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**ISOTOPIC COMPOSITION AND SOURCES
OF ATMOSPHERIC PRECIPITATION IN CENTRAL YAKUTIA**

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The data on the isotopic composition of precipitation sampled during the cold period of 2013–2014 and the warm period of 2014 in Central Yakutia have been presented. The isotopic composition of precipitation of the cold period has been revealed to be essentially dependent on the air temperature, and the angle of inclination of the local meteoric water line (slightly greater than the global meteoric water line angle) and deuterium excess (above 10 ‰) have confirmed the cryogenic fractionation of precipitation. The situation for the warm period has been demonstrated to differ: independence on the ambient temperature, the angle of less than 8 degrees and negative deuterium excess collectively suggest the possibility of evaporative fractionation and changes in the precipitation sources. Based on the method of analysis of the reverse trajectories of air masses (model HYSPLIT) and the isotopic composition of precipitation, seven regions have been identified as sources of the atmospheric moisture which precipitated in Central Yakutia during the analyzed period. It has been demonstrated that in the warm season the Sea of Okhotsk is the dominant source of precipitation in Central Yakutia; its contribution has been estimated as 41.1 % of the total rainfall of the warm season of 2014.

Central Yakutia, precipitation of warm and cold periods, oxygen and hydrogen isotopes, deuterium excess

INTRODUCTION

The genesis of ice wedges and of textural ice, the key objects of the permafrost zone, is the subject of continuing discussion [Ershov, 1989; Vasil'chuk, 1989; Dereviagin et al., 2010, 2013; Kritsuk, 2010; Vasil'chuk et al., 2012]. The results of the geocryological studies obtained using isotopic methods [Vasil'chuk, 1992; Meyer et al., 2002, 2015; Raffi et al., 2004; Wetterich et al., 2008, 2011; Kritsuk, 2010; Opel et al., 2011; Vasil'chuk Yu.K., Vasil'chuk A.C., 2011; Boereboom et al., 2013; Dereviagin et al., 2013], confirm the previously made assumption that the isotopic composition of ice wedges primarily reflects the winter conditions of moisture accumulation, while that of textural ice suggests the summer conditions [Vasil'chuk, 1989].

As a rule, the results of paleo reconstructions based on the isotopic data of ice wedges and of textural ice are poorly verified and insufficiently substantiated due to insufficient information relating to seasonal changes in the isotopic composition of the original sources of moisture, in particular, of atmospheric precipitation. Therefore, analysis of seasonal variations of the modern isotopic composition and of the sources of atmospheric moisture is not only of interest for evaluation of the natural and climatic con-

ditions and global circulatory processes controlling precipitation in the territory under study but is also extremely important for paleo climatic and paleogeocryological reconstructions.

It is known that the correspondence between the stable oxygen isotopes ($\delta^{18}\text{O}$) and hydrogen isotopes (δD) in atmospheric precipitation is determined by an empirical relation which was named the global meteoric water line (GMWL): $\delta\text{D} = 8 \cdot \delta^{18}\text{O} + 10$ [Craig, 1961; Rozanski et al., 1993]. Changes in the isotopic ratios $\delta^{18}\text{O}/\delta\text{D}$ in the falling atmospheric precipitation allow the ways of moisture delivery to the region in question to be ascertained. The deviation of the curve of isotopic ratios $\delta^{18}\text{O}/\delta\text{D}$ from the GMWL may allow evaluation of the processes of isotopic fractioning, resulting in the fact that the ratio $\delta^{18}\text{O}/\delta\text{D}$ in this precipitation may be described by its local meteoric water line (LMWL). The estimate indicator is the deuterium excess (d-excess, or $d_{\text{exc}} = \delta\text{D} - 8 \cdot \delta^{18}\text{O}$), proposed by [Dansgaard, 1964] on the basis of the GMWL-dependence to characterize the regional specifics of the atmospheric water vapor or atmospheric precipitation, is successfully applied to identification of its sources [Merlivat and Jouzel, 1979; Fricke and

O'Neil, 1999; Froehlich *et al.*, 2002]. In interpreting the isotopic analysis data, special attention was paid to the correspondence between $\delta^{18}\text{O}$ (or δD) in atmospheric precipitation and the temperature of the ambient air, allowing their use as transient functions of an "isotopic paleo thermometer" [Jouzel, 1997].

Unfortunately, changes and formation of the isotopic composition of atmospheric precipitation are insufficiently studied in the vast territory of Russia. Whereas rather detailed studies in this area have been published for certain northern and mountainous regions of primarily the western part of Russia in this area of research [Brezgunov *et al.*, 1998; Vasil'chuk *et al.*, 2005, 2006; Vasil'chuk and Chizhova, 2010; Chizhova *et al.*, 2013], there are only few studies of this kind relating to the Asian part of Russia, with the studies headed by N. Kurita being the most significant ones [Kurita *et al.*, 2003, 2005].

The goal of this study was to investigate the isotopic composition of atmospheric precipitation of Central Yakutia (each specific case of precipitation fall was considered individually) and the reverse trajectories of the air masses accounting for the fall of this precipitation, in order to determine the main sources of atmospheric moisture and to evaluate the contribution of these sources to the total amount of precipitation falling in the region throughout the year.

THE AREA UNDER STUDY

Central Yakutia is situated in the middle course of the Lena River, practically in the center of Eastern Siberia. In the east and north-east, it is surrounded by the Verkhoyansky Ridge, while in the south it is backed by the Aldanskoye Highland (Fig. 1); its setting in the midst of mountain ranges emphasizes the central position of both the territory of the Sakha Republic (Yakutia) and of its capital, Yakutsk.

For a large part of the year, Central Yakutia is subject to the Siberian anticyclone and is characterized by a sharply continental climate with the annual temperature fluctuations exceeding 100 °C and the mean annual amount of atmospheric precipitation of about 200 mm, comparable to the precipitation in steppe and semi-desert regions [Gavrilova, 1962; Skachkov, 2012]. In accordance with the data of [The Second... Report..., 2014], in the period of 1976–2010, reduction of both the annual (the linear trend coefficient is $-1.09 \text{ mm/month/10 years}$) and seasonal (the linear trend coefficients are negative, except the spring season of $+0.47 \text{ mm/month/10 years}$) amount of atmospheric precipitation was recorded in Eastern Siberia. The amount of precipitation of the cold season in Central Yakutia is about 1/6 of its total amount [Gavrilova, 1962], whereas in the warm season evaporation often exceeds the amount of the precipitation coming to the region [Ohta *et al.*, 2001].

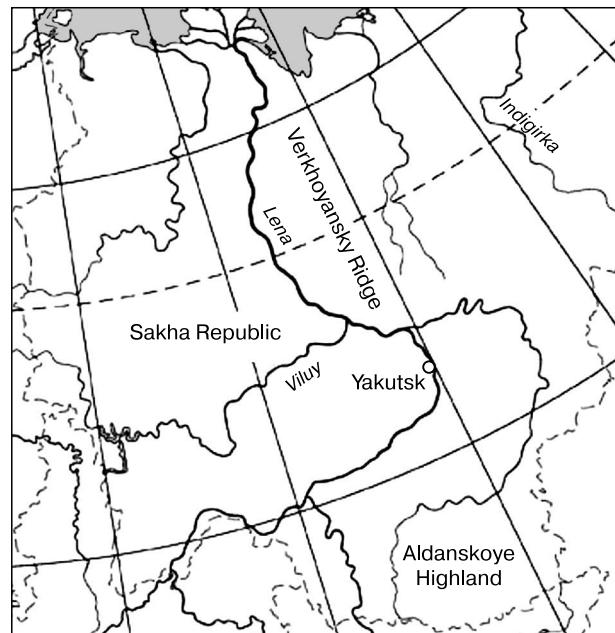


Fig. 1. The region under study and the location of the sampling point (Yakutsk).

ANALYSIS METHODS

Sampling

The samples of precipitation were put into plastic samplers at the stationary research site of the Melnikov Permafrost Institute (MPI) SB RAS, located in the outskirts of Yakutsk (62.1° N , 129.8° E , 103 m asl). Soon after sampling, liquid atmospheric precipitation was put into pressure-tight plastic vials. The samples of solid atmospheric precipitation (snow) were kept frozen in pressure-tight plastic bags, they were melted before being transported to the laboratory and put into pressure-tight vials. In total, from October 2013 to September 2014, 31 samples of liquid and solid atmospheric precipitation were taken.

Isotopic analysis

Analysis of the composition of stable isotopes ($\delta^{18}\text{O}$, δD) was carried out in the chemical analytics center of the Institute for Water and Environmental Problems, SB RAS, Barnaul. The precipitation samples delivered to the laboratory were filtered and put into pressure-tight vials; they were stored in a refrigerator until analysis. Stable isotopes were determined by the method of laser absorption IR-spectrometry using the PICARRO L2130-I analyzer, equipped with the WS-CRDS (Wavelength-Scanned Cavity Ring Down Spectroscopy) system. The use of the WS-CRDS technology allowed elimination of spectral overlays (<http://meetingorganizer.copernicus.org/EGU2014/EGU2014-14973.pdf>) and achievement of high accuracy and reproducibility of deter-

mining the isotopic composition. In this study, the accuracy of δD и $\delta^{18}\text{O}$ ($1\sigma, n = 5$) measurement was ± 0.4 and $\pm 0.1 \text{ \textperthousand}$, respectively. Samples of water calibrated relative to the International Standard V-SMOW-2 (IAEA) were used as internal standards.

Reverse trajectories and weather conditions

The weather conditions for the period of the falling and sampling of atmospheric precipitation were evaluated based on meteorological observations conducted from the Tuimaada site (the territory of the MPI, SB RAS), as well as using the data provided by Rosgidromet (Federal Service of Hydrology, Meteorology and Environmental Monitoring of Russia) and by the National Oceanic and Atmospheric Administration (NOAA), USA, available at the respective websites (<http://rp5.ru/docs/about/ru>, 2015; <http://www.noaa.gov>).

The reverse trajectories of air masses accounting for the fall of atmospheric precipitation were calculated with the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model [Draxler and Rolph, 2015; <https://ready.arl.noaa.gov/HYSPLITtraj.php>]. As original meteorological information, the GDAS archives were used, having spatial resolution of 0.5° and encompassing the time period from September 1, 2007 to the present time. The reverse trajectories were calculated individually for each case of precipitation fall. The beginning of building the trajectories corresponded to the moment of the start of precipitation fall and was counted off from the point of precipitation sampling (Yakutsk). Each calculated trajectory covered the time interval from 96 to 240 hours, depending on the remoteness of the potential water source (ocean/large water reservoir). The water area of the Atlantic Ocean is normally con-

sidered to be the major source of atmospheric moisture falling as precipitation in the northern part of the Eurasian continent [Numaguti, 1999]. Therefore, the reverse trajectories were calculated in such a way as to consider the influence of this source, namely, the duration of up to two natural meteorological periods was included. The trajectories were determined for three absolute altitudes, allowing the influence of local (500 m), regional (1500 m) and global (3000 m) potential sources of atmospheric moisture to be evaluated.

Analyzing the data of the height of the cloud's lower boundary at the time of precipitation, for each case a "leading" trajectory was chosen, which was higher than the lower cloud boundary and described the movement of the air masses that are a source of precipitation formation and fall. Selection of the "leading" trajectory was necessitated by the fact that, in the absence of significant change in the isotopic composition of atmospheric precipitation below the cloud base during the precipitation, the variations of the height of the cloud boundary from one event to another may be significant (more than 2,500 m) [Vasil'chuk and Kotlyakov, 2000]. The selected trajectories were scaled uniformly to make a catalogue of reverse trajectories of air masses for the period of atmospheric precipitation.

RESULTS AND DISCUSSION

A characteristic of the meteorological conditions of the period under study

The mean annual air temperature in Central Yakutia in the period of 2013–2014 was 2°C higher than the climatic norm of 1981–2010. The cold period (October–March) made a significant contribution

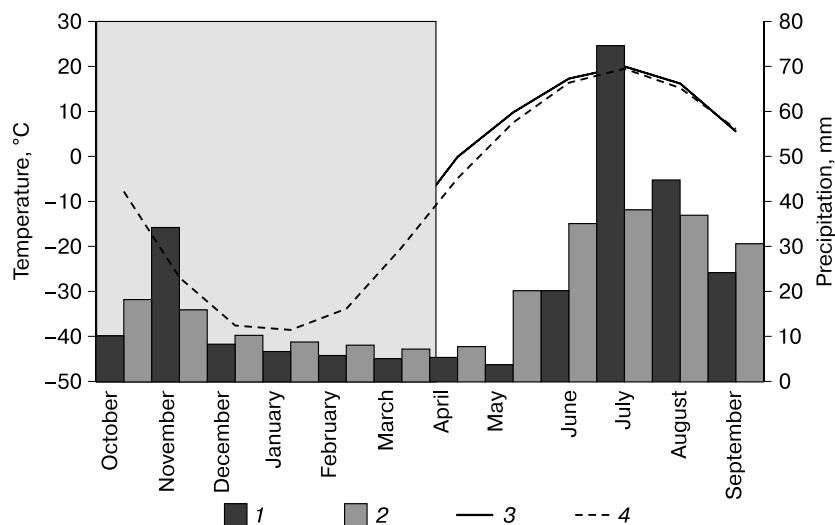


Fig. 2. Meteorological conditions of the period of sampling from October 2013 to September 2014 and of the climatic norm of 1981–2010.

1, 2 – temperature, $^\circ\text{C}$ (1 – 2013–2014; 2 – 1981–2010); 3, 4 – precipitation, mm (3 – 2013–2014; 4 – 1981–2010). The gray area stands for the cold season.

to the difference in temperatures, as it was 2.5 °C warmer than the normal season (1981–2010), unlike the warm season (April–September), which turned out to be only 1.5 °C warmer. The maximum difference of the mean monthly temperatures (7.4 °C) was obtained for December, whereas the minimal difference (0.5 °C) was obtained for July (Fig. 2). The total amount of precipitation was only 7 mm greater than the climatic norm (2 mm greater for the cold period of 2013–2014 and 5 mm greater for the warm period), but the breakdown by the months was not typical. In the warm period of 2014, in July, the rainfall was nearly 100 % above the norm. This fact is described in the paper dealing with anomalous hydrometeorological phenomena in the territory of RF in July 2014, namely, on July 4–7, heavy and very heavy rainfall occurred in the southern, central and south-western regions of Yakutia (40–68 mm of precipitation) [Berezhnaya *et al.*, 2014]. In the remaining months of the warm period, there was less precipitation than the norm, except August. During the cold period of 2013–2014, there was twice as much precipitation only in November, and in the remaining months, precipitation was less than the norm.

The isotopic composition of atmospheric precipitation

The results of the isotopic analysis of atmospheric precipitation sampled in Yakutsk in 2013–2014 showed essential variation from –6.12 to –45.0 ‰ for $\delta^{18}\text{O}$ and from –72.1 to –350.1 ‰ for δD (Fig. 3). The lightest isotopic composition was characteristic of the cold season, gradually getting lighter from the beginning to the end of the season (except the sample of 20.10.2013) with the weighted average seasonal value –31.65 for $\delta^{18}\text{O}$ and –237.1 ‰ for δD [Malygina *et al.*, 2015b]. For the warm season, variations in the isotopic composition ranged from –6.1 to –23.8 ‰ for $\delta^{18}\text{O}$ and from –72.1 to –198.3 ‰ for δD (Fig. 3), with the lightest isotopic composition characteristic of the precipitation which fell at the beginning of July, while the heaviest figure was obtained for the July and August samples. The weighted average isotopic composition of the precipitation of the warm season of 2014 was –13.0 ‰ for $\delta^{18}\text{O}$ and –109.3 ‰ for δD .

The calculated values of d_{exc} for the atmospheric precipitation in the period under study varied within a rather wide range – from +21.4 to –24.6 ‰. The precipitation values $d_{\text{exc}} > 10$ ‰ were characteristic of the cold period, suggesting the prevalence of cryogenic metamorphism of the isotopic composition. For the warm period with the value of $d_{\text{exc}} << 10$ ‰, evaporative fractioning seems to have exerted essential influence on the formation of the isotopic composition.

The weighted average ratios of stable isotopes in atmospheric precipitation of the cold period of 2013–

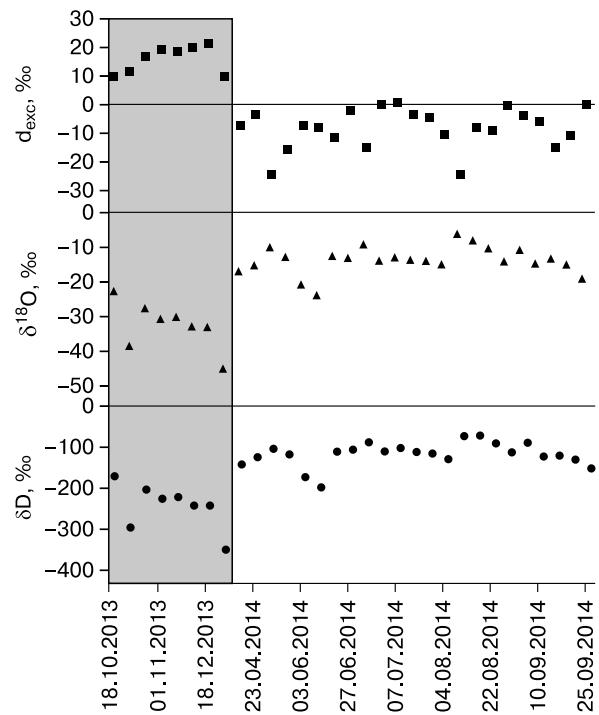


Fig. 3. The composition of stable isotopes of precipitation in Central Yakutia in the cold season of 2013–2014 (the gray area) and in the warm season of 2014.

2014 and of the warm period of 2014 obtained by the authors are in good agreement with the previously published weighted average values of isotopic composition of precipitation of the warm period (–12.9 ‰ for $\delta^{18}\text{O}$ and –106.0 ‰ for δD) and of the cold period (–33.0 ‰ for $\delta^{18}\text{O}$ and –265.8 ‰ for δD), sampled in Yakutsk in 1996–2000 [Kurita *et al.*, 2004]. In the period from 1969 to 2000, sampling and analysis of monthly precipitation was carried out on a regular basis in Yakutsk in the framework of the international GNIP program. The results obtained in the course of the program (http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html) are also in good agreement with the values obtained by the authors. However, comparing our data with the literature, a number of details have to be considered: 1) In 1996–2000, monthly samples were taken, as contrasted to the event samples taken by the authors; 2) The results of those months of the period of 1996–2000, when the amount of precipitation was less than 10 mm, were ignored, as, in the authors' opinion [Kurita *et al.*, 2004], during sampling and storage of the samples, evaporation could have significantly affected the isotopic composition; 3) N. Kurita and colleagues [Kurita *et al.*, 2004] considered the winter and summer periods to last only three months each, whereas in this study the entire year was divided by the authors

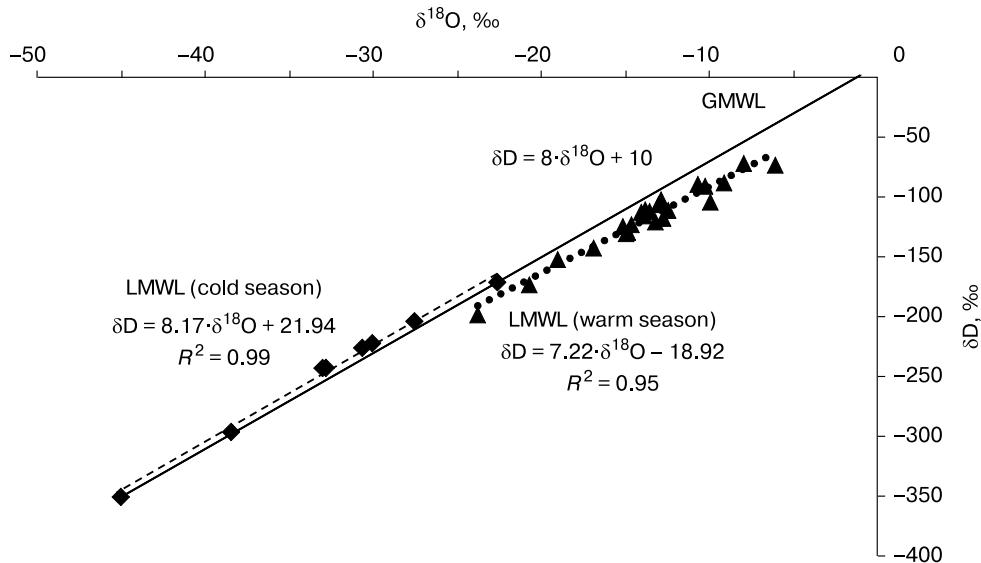


Fig. 4. Local meteoric water lines (LMWL) for the precipitation of the cold season of 2013–2014 (the long-dotted line) and the warm season of 2014 (the dashed line) in Central Yakutia and the global meteoric water line (GMWL) (the solid line).

into two seasons: the cold season, when solid precipitation fell, and the warm period, when liquid precipitation fell.

For the precipitation of the cold season of 2013–2014 and of the warm season of 2014, the local meteoric water lines were calculated. The regression equation of the LMWL for the precipitation of the cold season looks as follows: $\delta D = 8.17 \cdot \delta^{18}\text{O} + 21.9$ (coefficient of determination $R^2 = 0.99$). The slope of LMWL takes higher values than the slope of GMWL (Fig. 4), indicating the influence of cryogenic fractioning in forming the isotopic composition of atmospheric precipitation. The LMWL of the warm season precipitation is described by the equation $\delta D = 7.22 \cdot \delta^{18}\text{O} - 18.9$ ($R^2 = 0.95$), having the slope less than 8 (GMWL), indicating the impact of evaporative fractioning on the isotopic composition of precipitation.

The regression analysis showed the presence of significant dependence between the isotopic composition of precipitation of the cold season and the mean air temperature during the precipitation: $\delta^{18}\text{O} = -0.59t^\circ - 19.7$ ($R^2 = 0.88$) и $\delta D = 4.16t^\circ - 149.38$ ($R^2 = 0.89$), where t° is the temperature of the ambient air [Malygina et al., 2015a]. The calculated coefficients are close to the values obtained for 40 WMO stations [Dansgaard, 1964], equal to 0.69 and 5.6 for $\delta^{18}\text{O}$ and δD , while “free terms” have lower values reflecting the continental effect [Vasil'chuk and Kotlyakov, 2000; Ferronsky and Polyakov, 2009]. The absence of significant dependence between the isotopic composition of the precipitation of the warm season and the air temperature: $\delta^{18}\text{O} = 0.38t^\circ - 17.87$

($R^2 = 0.27$); $\delta D = 2.91t^\circ - 150.15$ ($R^2 = 0.30$) may suggest the influence of different sources of atmospheric moisture coming to the region, the contribution of which to formation of the isotopic composition of precipitation throughout the warm period may essentially change. A similar supposition about significant variation among the source of atmospheric moisture was made in [Kurita et al., 2003], where it was shown that in 2002 changes in the isotopic composition of summer precipitation in Yakutia did not demonstrate reliable direct dependence on temperature.

Identification of the sources of atmospheric moisture

To identify the sources of atmospheric moisture falling as precipitation in Central Yakutia, reverse trajectories were built for each date of sampling, which, considering the cloud boundary were brought to the same scale and united into a single catalogue of reverse trajectories (Fig. 5).

Precipitation of the cold period. Spatial analysis of the trajectories of air masses in the cold period of 2013–2014 allowed five groups of potential regions-sources of atmospheric moisture which fell as precipitation in Central Yakutia, to be identified (the regions indicated by Roman figures in Fig. 5, Table 1). It is to be noted that in all the cases of determining water reservoirs as potential sources of moisture in the cold season, the data of the National Oceanic and Atmospheric Administration (NOAA) (<http://www.noaa.gov>) were used, allowing the degree of ice coverage of the water reservoirs in the Northern Hemisphere to be evaluated with the daily resolution.

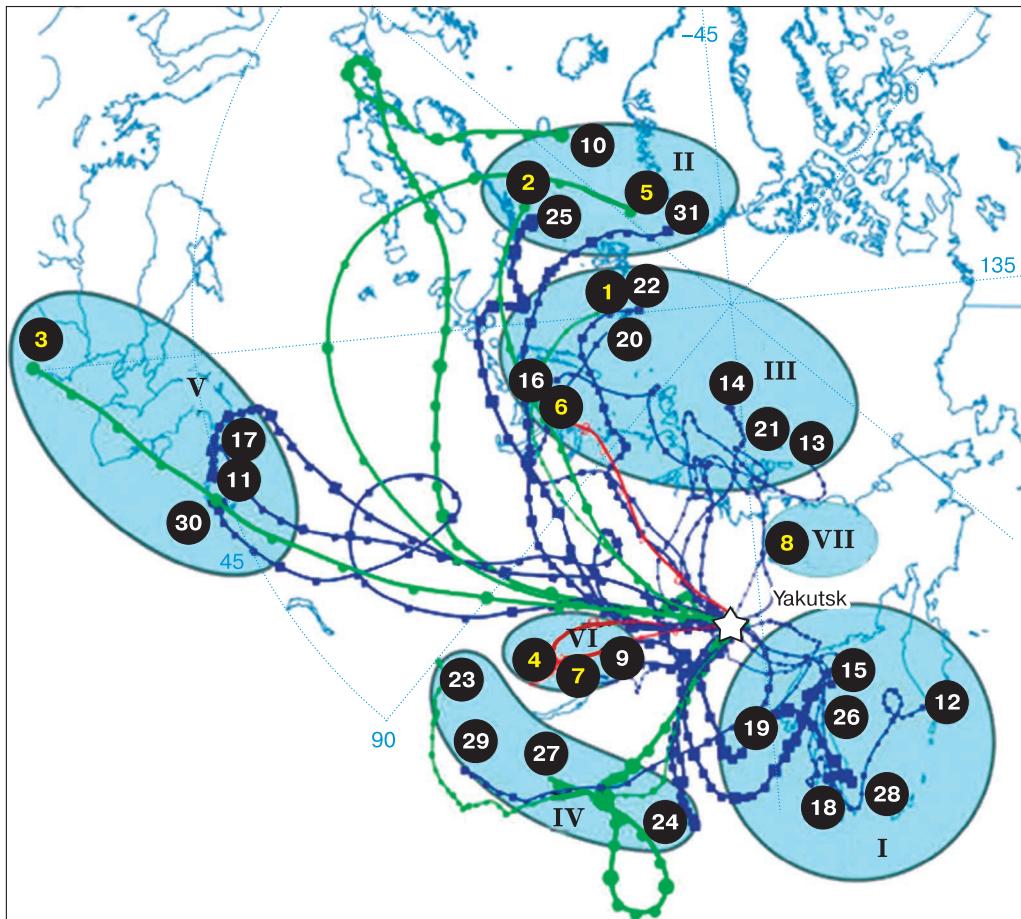


Fig. 5. Reverse trajectories of air masses at the height of 500 m (red line), 1500 m (blue line) and 3000 m (green line) at the dates of precipitation in the cold period of 2013–2014 (trajectories 1–8 – yellow numbers) and in the warm period of 2014 (trajectories 9–31 – white numbers) in Yakutsk (asterisk).

Regions I–VII – groups of regions potential sources of atmospheric moisture (see the names in Table 1).

Among the five identified groups of the regions-sources of atmospheric moisture, two groups made the most significant contribution (26.2 % each) – Northern Atlantic (group II, trajectories 2 and 5) with the weighted average isotopic composition of the precipitation -31.0 and -230.1‰ and the Arctic Ocean (group III, trajectories 1 and 6) with the weighted average isotopic composition -27.2 and -202.9‰ for $\delta^{18}\text{O}$ and δD , respectively. Regional sources, namely, Bratskoye, Ust-Ilimskoye and Viluyeskoye water reservoirs (group VI, trajectories 4 and 7), which at the date of precipitation were not yet covered with ice, made a comparable contribution to precipitation. This precipitation was isotopically lighter (the weighted average values -31.0‰ for $\delta^{18}\text{O}$ and -228.1‰ for δD), which is connected with the initial evaporation of moisture from the surface of reservoirs under conditions of negative temperatures (November, December).

The influence of local regions-sources (group VII, trajectory 8), which accounted for 14.5 % precipitation of the cold season of 2013–2014, may be primarily due to low-temperature freezing. The precipitation formed under the influence of this group, had the lightest isotopic composition (-45.0‰ for $\delta^{18}\text{O}$ and -350.1‰ for δD).

The Aral-Caspian region (group V, trajectory 3) made the lowest contribution to the total amount of precipitation of the cold season (10.8 %), which accounted for the fall of some of the heaviest atmospheric precipitation (-27.6‰ for $\delta^{18}\text{O}$ and -203.6‰ for δD).

Atmospheric precipitation of the warm period. Analysis of catalogue trajectories, calculated for the warm season of 2014, allowed identification of six groups of potential regions-sources (Fig. 5, Table 1).

The Sea of Okhotsk, which accounted for 41.1 % of the precipitation of the warm season of 2014, was

the main source of moisture, which is confirmed by the reverse trajectories of air masses at the height of 1,500 m (group I, trajectories 12, 15, 18, 19, 26, 28) (Fig. 5 and Table 1). The values of $\delta^{18}\text{O}$ and δD were close for all the analyzed samples, and their weighted average values were -13.2 and -107.6 ‰ , respectively. Such a light isotopic composition of precipitation coming from the Sea of Okhotsk is quite in agreement with the fact that in the summer time evaporation from the sea surface takes place at low temperatures (the average water temperature in the north-western part of the water area does not exceed $+12^\circ\text{C}$), while its initial isotopic composition $\delta^{18}\text{O}$ is -7.7 ‰ [Le-Grande and Schmidt, 2006]. The results we obtained are essentially different from those published earlier [Kurita et al., 2003], where the western atmospheric transfer and regional sources bringing moisture from the north and from the south (including evaporation of water during thawing of the upper layer of permafrost) are indicated as the main sources of atmospheric moisture of the warm period. Thus, in the paper cited the Sea of Okhotsk was not even considered as a source of moisture for precipitation falling in Central Yakutia.

The northern part of the Atlantic Ocean group II, trajectories 10, 25, 31) with the weighted average values -11.8 ‰ for $\delta^{18}\text{O}$ and -101.4 ‰ for δD (Fig. 5) made the second largest contribution (22.6 %) to the inflow of summer precipitation in Central Yakutia in 2014. The arctic air masses coming from the Arctic Ocean accounted for 20.5 % precipitation in Yakutsk in the summer of 2014 (group III, trajectories 13, 14, 16, 20, 21, 22). The lightest isotopic composition (the weighted average values -15.6 ‰ for $\delta^{18}\text{O}$ and -130.0 ‰ for δD) was characteristic exactly for this group of precipitation.

The heaviest isotopic composition (the weighted average values -10.1 and -91.1 ‰ for $\delta^{18}\text{O}$ and δD , respectively) was determined for the precipitation caused by the air masses coming from the internal continental trajectories (the region of China and Mongolia, including the aquatic areas of the local water reservoirs), which is confirmed by the reverse trajectories of their movement (group IV, trajectories 23, 24, 27 и 29) (Fig. 5). The contribution of these regional sources was 9.6 % of the total precipitation. According to the International Station for Monitoring the Isotopic Composition of Precipitation [Atlas..., 2008], in China (the area of Zhāngyè), the average value $\delta^{18}\text{O}$ in precipitation and in the open reservoir water is -7.4 and -4.0 ‰ , respectively, and in Mongolia in the area of Ulaanbaatar, it is -9.5 and -3.5 ‰ . This agrees well with the fact that atmospheric moisture coming from the water sources of the given regions, when moving in the meridional direction northwards, could have formed precipitation of the isotopic composition we measured.

The Aral-Caspian region served as a source only for 4.8 % precipitation of the warm season (group V, trajectories 11, 17, 30) with the weighted average value -10.2 ‰ for $\delta^{18}\text{O}$ and -99.0 ‰ for δD (Fig. 5). Despite the significant remote position, due to the heavy isotopic composition of the initial water ($+2.8 \text{ ‰}$ $\delta^{18}\text{O}$ for the Aral Sea and -1.7 ‰ $\delta^{18}\text{O}$ for the Caspian Sea [Oberhänsli et al., 2009]) and considerable warming in the summer period (up to $+35^\circ\text{C}$), the cyclones coming from the Aral-Caspian region bring precipitation of the heavier isotopic composition to Central Yakutia than that coming from the Sea of Okhotsk located nearby. The most negative values of the deuterium excess (-17.2 ‰) confirm the appurtenance of the initial atmospheric

Table 1. Regional characteristics of moisture which fell as precipitation in the cold season of 2013–2014 and in the warm season of 2014 in Central Yakutia (Yakutsk), the weighted average values of the isotopic composition of precipitation and their contributions (%) to the total amount of moisture

Number	Region source of moisture	Sample (see the trajectories in Fig. 5)	$\delta^{18}\text{O}$, ‰		δD , ‰		d_{exc} , ‰		Contribution, %	
			Cold season	Warm season	Cold season	Warm season	Cold season	Warm season	Cold season	Warm season
I	Sea of Okhotsk	12, 15, 18, 19, 26, 28	—	-13.2	—	-107.6	—	-1.6	—	41.1
II	Northern Atlantic Ocean	2, 5, 10, 25, 31	-31.0	-11.8	-230.1	-101.4	17.8	-7.4	26.2	22.6
III	Arctic Ocean	1, 6, 13, 14, 16, 20, 21, 22	-27.2	-15.6	-202.9	-130.0	14.4	-4.9	26.2	20.5
IV	Inner continental sources (the water reservoirs of China and Mongolia)	23, 24, 27, 29	—	-10.1	—	-91.1	—	-10.0	—	9.6
V	Aral-Caspian region	3, 11, 17, 30	-27.6	-10.2	-203.6	-99.0	16.8	-17.2	10.8	4.8
VI	Regional sources (Lake Baikal, Bratskoye, Ust-Ilimskoye and Viluyeskoye reservoirs)	4, 7, 9	-31.0	-16.9	-228.1	-142.5	19.6	-7.3	22.4	1.4
VII	Local sources	8	-45.0	—	-350.1	—	10.0	—	14.5	—

moisture of group V of the precipitation to the Aral-Caspian region.

Standing apart is the case of precipitation (1.4 %), the sources of which may be the water surface of Lake Baikal (-15.8 ‰ $\delta^{18}\text{O}$ [Seal and Shanks, 1998]) and the adjacent territories (group VI, trajectory 9) (Fig. 5).

CONCLUSIONS

1. The isotopic composition of precipitation of the cold season of 2013–2014 in Central Yakutia and of the warm season of 2014 varied in a wide range from -6.12 to -45.0 ‰ for $\delta^{18}\text{O}$ and from -72.1 to -350.1 ‰ for δD . The weighted average values of isotopic composition of atmospheric precipitation of the cold season were equal to -31.65 and -237.1 ‰ , whereas those of the warm season were -13.0 and -109.3 ‰ for $\delta^{18}\text{O}$ and δD , respectively. The results obtained agree well with the previously published data.

2. The change in the isotopic composition of precipitation of the cold period is essentially dependent on the air temperature, whereas the slope of the local meteoric waterline (LMWL) and deuterium excess (above 10 %) suggests the cryogenic fractionation of precipitation.

3. In the warm period, there is no significant dependence of the change in the isotopic composition of precipitation on the ambient temperature, which primarily may be related to a change in the sources of atmospheric moisture, whereas the angle of less than 8 degrees and a negative deuterium excess collectively suggest the possibility of evaporative fractionation of precipitation.

4. Based on analysis of the reverse trajectories of air masses and the isotopic composition of precipitation, regions-sources of the atmospheric moisture falling as precipitation in Central Yakutia have been identified for the cold and warm periods of the year.

The cold period of 2013–2014

- Ice-free water surfaces of the northern part of the Atlantic Ocean and of the Arctic Ocean (26.2 % each) have made essential contribution to the precipitation, with the weighted average values of isotopic composition being -31.0 and -27.2 ‰ for $\delta^{18}\text{O}$ and -230.1 and -202.9 ‰ for δD , respectively.

- Bratskoye, Ust-Ilimskoye and Viluyskoye water reservoirs jointly made a comparable contribution to precipitation (22.4 %). This precipitation was isotopically lighter (the weighted average values -31.0 ‰ for $\delta^{18}\text{O}$ and -228.1 ‰ for δD), which is related to the initial evaporation of moisture from the reservoir surface under negative temperatures (November, December).

- The precipitation the source of which was the low-temperature freeze-out of the local sources of moisture had the lightest isotopic composition

(-45.0 ‰ for $\delta^{18}\text{O}$ and -350.1 ‰ for δD). The contribution of the low-temperature freeze-out of precipitation was 14.5 % of the winter-season precipitation.

The warm period of 2014

- It has been shown that in the warm period of 2014, the Sea of Okhotsk was the dominant source of atmospheric precipitation in Central Yakutia. Its contribution was 41.1 % of the total amount of precipitation of the warm season of 2014, with the weighted average values of isotopic composition being -13.2 ‰ for $\delta^{18}\text{O}$ and -107.6 ‰ for δD .

- Atmospheric precipitation coming from the Arctic Ocean (20.5 %) had the lightest isotopic composition (the weighted average values -15.6 ‰ for $\delta^{18}\text{O}$ and -130.0 ‰ for δD). the northern part of the Atlantic Ocean (22.6 %) made the comparable contribution, with the weighted average values of the isotopic composition being -11.8 ‰ for $\delta^{18}\text{O}$ and -101.4 ‰ for δD .

- The heavy isotopic composition (the weighted average values -10.1 and -91.1 ‰ for $\delta^{18}\text{O}$ and δD , respectively) was characteristic of the precipitation coming from the inner continental regions of China and Mongolia, as well as from the Aral-Caspian region (the weighted average values -10.2 ‰ for $\delta^{18}\text{O}$ and -99.0 ‰ for δD). Their contribution to the total amount of atmospheric precipitation was 9.6 % for the inner continental sources of China and Mongolia and 4.8 % for the Aral-Caspian region.

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