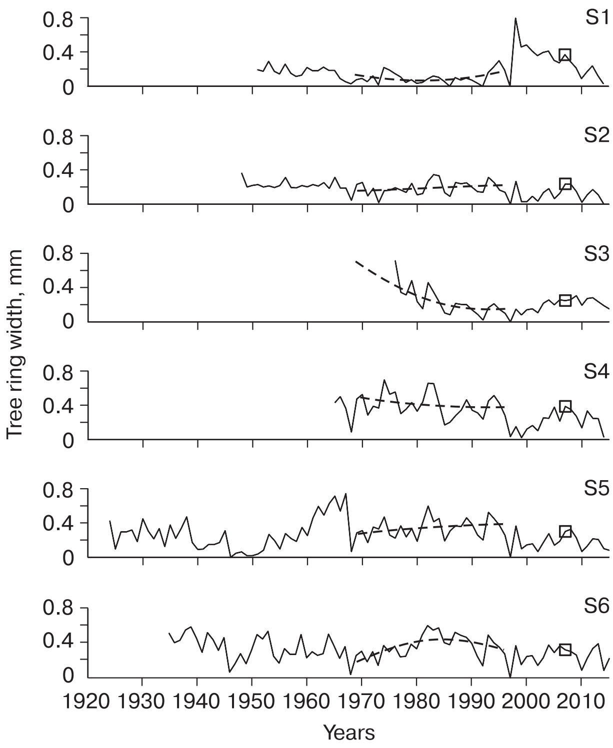

Fig. 2. Absolute chronologies (lines *1*) of the shrub ring width (mm) in the the emission zone.

Lines *2* – 2nd-degree polynomial trends of chronologies for the period of 1969–1996; a square indicates the window for evaluating agreement among the chronologies in 2008.

The conditions for willow growth emerged the latest (in 1965–1976) in the loci which were on the steep slope of the mound by the time of the gas emission (S3 and S4). Comparatively low sensitivity and high auto-correlation of TRWC of the willow shrubs on the side of the slope indicate the impact of the factors that determined the specific soil and climatic regime in these loci.

Analysis of the spatial and temporal changes of TRWC

Comparative analysis of absolute TRWC, recording all the background and local factors, influencing the shrubs' growth, suggests both similarity and differences in the willows' growth in different loci of the mound (Fig. 2). In most TRWC, negative annual willow growth anomalies occurred, judging by Fig. 2 and 3, in the years with unfavorable conditions of the vegetation season (a cold and short summer): 1941, 1946, 1949, 1968 (loci S4, S5), 1980, 1985, 1992, 1997, 2010, 2014 (Figs. 2, 3). Positive annual willow growth anomalies, normally synchronous with the prolonged warm vegetation seasons, occurred in 1938, 1953, 1956, 1965, 1974, 1982, 1989, 1993, 1998, 2007, and 2012 (Figs. 2, 3). The dates and the climatic causes of these anomalies agree well with the results of studying the TRWC of the willow shrubs both on the territory of the Bovanenkovo gas condensate field 50 km north [*Arefyev, 1998, 2015; Nikolaev and Samsonova, 2012*] and on the geocryological testing site Vas'kiny Dachi, located 40 km east of the crater [*Leibman et al., 2000*].

The many years' period of the decrease in the willow growth increment, related to the cold vegetation seasons of the 1940s, can be traced by the TRWC of the background tundra (S6). The depression was especially deep and prolonged in the lowest locus of the mound slope (S5), where dropping out of the rings was recorded in the shrubs in 1939–1952, while their average width was close to zero (Fig. 2). The beginning of the willow growth in the higher loci of the willow was recorded not earlier than at the end of the

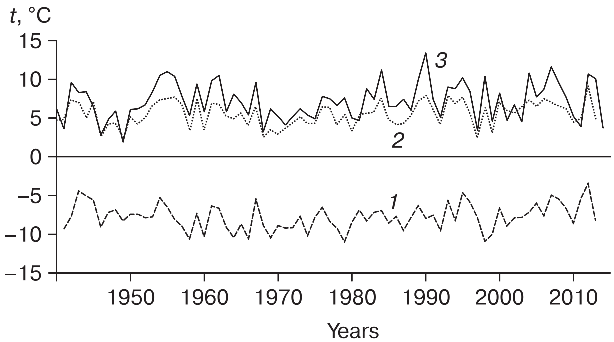

Fig. 3. Perennial behavior of the mean annual (*1*), summer (*2*) and July (*3*) air temperature *t* according to the data collected at Marre-Sale meteorological station.

vegetation period. At the same time, in the locus of the mound top S2, where it was recorded in 1948, no depression in the willow growth was observed. On the contrary, in 1948, the width of an annual tree ring was the highest over the entire period of the stem's life (0.36 mm), and in the following 1949, there was no anomalous drop in the willow growth, as in S5 and S6. We can suppose that locus S2, which in 2013 was on top of the mound, in 1948–1949 was yet in the zone of low snowdrifts at a low height near the then top of the mound or at its foot, but soon it was raised by the growing gas-inflated mound to the height from which the snow was blown by the winds. In the locus of the mound top S1, where the beginning of the willow growth is dated by 1951, no such picture can be seen: the first rings were narrow (0.19–0.18 mm), the growth decrease occurred in the late 1960s (to the level of about 0.1 mm), which was related to the anomalously cold summer season, seen in the loci, too.

The cause of the intense willow growth in S5 (up to 0.74 mm) compared to the control S6 (not more than 0.50 mm) in the 1960s is not quite clear. It is to be noted that 1957 was the year of the boundary between the epochs of atmospheric circulation [*Kononova, 2015*], determining, besides other things, the main bearings and the wind velocities, hence, the position of snowdrifts in relation to the mound, which is reflected on the shrubs' growth. Beginning with 1998, signs of transition to the northern meridian circulation with the highest variety and the least stability of the circulation regimes [*Kononova, 2015*] are noted. Thus, the configuration of the meteorological zone of the mound's impact on the willow growth could change depending on the type of atmospheric circulation, but throughout the circulation epochs and periods, the orientation of this zone in relation to the mound was determined by the prevailing bearings primarily of the snow period.

The willow growth on top of the mound (S1, S2) is less dependent on the direction of the winds, as whatever the direction is, snow is blown away from the mound top, and the shrub growth is constantly limited by the low height of the snow cover and by nivation. As a result, willows on top form low prostrate forms and are generally characterized by small (less than 0.2 mm) chronically depressive width of the annual rings. In locus S1, the width of the willow rings was the least before 1995 (on average about 0.1 mm); however, later it increased dramatically (up to 0.80 mm in 1998), indicating the influence of an additional local factor, which, judging by many things, was formation of a fracture in the mound roof.

As the mound height decreases on the mound slope, spatial-temporal shift of the willow growth depression and rise phases is observed (Fig. 2). In the upper part of the mound slope S3, the willow growth entered the depression phase (0.1–0.2 mm) in 1985–2002. Lower on the mound slope and in the control point (S4–S6), deep depression is noted for the later period, 1997–2002. It was initiated by extremely drastic climatic conditions of the summer of 1997, which resulted not only in the almost total dropout of that year's ring but also in drying of a part of the willow branches and generally long-lasting deterioration of the plants' living conditions as a whole. The depression was aggravated by the unfavorable weather conditions of 1999. No recovery of the willow growth to the previous level occurred in these loci (both in S2 and on top) until 2013. Only in two upper loci of the mound (S1 and, to a lesser degree, S3, the ring width exceeded the level which had existed before 1997.

Considering prolonged negative influence of the anomalously cold summer seasons on the willow shrubs' growth increment, many years' features of the willow growth can be best seen on the interval between the two deepest negative anomalies of 1968 and 1997. It is to be noted that it coincides with the most stable period of the epoch of southern atmospheric circulation [*Kononova, 2015*]. Approximation of TRWC in this time interval with a 2nd degree polynomial demonstrates a logical picture of changes in the trend of the willow growth depending on its position on the mound (Fig. 2). In the background tundra (S6), after the unfavorable year of 1968, gradual recovery of the growth increment is observed from 0.25 mm to a high level (about 0.5 mm) in the first half of 1980s, followed by a certain growth reduction.

On the flat slope of the mound (S5), recovery of the willow growth level first occurred in a similar way, but then certain increment in the willow growth was recorded before the end of the period under study, which may suggest an increase in the height of the snow cover and the wind shadow of the growing mound, favorable for the willow growth. It is to be noted that reliable multiple regression of the absolute willow growth has been recorded, with the amount of precipitation fall in the winter period preceding the ring formation (R = 0.58, the confidence level p = = 0.02), with the sums of the November precipitation (β = 0.45) and of the January precipitation (β = 0.36) being the significant factors of regression. This indicates that the level of the snow cover in the locus was largely determined by the background factors, whereas the influence of local factors on it was the lowest compared to other loci.

In the lower part of the steep slope (S4), recovery of the willow growth to a high level 0.48 mm occurred already in 1969, indicating a higher level of the snow cover in this locus in those years; then, throughout the period in question, the willow growth remained to be at almost the same level with a small trend for decrease.

Finally, in the upper part of the slope, the willow shrubs started to grow only from 1976, first forming very wide rings (up to 0.72 mm), characteristic of potentially the tallest stems and corresponding to a high level of snow. In this locus, a trend for growth decrease is manifested: already by 1985, it drops to 0.1 mm (0.2 mm in the approximating curve), which corresponds to the growth of prostrate willow shrubs on top of the mound, where snow is blown away by the winds. This may indicate that, as the mound grew, locus S3 left the zone of high snowdrifts and moved up the slope into the wind-exposed zone within 10 years, as the mound height increased by approximately 0.8 m (the willow shrub height in the zone of tall snowdrifts, see Table 1). Thus, the growth rate of the mound could roughly constitute about 8 cm/year, and the mound could reach its final height of 5–6 m in 62–75 years.

It is to be noted that in the longest chronology S5 depressions of 1939–1949 and 1997–2010 are most visible, the time interval between which is about 60 years. This is close to the 61–65-years' cycle, characteristic TRWC of the Polar Urals region [*Shiyatov, 1986*], and to the cycle of the 'atmosphere–Arctic ice–ocean' system [*Semenov, 2015*]. For its duration, such a cycle is close to the period from the beginning of the willow growth on top of the mound to its destruction (63–66 years).

A general picture of the recorded changes in the TRWC of the profile is provided by cluster analysis, conducted for the periods of 1978–1996 and 1997–2013, divided by the year of 1997 with its almost zero willow growth (all the six loci considered are present in these periods).

Clusterization of the absolute growth chronologies considers all the external factors affecting the ring width, both background and local factors. Its results for the period before 1997 allow identification of two clusters: the background cluster, including the control locus S6 and the lower loci S4, S5, and the cluster exposed to the mound formation processes, including the upper loci S1, S2, S3 (Fig. 4, *a*). After 1997, three clusters were formed: the drained locus of the mound top S1; the remaining loci of the mound; the control locus S6 (Fig. 4, *b*).

Clusterization of standardized TRWC distributes them by the specific features of the influence of macroclimatic factors on the willow growth in different loci (for example, the same climatic background exerts different influence on the tree growth in dry and bogged forests). In the period before 1997, we see gradual increase in the differences of the standardized TRWC from the control (S6) to the mound top (S1), which is caused by intensification of the transformation of the background macroclimatic signal in the willow growth by the local conditions of the mound in approaching to the mound top (Fig. 4, *c*, *d*). After 1997, three TRWC clusters were formed: S4 from the

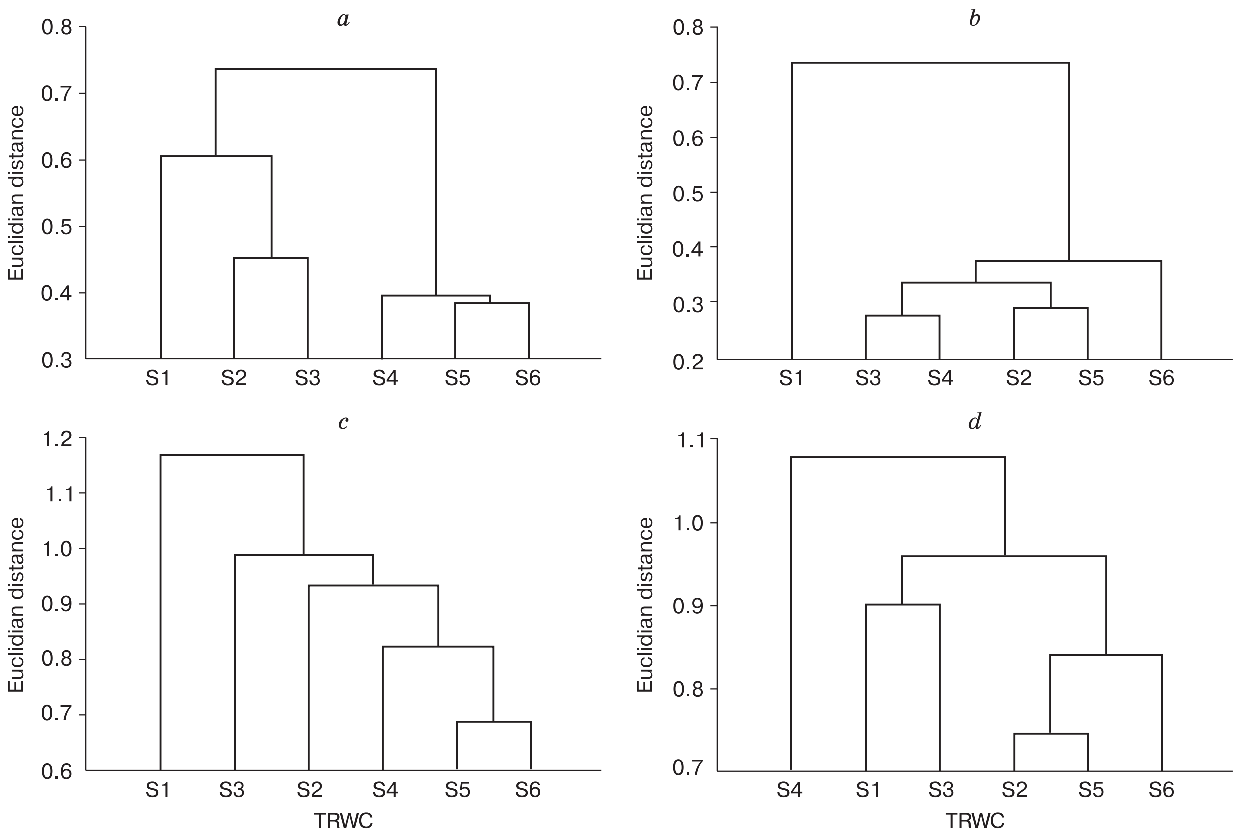

Fig. 4. Changes in the cluster position of the willow TRWC in the process of the mound growth.

Absolute tree ring width: *a* – 1978–1996, *b* – 1997–2013; standardized tree ring width: *c* – 1978–1996, *d* – 1997–2013.

lower part of the steep slope of the mound, the most isolated one from the others; drained loci S3, S1; poorly drained mossy loci S6, S5, S2.

The described regularities of TRWC clusterization confirm the conclusions presented in the analysis of the absolute growth curves regarding the increase in the mound size and intensification of the destructive processes in its cupola. Judging by them, before 1997, the lower locus S5 was not yet in the exposure zone of the mound, while locus S4, although exposed to its influence, did not entail many years' changes in the willow growth, essentially differing from the control. After 1997, loci S5 and S4 entered the influence zone of the forming mound, and S4 became exposed to the greatest impact. At the same time, on top of the mound, differentiation of the condition of individual loci took place, suggesting local surface damage, for example, formation of fractures. In such a damaged area of the mound top (S1) willow growth drastically rose due to drainage, the rise in the temperature of the active layer and protection from nivation of the willow stem prostrate in the fracture.

The specific features of the macroclimatic factors on the willow growth from the mound

To make search for the indicators of mounds preceding gas emission craters possible, parameters of multiple regression of standardized willow growth from the background tundra (S6) and from the mound (total TRWC S1–S5) were determined, with average monthly air temperatures in the time period from the spring of the year $t-1$, preceding the year of the ring formation, to August of year t of the ring formation. The only significant regression component in both cases is the air temperature in July, its response being 0.6–0.7. The response of the TRWC from the mound in the summer period lags behind compared to the control: the response to the June air temperature is lower than in the control and high to the August air temperature (Fig. 5). A similar delay was noted for the willow TRWC recorded in the north of the Gydan Peninsula, compared to the willow TRWC from the north of the Yamal Peninsula [*Arefyev, 2015*].

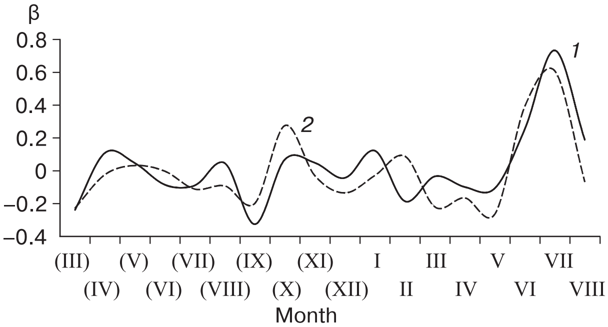

Fig. 5. Response β of standardized willow growth from the mound S1–S5 (line *1*) and from the background tundra S6 (line *2*) per year *t* to the mean monthly air temperatures per year *t* – 1 (in brackets) and per year *t* in the period of 1977–2013.

This delay is considered in more detail in the regression models providing reliable multiple correlation R of the standardized width of the willow rings with climatic factors, constituting from 0.61 to 0.74 for different loci (Table 2). In four out of six loci, including the control locus, the July air temperature is the only significant regression component. However, the August air temperature becomes a significant component in the drained locus of the mound top S1 and especially in the locus of the base of the steep mound slope S4. Moreover, in S4, it is most common-

Table 2. **Regression parameters of TRWC of the mound by mean monthly air temperatures *t* and monthly amounts of precipitations *h* of the previous (in brackets) and current years for different combinations of months**

TRWC	Parameter	*t*					*t*, [*h*]	
		VI–VIII	V–VIII	III–VIII	(VI–VIII), VI–VIII	(V–VIII), V–VIII	VI–VIII	V–VIII
S6	*M*	VII	VII	VII	VII	VII	VII, [*h*: VII]	VII
	p	0.001	0.001	0.0009	0.005	0.009	0.002	0.005
S5	*M*	VII	VII	VII	VII	VII	VII	VII
	p	0.0001	0.0002	0.0003	0.0009	0.0003	0.0003	0.002
S4	*M*	VII, VIII	VII, VIII	VII, VIII	VIII	VIII	VIII	VIII
	p	0.001	0.003	0.02	0.01	0.04	0.01	0.04
S3	*M*	VII	VII	VII	VII	VII	VII	–
	p	0.001	0.003	0.01	0.01	0.03	0.01	0.02
S2	*M*	VII	VII	VII	VII	VII	VII	VII
	p	0.001	0.001	0.003	0.009	0.008	0.004	0.01
S1	*M*	VII, VIII	VII, VIII	VII, VIII	VII	VII	VII, VIII	VIII
	p	0.0002	0.0002	0.001	0.0005	0.001	0.0009	0.0004

Note. *M* – meaningful components (month); *p* – level of reliability of the regression model.

ly the significant component. It is these two loci that were most isolated from the other loci in the period after 1997 in clusterization by Euclidean distance (Fig. 4). It is likely that the TRWC response to the background climatic regime is changed by the process of mound formation. Significant response of TRWC to the August air temperature in Subarctic was recorded only for the larch from extreme north-east of Yakutia [*Vaganov et al., 1996*].

The regularities of manifestation of TRWC-dissonances on the mound

Analysis of the concordance between standardized TRWC of the mound willows and the TRWC of the control willow shrubs allowed us to reveal a number of TRWC-dissonances (Fig. 6), which, as noted above, are considered as an indicator of tensions arising in the mound rocks in the process of mound growth. To make the presentation more demonstrative, the window of calculating the TRWC-dissonance of 2008 is highlighted with a square in Fig. 2. Considering individual TRWC-dissonances for each locus (S6:S5, etc.), their manifestation looks spontaneous. However, the chronology of the minimum values of concordance r_t per year t for all the five mound loci min [r_t (S6:S1), ..., r_t (S6:S5)] demonstrates synchronicity and cyclic orderliness of the TRWC-dissonances of the mound (Fig. 6, Table 3). It is interesting that the last dissonance occurred in the year of the mound destruction during the gas emission (the year of 2013).

TRWC-dissonances correspond to the year with a comparatively cold summer and low willow growth, immediately following the year with a comparatively warm summer or several such years with high shrub growth (Fig. 7).

The clear 6-years' cyclic nature of the TRWC-dissonances on the mound can be seen in Fig. 6. It can be seen from Table 3 that regularity of manifestation of this cycle in different loci is unequal; the most regular manifestation of the TRWC-dissonances is observed with a period of 24 years (in 1989 and in

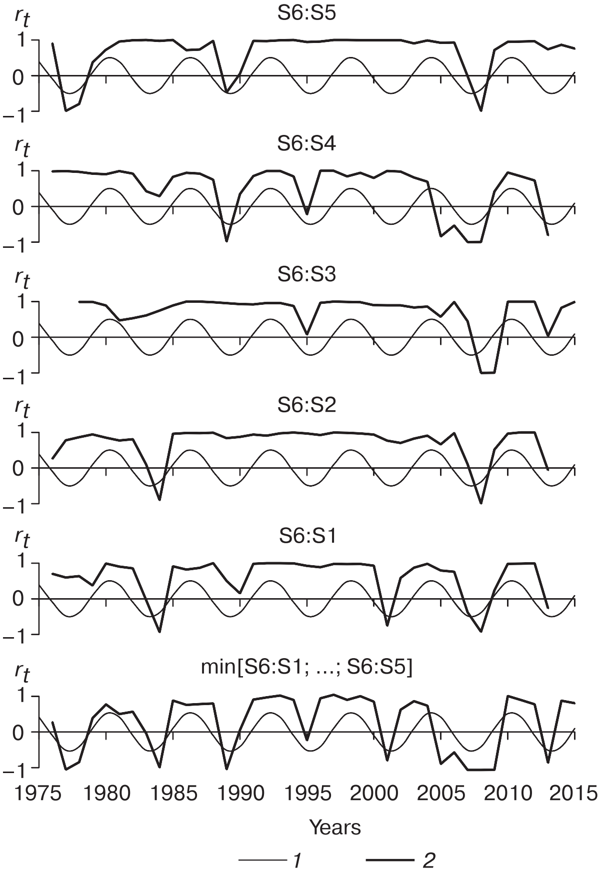

Fig. 6. Changes in concordance r_t between TRWC of the mound S1–S5 and TRWC of the background tundra S6 (line *2*) and in the framework of a 6-years cycle (line *1*).

Table 3. **Dating and manifestation of TRWC-dissonances in the mound**

Mound locus	Dissonance year						
	1977	1984	1989	1995	2001	2008	2013
S5	+		+			+	
S4		+	+			+	+
S3				+		+	+
S2		+	+			+	+
S1	+	+	+		+	+	+
The number of loci marked by dissonance	2	3	4	1	1	5	4

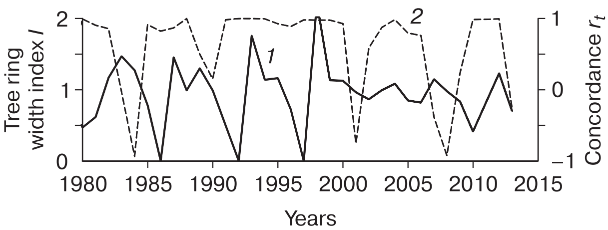

Fig. 7. Standardized TRWC of the background tundra S6 (line *1*) and its concordance, min [r_t (S6:S1... S5)] with TRWC of the mound (line *2*).

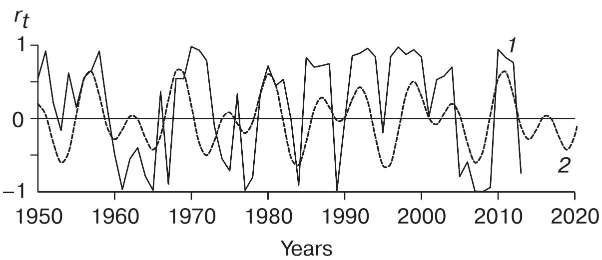

Fig. 8. Chronology of concordance in the willow growth from the mound top r_t (S1:S6) (line *1*) and its approximation by the Fourier harmonica (line *2*), periods 6 and 20 years, r = 0.61.

2013). The method of auto-correlation provides a similar picture.

Fourier's spectral analysis method also shows the presence of a cycle of TRWC-dissonances with a period of 5.4–6.0 years, also 12-years' and 18-years' cycles are reliably manifested (likely multiple of the 6-years' cycle), the Wolf cycle (10.6–10.8 years) and the Hale cycle with a period of 20–21 years (Fig. 8). At that, the 5.4–6.0-years' cycle и the Hale cycle are characteristic of the TRWC of the Polar Urals region [*Shiyatov, 1986*]. The tidal forces of the Moon and of the Sun are indicated as causes of their emergence [*Yavorsky, 1975; Yavorsky et al., 1979*], which seem to destabilize the condition of the mound from time to time. It is also to be noted that the gas emission occurred at Wolf's solar activity peak registered in 2011–2013 [*Review..., 2014*]. Similar TRWC-dissonances in the mound loci correspond to the high peaks of the solar activity of 1989 and 2000–2001. On the contrary, the TRWC-dissonances of 1984, 2001, and 2008 were synchronous with the solar activity minima.

CONCLUSIONS

Analysis of the shrub ring width chronologies from the area of a crater formed in Central Yamal as a result of gas emission allowed the following conclusions to be drawn.

The mound which preceded the emergence of the gas emission crater seems to have started to get formed in the 1940s. This is testified by the stably low level of the willow growth in the locus of the mound top, characteristic of the elevated areas exposed to winds, which followed the period of the first two years of the willow growth (1948–1949). Similar dating of the beginning of the mound growth was obtained in calculating based on the approximate growth rate of the mound, evaluated by the TRWC of the willows from the mound slope.

In the period from 1976 to 1985, the mound height increased by approximately 0.8 m. This is testified by the reduction in the level of the willow growth from the upper locus of the mound slope, probably related to the change in the position of the willow shrubs on the mound in the process of mound formation. The originally high willow growth corresponded to the potential height of the willow shrubs under 0.8 m and their presence in the zone of snow drifts in the lower part of the mound slope. By the end of the period, judging by the low value of the willow growth, characteristic of prostrate shrubs, the willow shrubs turned out to be growing on the higher zone of the slope exposed to the winds. This allowed us to evaluate the vertical growth rate of the mound as approximately 8 cm/year and the estimated time of the mound growth to reach the ultimate height as 62–75 years.

The vertical growth of the mound and its growth in the diameter continued in the period of 1997–2013 until its destruction due to gas emission. This is evidenced by the increase of the mound's zone of impact on the willow growth prior to the gas emission, compared to the previous period by the results of the cluster analysis of the TRWC of the willow from different loci of the profile from the background tundra to the mound top.

The dramatic increase in the willow growth in the locus of the mound top in 1995–1998 seems to be related to the emergence of fractures in the mound roof and to respective increase in the draining degree and the depth of seasonal melting around the fractures, as well as to protection of the shrub growing in the fracture from nivation.

Dissonances between the TRWC of the willows growing on the mound and in the background tundra are caused by the local factors of mound formation and are manifested cyclically with a period of 6 years. The cycle of such duration is related to the effect of the tidal forces, which have possibly influenced the process of mound formation. In manifestations of the TRWC-dissonances, natural cycles were also identified: the Wolf cycle (10.6–10.8 years) and the Hale cycle (20–22 years). The 2013 emission occurred in the year of the TRWC-dissonance and Wolf's solar activity peak.

For certain mound loci, tree ring width growth has been reliably determined as caused not only by July but also August air temperatures in the year of ring formation, which is unusual for the transpolar region. The relation between the width of the tree rings and the air temperature in August may be considered as an indicator of the processes that resulted in the gas emission.

The authors extend their gratitude to V.A. Glazunov for the descriptions of the vegetative cover he made.

The study was performed with partial support of the Russian Science Foundation (grant 16-17-10203).

Reference

Alsos, I.G., Eidesen, P.B., Broekman, R., Loonen, M., Rozema, J., 2012. No divergence in *Cassiope tetragona*: persistence of growth response along a latitudinal temperature gradient and under multi-year experimental warming. Ann. Botany, No. 110, 653–665.

Arefyev, S.P., 1994. Evaluation of the condition of the shrub vegetation in the tundra in the areas of gas condensate production of Middle Yamal, in: Development of the North and Re-cultivation Issues: Proceedings of the II International Conference. Syktyvkar, pp. 117–122. (in Russian)

Arefyev, S.P., 1998. Chronological evaluation of the condition of the shrub tundras in Yamal. Sib. Ecol. Zhurn., No. 3–4, 237–243.

Arefyev, S.P., 2003. Correlation analysis of the growth anomaly in trees and shrubs on the Taz Peninsula, in: Dendrochronology: Achievements and Perspectives: proceedings of the all-Russia meeting with participation of foreign scientists, Sukachev Forest Institute, Krasnoyarsk, SB RAS, p. 51. (in Russian)

Arefyev, S.P., 2015. Fixation of climate warming in the grow ring chronologies in the north of Yamal and of the Gydan Peninsula. Zhurn. Sib. Federalnogo Un-ta, biology series 8 (4), 377–393.

Buchwal, A., 2014. Dendroclimatological records of annual growth in high and low arctic sites (central Spitsbergen, W. Greenland), in: Tree Ring in Archeology, Climatology and Ecology (TRACE 2014). Aviemore, Scotland, 27 pp.

Buchwal, A., Rachlewicz, G., Fonti, P., Cherubini, P., Gärtner, H., 2013. Temperature modulates intra plant growth of *Salix polaris* from a high arctic site (Svalbard). Polar Biology 36 (9), 1305–1318.

Carey, S., Sparks, R.S.J., 1986. Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. Bull. Volcanol. 48, 109–125.

Dobrinsky, L.N., (Ed.), 1995. The Nature of Yamal. Nauka, Yekaterinburg, 437 pp. (in Russian)

Douglass, A.E., 1936. Climatic cycles and tree-growth. Wash., Carnegie Inst., vol. 3, 171 pp.

Gorchakovsky, P.L., Shiyatov, S.G., 1985. Phytoindication of the Natural Conditions and Processes on Highlands. Nauka, Moscow, 209 pp. (in Russian)

Gorlanova, L.A., 2002. The method of dendrochronological dating of landslide events, in: Extreme Cryospheric Phenomena. Fundamental and Applied Aspects: abstracts of international conference. Moscow, Scientific Council on Earth Cryology, RAS, pp. 148–149. (in Russian)

Greshilov, A.A., Stakun, V.A., Stakun, A.A., 1997. Mathematical Methods of Making Forecasts. Radio i Svyaz, Moscow, 112 pp. (in Russian)

Kizyakov, A.I., Sonyushkin, A.V., Leibman, M.O., Zimin, M.V., Khomutov, A.V., 2015. Geomorphological conditions of the gas-emission crater and its dynamics in Central Yamal. Kriosfera Zemli XIX (2), 13–22.

Kononova, N.K., 2015. Changes in atmospheric circulation of the Northern Hemisphere in XX–XXI centuries and their consequences for the climate. Fundam. i Prikl. Klimatologiya, No. 1, 133–162.

Leibman, M.O., Kizyakov, A.I., Archegova, I.B., Gorlanova, L.A., 2000. Development stages of a cryogenic landslide on Yugra Peninsula and in Yamal. Kriosfera Zemli IV (4), 67–75.

Leibman, M.O., Kizyakov, A.I., Plekhanov, A.V., Streletskaya, I.D., 2014. New permafrost feature – deep crater in Central Yamal, West Siberia, Russia, as a response to local climate fluctuations. Geography, Environment, Sustainability 7 (4), 68–80.

Methods of dendrochronology: Applications in the environmental science, 1990. Cook, E.R., Kairiukstis, L.A. (Eds.). Kluwer Acad. Publ., Dordrecht; Boston; London, 364 pp.

Myers-Smith, I.H., Forbes, B.C., Hallinger, M., et al., 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environ. Res. Lett., 6 (4), 15 pp.

Nekrasov, I.A., 1981. Snow cover and deep freezing of the lithosphere, in: Thematic and regional studies of the permafrost soils of Northern Eurasia. Permafrost Institute, SB RAS, Yakutsk, pp. 3–21. (in Russian)

Nikolaev, A.N., 2010. Dendrochronological studies of aufeis in Central Yakutia. Led i Sneg 1 (109), 93–102.

Nikolaev, A.N., 2011. Dendrochronological analysis of natural processes in the permafrost zone (Central Yakutia): Author's abstract, doctorate thesis (biology), Yakutsk, 336 pp.

Nikolaev, A.N., Petrov, R.N., 2009. The influence of cryogenic processes on the forest ecosystems of Central Yakutia, in: The environmental and geographic aspects of forest formation: proceedings of the all-Russia meeting with participation of foreign scientists, Sukachev Forest Institute, Krasnoyarsk, SB RAS, pp. 124–127. (in Russian)

Nikolaev, A.N., Samsonova, V.V., 2012. The influence of overland flow processes on the growth of willows in Yamal. Vestn. TyumGU, No. 12, 195–203.

Nikolaev, A.N., Skachkov, Yu.B., 2011. Influence of the snow cover dynamics on the growth and development of forests, Central Yakutia. Kriosfera Zemli XV (3), 71–80.

Nikolaev, A.N., Skachkov, Yu.B., 2012. The influence of the snow cover and of the temperature regime of permafrost soils on the radial growth of trees in Central Yakutia. Zhurn. Sib. Federalnogo Un-ta, biology series, No. 5, 43–51.

Pozdnyakov, L.K., 1986. Permafrost Forest Studies. Nauka, Novosibirsk, 192 pp. (in Russian)

Review of the Condition and the Degree of Environmental Pollution in the Russian Federation after 2013. 2014. Federal Agency of Hydrometeorology and Environmental Monitoring (Rosgidromet), Moscow, 227 pp. (in Russian)

Schweingruber, F.H., Poschlod, P., 2005. Growth rings in herbs and stem anatomy. Forest Snow and Landscape Res. 79 (3), 195–415.

Schweingruber, F.H., Rump, H.H., 2010. Annual ring studies on plants in permafrost areas of the high Arctic, in: European Conf. on Permafrost (EUCOP III), Norway, Svalbard Sci. Centre, Longyearbyen, 2010, vol. 3, p. 75.

Semenov, V.A., 2015. Fluctuations of the modern climate caused by feedbacks in the atmosphere–Arctic ice–ocean system. Fundam. i Prikl. Klimatologiya, No. 1, 132–148.

Shiyatov, S.G., 1986. Dendrochronology of the Upper Boundary of the Forest in the Urals. Nauka, Moscow, 137 pp. (in Russian)

Yavorsky, N.H., 1975. Astro-dynamic and statistical prediction of climatic conditions accounting for possible formation of draughts and overwetting. Voprosy Agronomii, Kyrgyz Agricultural Institute, Frunze, pp. 118–125.

Yavorsky, N.H., Yavorsky, E.N., Yavorsky, V.N., 1979. Theoretically possible precipitation cycles due to the impact of atmospheric tides on them. Voprosy Agronomii, Kyrgyz Agricultural Institute, Frunze, pp. 131–137.

Vaganov, E.A., Shiyatov, S.G., Mazepa, V.S., 1996. Dendrochronological Studies in Ural-Siberian Sub-Arctic. Nauka, Novosibirsk, 246 pp. (in Russian)

Wohletz, K., Heiken, G., 1992. Volcanology and Geothermal Energy. Berkeley; Univ. California Press, Los Angeles; Oxford, 432 pp.

URL: http://Aisori.meteo.ru/ClimateR (submittal date: 01.06.2016).

Received June 14, 2016