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Concentration of ^{18}O in Precipitation over Moscow in 2014

Ju. N. Chizhova, I. D. Eremina, N. A. Budantseva, G. V. Surkova, and Yu. K. Vasil'chuk

Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991 Russia, e-mail: eacentr@yandex.ru

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Abstract—The series of ^{18}O values is presented for all precipitation events in Moscow in 2014. Precipitation samples were taken at the observation site of the Meteorological Observatory of Lomonosov Moscow State University (MSU MO), and the isotopic analysis was carried out in the isotopic laboratory of the Department of Geography of MSU. The concentration of stable ^{18}O in precipitation over Moscow in 2014 varied from –0.09 to –26.29‰. The maximum amplitudes of ^{18}O were registered in March–April and October. The pronounced interrelation was revealed between the oxygen isotopic composition of precipitation and surface air temperature (the correlation coefficient is 0.85). The computation of back trajectories of air masses and the analysis of weather charts demonstrated that the most isotopically light precipitation is typical of relatively cold air masses slowly moving over the continent during the last five days before precipitation. In this case, the ongoing condensation leads to the progressive isotopic depletion of precipitation (more and more isotope-depleted precipitation is registered). On the contrary, fast air transport from the middle and even from high latitudes of the Atlantic Ocean leads to the relatively constant of ^{18}O values of precipitation.

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INTRODUCTION

The isotopic composition of precipitation is an important parameter needed for meteorological, hydrogeological, and paleoclimatic studies. The global monitoring of concentration of the stable isotopes of hydrogen and oxygen in precipitation has been conducted since 1961 in the framework of GNIP (Global Network on Isotopes in Precipitation) program under the joint patronage of IAEA and World Meteorological Organization (WMO). Long-term continuous series of measurements of isotopic composition of precipitation were obtained for many cities in Europe, North America, Australia, and China. These series allow revealing its interannual variability, seasonality of annual variations, relation to air temperature and the North Atlantic Oscillation index (NAO), and the depletion of air masses as moving inland [10]. Isotopic studies of precipitation for Vienna have continuously been conducted since 1968 and were carried out for each individual precipitation event in 2001–2003.

In 1969–1971 the organizations of the Hydrometeorological Service of the USSR jointly with WMO/IAEA carried out routine observations of concentration of deuterium and ^{18}O in precipitation sampled in eight administrative regions of the Ukrainian and Moldavian SSR and in the Kamchatka and Irkutsk oblasts, the Primorsky krai, and Uzbek SSR (in particular, in Petropavlovsk-Kamchatsky, Irkutsk, Khabarovsk, and Tashkent). Since the concentration of deuterium and ^{18}O in all regions under study was determined in the samples of monthly precipitation, the interpretation of such data enabled obtaining the average seasonal or average annual isotopic pattern. It was revealed that the concentration of deuterium and ^{18}O in precipitation increased from north to south (the latitudinal isotopic effect) and decreased from west to east (the longitudinal isotopic effect) [3].

The observations of isotopic composition of precipitation at the stations of the Hydrometeorological Service of the USSR in Moscow, Gorky, Rostov, and other cities started a bit later. The isotopic composition of precipitation in Moscow was investigated from 1969 to 1983 (http://isohis.iaea.org). The ^{18}O and ^{2}H values were obtained for monthly mean precipitation (i.e., from monthly mean samples) [5],

and the isotopic composition of precipitation was mapped for the European part of Russia [1]. After 1983 routine observations stopped, but the intraannual cycle of isotopic composition of precipitation for specific meteorological conditions was not obtained even once. At present no routine observations of isotopic composition of precipitation are carried out in Russia; therefore, the data given in the present paper may partly fill this gap.

Good results may be obtained from the joint analysis of isotopic composition of precipitation and the trajectories of precipitation-bearing air masses because air mass properties are determined by its origin defining evaporation conditions and the source of water vapor inflow to the atmosphere. The further movement and transformation of an air mass determine the possibility of moisture condensation, the precipitation pattern, and the gradual isotopic depletion of precipitation. The isotopic composition of precipitation allows obtaining more accurate data on air mass origin than its ionic composition does, because in a big city the ionic composition is considerably affected by industrial and automobile emissions. The concentration of ^{18}O and deuterium is a distinctive feature of each precipitation event and is not directly affected by anthropogenic pollution.

The temperate continental climate of Moscow is characterized by seasonal contrasts of temperature, humidity, and radiation parameters. It is formed under the influence of air masses of different types (Arctic, mid-latitudinal, and tropical) each of which may be of maritime or continental origin and may have specific features depending on synoptic conditions and trajectory. Not only air mass origin (maritime or continental) but also the duration of its movement over the continent, temperature and humidity in the cloud and under-the-cloud layers, the precipitation pattern, and the rate and duration of precipitation are of great importance for the isotopic composition of precipitation.

METHODS

Precipitation was sampled and its acidity was determined in the Meteorological Observatory of Lomonosov Moscow State University (MSU MO). This station was chosen due to the observatory location: the territory of the Vorobyovy Gory is well ventilated and there are no large industrial objects and traffic arteries nearby.

The composition of the samples of any precipitation (rain, snow, or mixed precipitation) was studied from its beginning to the end on the current or adjacent day. Precipitation samples were taken with the rigid-vinyl funnel with the size of 80 80 cm located at the height of 2 m above the surface. To collect rainwater, a plastic bucket was installed under the funnel. In winter after snowfall end the snow from the funnel was collected with a plastic scoop to a bucket for melting at room temperature. Observations were conducted round the clock. All precipitation events in 2014 (101 samples) were investigated. Such parameters as the amount of precipitation, its duration, surface air temperature, relative air humidity, and pH were determined. The concentration of ^{18}O (expressed in ^{18}O, ‰) was determined in all samples taken with the Delta-V mass spectrometer equipped with the PAL automatic sampler and GasBench II interface (all equipment was produced by Thermo Scientific company). The analysis was carried out by the method of isotopic equilibration with CO_2. The composition of each sample was determined from the data of ten measurements. The IAEA standards (V-SMOW, SLAP, and GISP) were used for measurements and for the calibration of the results. The average measurement accuracy was equal to 0.1‰.

The method of back (120 hours backward) trajectories was applied to assess the effects of advective factors and to analyze the potential effects of long-range transport on the isotopic composition of precipitation samples. They were constructed using the HYSPLIT semi-Lagrangian transport model [9, 11] for every day of precipitation sampling with end points at the heights of 1000, 3000, and 5000 m at 12:00 UTC. Besides, the data of surface weather charts and 500 hPa geopotential charts were used for assessing synoptic conditions and the direction of the prevalent transport of precipitation in the atmosphere.

RESULTS

In 2014 the ^{18}O values of precipitation varied in rather wide limits: from 0.09 to –26.29‰ for the extremes and from –4.85 to –18.80‰ for 80% of samples. Figure 1 presents the annual course of ^{18}O for Moscow characterized by the complex nature of variations.

The general variations in the values of ^{18}O in 2014 exhibit natural increase in values in summer and decrease in winter. Such variations generally agree with annual variations in temperature. The ^{18}O values increased from January to May. However, the increase was not monotonous and was characterized by oscillations with the amplitude of 20‰ and two peaks (the ^{18}O values at night on April 23 and on May 13

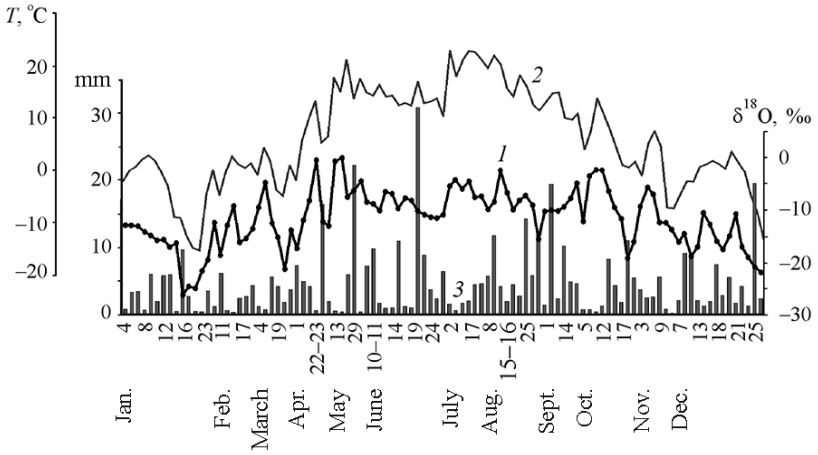

Fig. 1. (*1*) Concentration of ^{18}O in precipitation and the variations in (*2*) air temperature and (*3*) amount of precipitation in Moscow in 2014.

and 17 reached 0‰). The general decrease in ^{18}O from August to December cannot be called monotonous either; in October, high-amplitude (15‰) variations were observed.

Winter. In December, January, and February the ^{18}O values varied from –9.21 to –26.29‰ and monthly mean values were equal to –15.86, –17.7, and –15.69‰, respectively (Fig. 2a). The significant amplitude of variations in ^{18}O was observed within every month:

Month	December	January	February
^{18}O, ‰			
minimum	–22.09	–26.29	–19.52
maximum	–10.37	–12.85	–9.21

In January the most values of ^{18}O (–14…–16‰) characterized the typical influence of the Atlantic Ocean. Earlier the authors obtained the similar ^{18}O values for the snow cover in Moscow in the winter of 2010. The values of ^{18}O of snow in the Setun' River floodplain from February to April varied from –21.8 to –13.9‰ [2].

Spring. In the first month of spring the maximum ^{18}O value (–4.69‰) was registered on March 9, and the minimum (–21.29‰) was observed on March 20; monthly mean values in March, April, and May were equal to –12.89, –9.45, and –6.6‰, respectively. The amplitude of variations in ^{18}O in spring precipitation is considerable:

Month	March	April	May
^{18}O, ‰			
minimum	–21.29	–17.43	–13.02
maximum	–4.69	–0.35	–0.09

Summer. In June, July, and August monthly mean ^{18}O values are –8.97, –5.05, and –8.39‰, respectively. In June ^{18}O varied from –4.55 to –11.62‰, and the most precipitation events were characterized by the values of about –8…–10‰. In July only four precipitation events were registered and ^{18}O varied from –4.19 to –6.07‰. In August the values of ^{18}O varied from –2.22 to –15.56‰, and the most precipitation events were characterized by the concentration of ^{18}O from –7 to –9‰.

Autumn. In September, October, and November monthly mean ^{18}O values were equal to –8.73, –9.23, and –8.6‰, respectively. All precipitation registered in autumn was characterized by rather "heavy" isotopic composition. The ^{18}O values of precipitation in September (–4.8 to –10.19‰) better agreed with summer than with autumn. In October the largest (in autumn) amplitude of ^{18}O was observed: from –2.31 to –19.1‰. The maximum ^{18}O value (–2.31‰) was registered in precipitation on October 11. In November the ^{18}O values varied from –5.67 to –9.34‰ that is more typical of summer precipitation. The autumn of 2014 may be called "isotopically abnormally heavy."

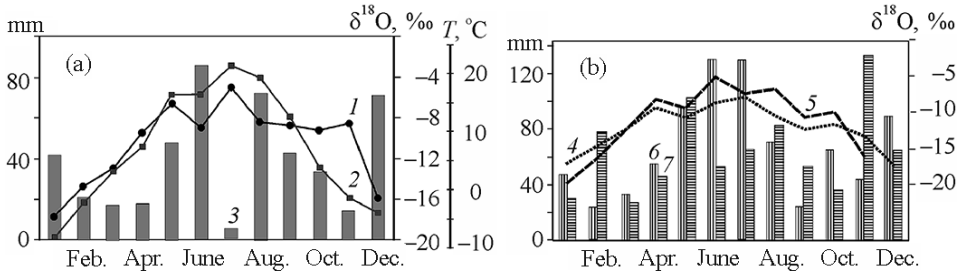

Fig. 2. (a) Monthly mean values of (*1*) ^{18}O, (*2*) air temperature and (*3*) amount of precipitation in 2014 and (b) monthly mean values of (*4*, *5*) ^{18}O and (*6*, *7*) amount of precipitation in 1976 and 1977, respectively, obtained from the partial implementation of the GNIP program (http://isohis.iaea.org).

Table 1. Concentration of ^{18}O in precipitation in Moscow in 2014

Date	Value	Pr, mm	pH	T_2, C	Upper-air sounding data			^{18}O, ‰
					T, C	T_d, C	f, %	
				Winter				
December 16	max	1.2	6.30	1.2	–11.1	–15.6	69	–10.37
January 4	av	0.4	6.75	–9.0	–20.0	–21.0	93	–16.27
January 16	min	9.7	6.45	–9.1	–18.0	–19.0	88	–26.29
				Spring				
March 4	av	1.2	6.85	–0.9	–13.0	–16.0	76	–9.60
March 9	av	0.7	7.20	4.3	–16.0	–35.0	16	–4.69
March 20	min	1.8	7.15	–5.0	–21.0	–39.0	19	–21.29
May 13	max	0.6	4.90	17.6	–2.0	–14.0	23	–0.62
May 17	max	0.4	4.55	15.0	3.1	–1.2	73	–0.09
				Summer				
June 19	av	0.9	7.20	12.5	–7.7	–7.9	98	–8.04
August 14–15	max	4.1	5.95	20.2	4.0	–18.0	20	–2.22
August 30	min	12.3	5.90	11.4	–6.1	–8.4	84	–15.56
				Autumn				
October 11	max	0.3	7.20	13.6	1.2	–3.8	69	–2.31
October 20	min	11.0	6.40	0.6	–10.0	–12.0	85	–19.10
November 3	av	3.8	6.20	–1.1	–3.9	–4.8	93	–9.34

Note: max, av, and min are the maximum, close-to-average, and minimum values of ^{18}O, respectively; Pr is the amount of precipitation; T_2 is the surface air temperature at MSU MO weather station; T, T_d, and f are air temperature, dew-point temperature, and relative air humidity at the height of 3000 m, respectively.

The concentration of ^{18}O in precipitation for some precipitation events in the four seasons of 2014 is presented in Table 1.

The ^{18}O values vary in accordance to surface air temperature variations from January to June and from September to December (Fig. 1): the coefficient of correlation between monthly mean ^{18}O values and T for these periods is 0.87. As to monthly mean values, the relation of isotopic composition to temperature is

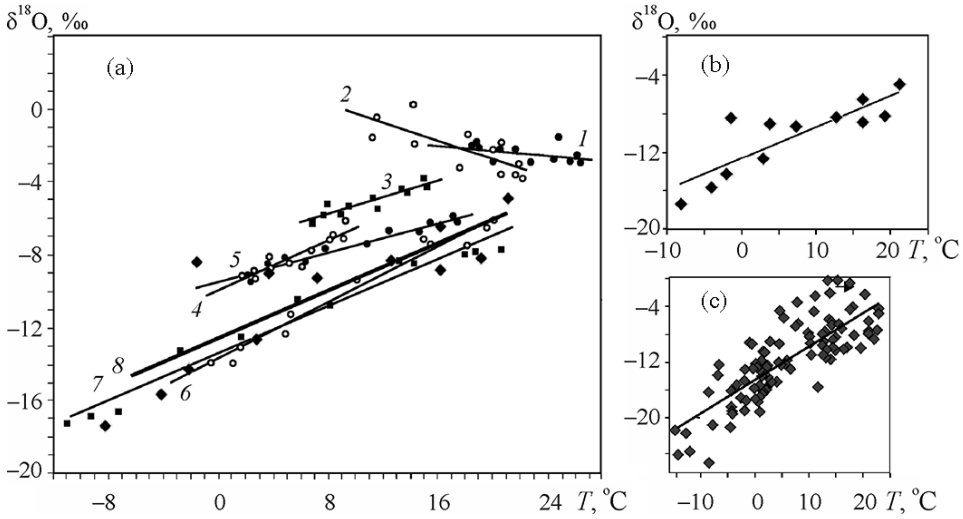

Fig. 3. (a) The relation of ^{18}O in precipitation in Moscow to the surface air temperature as compared with the average long-term data from the GNIP network data [10] and the dependences of (b) monthly mean and (c) separate values of ^{18}O on air temperature. The lines are linear approximations; the signs are monthly mean values. The numerals are the stations: (*1*) Midway, the Pacific Ocean; (*2*) Pretoria, South Africa; (*3*) Valentia, Ireland; (*4*) Stanley, the Falkland Islands; (*5*) Groningen, Netherlands; (*6*) Vienna, Austria; (*7*) Ottawa, Canada; (*8*) Moscow (the present paper data).

clearly pronounced as well as the natural increase in ^{18}O in summer months and the decrease in winter months (Fig. 2a), the coefficient of correlation between ^{18}O and T_2 is 0.85. The interrelation between monthly mean values of ^{18}O and air temperature (Fig. 3) is described by the equation $^{18}O = 0.33T - 12.83$ (the coefficient of validity of linear approximation $R^2 = 0.72$). The interrelation between individual ^{18}O values and air temperature is described by the equation $^{18}O = 0.47T - 14.38$, $R^2 = 0.62$. Average annual temperature was equal to 7.05 C in 2014. Average annual value of ^{18}O 11.53‰. The equation for average annual values is $^{18}O = 0.31T - 13.64$.

DISCUSSION OF RESULTS

Monthly mean ^{18}O values obtained by the authors agree well with the data of GNIP monthly mean samples. Over the whole period of isotopic measurements in the framework of WMO/IAEA program in Moscow from 1969 to 1983, the values of ^{18}O were obtained in 1970 and 1975–1979: 61 samples (in 6 years) of monthly mean precipitation, i.e., the samples including all precipitation during a month were measured. Average annual values of ^{18}O varied from –9.9 to –11.92‰ (in 1976 and 1977, monthly mean values of ^{18}O varied from –8 to –17.2‰ and from –5.2 to –19.8‰, respectively; Fig. 2b), and average annual values of air temperature varied from 7.58 to 2.48 C (http://isohis.iaea.org). The equation of interrelation between the isotopic composition of precipitation over Moscow and air temperature for average long-term values is $^{18}O = 0.36T - 13.05$.

The dependence of average annual values of precipitation ^{18}O on temperature was for the first time revealed by W. Dansgaard from the data of observations at 38 stations which were included to the research program under the auspices of WMO and IAEA in the early 1960s: $^{18}O = 0.69T - 13.60$ [7]. This dependence is true for the stations located in the areas with the moderate and cold climate not far from the coast. As moving inland, the continental isotopic effect (the decrease in ^{18}O) is considerably manifested. This effect is associated with the fact that clouds lose moisture as moving inland. As a result, heavy molecules precipitate first of all and moisture remaining in the cloud is isotopically "lightened." The dependence $^{18}O = 0.52T - 14.96$ was obtained for the GNIP network stations situated in the Atlantic Ocean area and in Europe [13].

The dependences derived from the monthly mean data on precipitation in Moscow in 2014 agree well with the equation for $^{18}O/T$ for other European cities (Fig. 3a). They are similar (numerically and in the angle of inclination of linear approximation) to the respective dependences for Groningen, Vienna, and Ottawa. It should be noted that isotopic dependences for Ottawa were obtained from monthly mean values of ^{18}O: long-term monthly mean values of ^{18}O in 1970–2007 varied from –16.71 in January to –7.81 in

Table 2. The basic trajectories of air masses and typical values of ^{18}O for precipitation fallen from them

Type of trajectory	Number of trajectories	^{18}O, ‰	
		mean	range
	Winter		
Arctic	4	–18.21	–12.36...–25.06
Greenlandic	2	–18.41	–15.97...–20.85
Atlantic sublatitudinal (between 45 and 60 N)	15	–15.03	–9.21...–22.08
Atlantic long and high-latitude (northward of 60 N)	7	–15.03	–10.58...–18.80
Atlantic, continent, short	3	–22.41	–16.27...–26.29
Atlantic, southward of 45 N	6	–15.67	–12.32...–19.52
	Summer		
Greenlandic	4	–9.21	–7.79...–11.03
Northern and northeastern	9	–9.10	–6.07...–11.62
Intracontinental	4	–7.60	–5.42...–9.95
Atlantic	12	–7.42	–2.22...–15.56

July and –7.43 in August (http://isohis.iaea.org), and the range of variations of about 10‰ is similar to that obtained for precipitation in Moscow.

It is clear from Figs. 3b and 3c that in the case of averaging to monthly mean values the inclination of the line $^{18}O/T$ (0.33) decreases as compared with $^{18}O/T$ for separate events (0.47), i.e., the averaging leads to the concealing of the Moscow climate continentality. The same effect was registered from the data of the analysis of precipitation in Debrecen (eastern Hungary) where the sampling and isotopic analysis of all separate rainfalls and snowfalls were carried out in 2001–2009. In that case the ratio $^{18}O/T$ was equal to 0.32 for monthly mean values and 0.37 for separate events (the weighted averages of ^{18}O) [12]. Paper [14] presented the average value of $^{18}O/T = 0.34$ for Central Europe and the variations from 0.2 to 0.45 for the most European stations; it was noted that the ratio $^{18}O/T$ increases as the temperature range and, hence, continentality increase [8].

Back trajectories of air masses 5 days before a precipitation event were retrieved for all precipitation events in Moscow in 2014. All trajectories of air masses (Fig. 4a) can be divided to 6 types in winter (Table 2) and 4 types in summer following their source and path. The ranges of values of ^{18}O in summer are similar for intracontinental and Atlantic trajectories and for Greenlandic and northeastern trajectories. In winter, three groups of trajectories are identified following the isotopic composition: Greenlandic and Arctic; Atlantic; short Atlantic characterized by the lowest values of ^{18}O (Table 2). The trajectories of air masses can be analyzed for each separate precipitation event taking into account not only weather charts but also local conditions of precipitation. For example, in Melbourne precipitation samples were taken from March 2005 to September 2009. Their isotopic composition and back trajectories of air masses were identified [6]. The air masses of oceanic origin were isotopically considerably lighter ($^{18}O = –7.1‰$) as compared with the continental ones ($^{18}O = –3.5‰$). However, no relation of the ^{18}O values to the sources of air masses was revealed for four different types of oceanic trajectories. The analysis by the authors of [6] revealed that the isotopic composition of precipitation in Melbourne is defined not as much by the source of formation of air masses in the ocean as by the degree of moisture loss in the process of their movement and by local meteorological conditions at the moment of precipitation fall. This partly agrees with the data on the concentration of ^{18}O in winter precipitation obtained by the authors of the present paper; we relate two cases of isotopically light snowfall to the short trajectories of air masses (the heavy lines in Fig. 4a) and to the significant isotopic depletion as a result of ongoing precipitation over Europe.

Let us consider several precipitation events in Moscow with the extreme ^{18}O values in 2014.

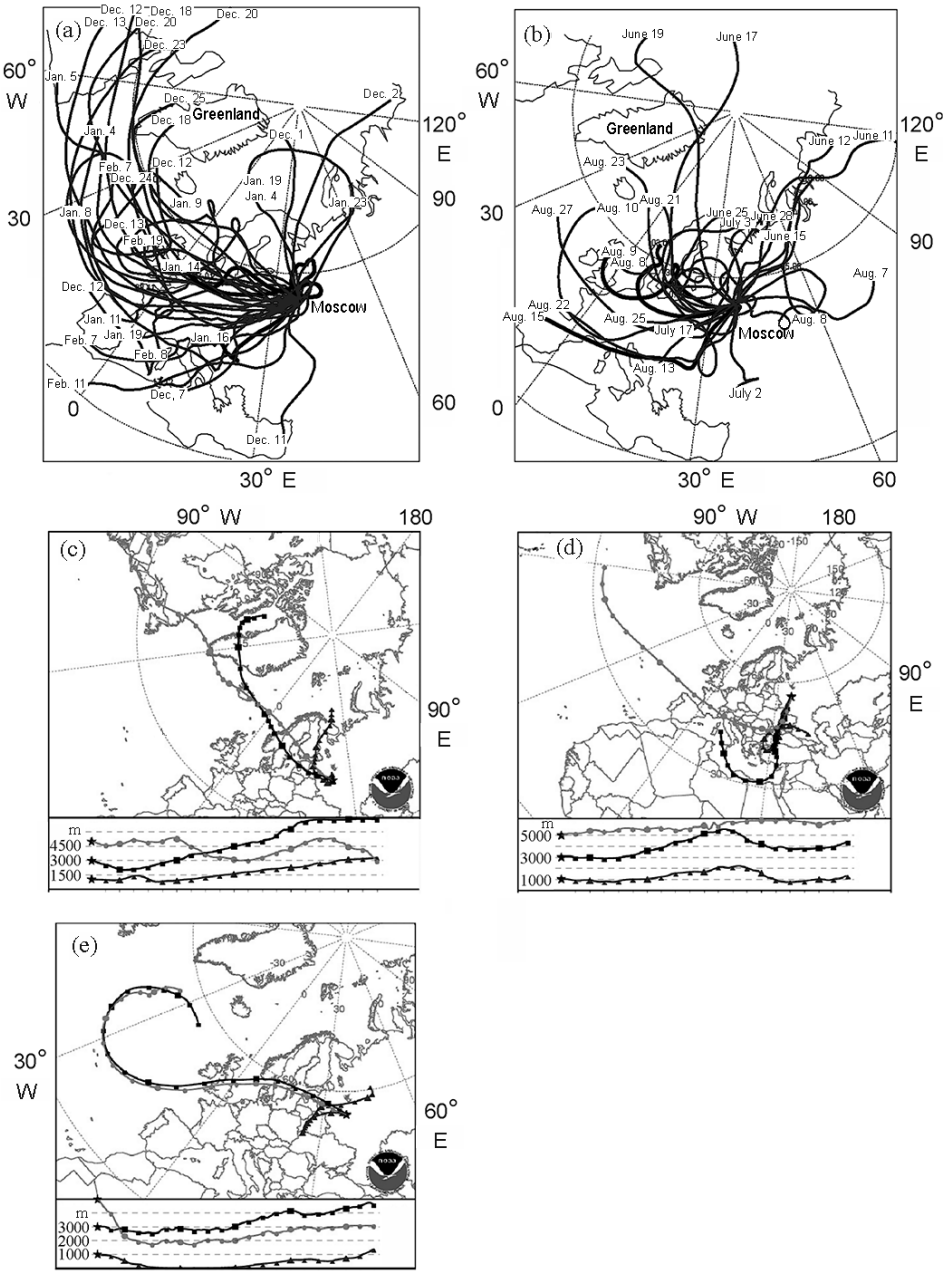

Fig. 4. Retrieved back trajectories (a) for the winter of 2014 for precipitation with the lowest ^{18}O values and (b) for the summer of 2014 for precipitation with the highest ^{18}O values and the examples of typical trajectories for different precipitation events: (c) March 20, cold air transport from the polar latitudes (the low ^{18}O values); (d) May 13, the transport of air masses to Moscow from the southwest after they had passed over the Mediterranean and Black seas; (e) October 20, transport from the Atlantic Ocean and the rapid inflow of fresh Atlantic air to Europe and the European part of Russia. Explanations are given in the text.

January 14. The constructed back (5 days backward) trajectories of air masses in the lower troposphere, where the most part of moisture-bearing flow moves, indicate that the discharge is possible of maritime air masses rather rapidly moving from the west in the system of a cyclone and, evidently, transporting moisture from the Atlantic. On that day the amount of precipitation equal to 0.4 mm was registered at the surface air temperature of –9 C. Probably, condensation occurred under equilibrium conditions: air temperature at the height of 3000 m was equal to –18 C, dew point temperature was –19 C, and relative air humidity was equal to 93% (the upper-air sounding data from the University of Wyoming

database, www.weather.uwyo.edu/upperair/sounding.html). It may be supposed that the difference between the temperature of the under-the-cloud layer and dew point temperature (at the height of 3000 m) as well as relative air humidity may indicate the more or less equilibrium conditions of condensation: when relative humidity is low, evaporation and sublimation which lead to the isotopic fractioning are possible. If the values of air temperature and dew point temperature are close while relative humidity is high, no fractioning occurs and the conditions are close to equilibrium.

On January 16, when surface air temperature was the same as on January 14, the amount of precipitation was equal to 9.7 mm but the ^{18}O value was extremely low (–26.29‰). The trajectories of air masses at the height of about 3000 m enable supposing that the movement of air masses which generated precipitation, slowed down. This weakened the invasion of fresh Atlantic air and strengthened the continental effect in the isotopic composition of precipitation; therefore, precipitation that arrived to Moscow was more isotope-depleted as compared with precipitation on January 14. The isotopic depletion due to the transport slowdown and continental effect strengthening is also corroborated by the fact that the temperature of the air mass in the middle troposphere remained almost the same on those days. It can be supposed that condensation in the under-the-cloud layer occurred under relatively equilibrium conditions (at the height of 3000 m $T = -18$ C, $T_d = -19$ C, $f = 88\%$). In general, in winter precipitation is particularly defined by cyclonic activity in the process of mid-latitude westerlies.

March 9 and 20. Back trajectories demonstrated that the most isotopically heavy precipitation registered on March 9 is associated with the air masses which came from the Atlantic Ocean and North Sea. These air masses passed the significant distance over the North Atlantic and Norwegian Sea, reached the European part of Russia, and did not lose the significant part of moisture. Synoptic conditions on March 20 differ much from those on March 9 although the visual appearance of trajectories is rather similar (Fig. 4c). Firstly, in the area of warm North Atlantic Current on March 20 the speed of air masses was much higher than on March 9. Secondly, on those two days the difference in the values of air temperature was almost 9 C in the surface layer and about 5 C at the height of 3000 m (Table 1). Thirdly, the analysis of surface and upper-air weather charts revealed that the invasion of cold air masses from the north to the European part of Russia took place in the lower atmospheric layer in the rear of the vast cyclone on those days. On the contrary, on March 9 the western component of air transport prevailed throughout the troposphere and Moscow was affected by the pressure trough in the warm sector of the cyclone with the center over the Barents Sea. The values of ^{18}O in precipitation from –12 to –15‰ typical of March characterize the Atlantic and Mediterranean effects. For example, the value of ^{18}O was equal to –9.6‰ on March 4 and, according to the retrieved back trajectories, this air mass came from the center of the Mediterranean Sea.

May 13 and 17. Extremely high ^{18}O values equal to –0.62 and –0.09‰ were registered in precipitation in the form of short-term showers that occurred on May 13 and 17 (0.6 and 0.4 mm, respectively) at the surface air temperature of 17.6 C. The retrieval of back trajectories for May 13 revealed that air masses came to Moscow after they had passed over the warm Mediterranean and Black seas (Fig. 4d) which became the additional sources of ^{18}O due to active evaporation from the sea surface.

Another factor of isotopic weighting of precipitation to 0‰ may be the fractioning that occurred at the moment of condensation while raindrops fall in the atmosphere and exchange isotopic molecules with ambient water vapor. The conditions for the non-equilibrium process of condensation were formed at the height of 3000 m on May 13 ($T = -2$ C, $T_d = -14$ C, $f = 23\%$). Moreover, conditions for the evaporation of falling drops are often formed in May (or after long summer drought) that was registered for a summer rain in 2010 [4]. However, such heavy isotopic composition can be not associated with the fractioning but is indicative of the individual isotopic characteristic of extremely warm air masses. For example, rainfalls with $^{18}O = 0‰$ were registered in May and June in Vienna (Austria), Schweizerhof (Germany), and Debrecen (Hungary) not more than twice a year and not every year, as a rule (according to the GNIP database, http://isohis.iaea.org). The conditions of atmospheric saturation and the conditions in the under-the-cloud layer were different in all these cases; hence, such high concentration of ^{18}O in precipitation may be not associated with the processes of fractioning and non-equilibrium condensation.

August 14–15. The amount of precipitation of 4.1 mm with the value of $^{18}O = -2.22‰$ was registered at night on August 15 (at the surface air temperature of 20.2 C). At that time the weather in the European part of Russia was defined by the strong ridge of the Azores high. Against its background the trough was formed in the surface pressure field which stretched from the cyclone with the center over the Barents Sea and induced precipitation. However, maritime air masses generally moved from hot subtropical regions of the Atlantic Ocean and Mediterranean Sea that favored the rather high concentration of ^{18}O.

October 20. In autumn cyclonic activity and westerlies intensify that favors the rapid inflow of fresh Atlantic air to Europe and the European part of Russia. The minimum value of $^{18}O = -19.1‰$ is typical of

precipitation registered on October 20. At that time the European part of Russia was influenced by the front part of the low cyclone which caused light southwestern wind in the surface layer. At the height of 1500 m, the wind had the pronounced northwestern component that was indicative of the air inflow from high latitudes (Fig. 4e).

The analysis of synoptic conditions in the period of precipitation fall in 2014 and the computation of back trajectories of air masses in the lower and middle troposphere during 5 days before precipitation revealed the following. Lighter isotopic composition is typical of relatively cold air; if it moves over the land for a long time, it loses isotopically heavy molecules and becomes more and more isotopically light as precipitation occurs. High ^{18}O values in precipitation are not as much typical of warm air as of the cases of its fast inland movement. This is most often observed when cyclonic activity increases in the mid-lati- tudes and westerlies intensify. It should be noted that the events related to the passage of air masses over inland seas (Mediterranean, Black, and Caspian) were most often accompanied by the increase in the concentration of ^{18}O.

CONCLUSIONS

The annual series of ^{18}O values for all precipitation events in Moscow in 2014 was obtained for the first time and was characterized by significant variations (from –0.09 to –26.29‰). General variations in the ^{18}O values exhibit their natural increase in summer and decrease in winter. The largest amplitudes of ^{18}O were registered in March–April and October. Monthly mean values of ^{18}O are comparable with monthly mean values obtained before except for the autumn months when precipitation over Moscow was characterized by the relatively high concentration of ^{18}O.

The significant correlation was revealed between the ^{18}O values and surface air temperature: the correlation coefficient is equal to 0.85 for the year and 0.87 for winter.

The method of back trajectories based on the HYSPLIT transport model was used to assess the effects of advective factors and to analyze the possible influence of long-range transport on the oxygen isotopic composition of precipitation.

The most isotopically light precipitation may be associated with the invasion of cold air masses from high latitudes and with the continental effect manifested in the isotopic depletion of atmospheric moisture as the precipitation fall is observed in the air mass moving over the land. The highest values of ^{18}O are typical of the processes causing the fast movement of air masses from the North Atlantic to the European part of Russia. This occurs as a result of activation of westerlies and cyclonic activity as well as in the case of air advection from the warm Mediterranean and Black seas being able to act as additional sources of ^{18}O in atmospheric moisture. The conditions in the under-the-cloud layer which affect the equilibrium or non-equilibrium nature of isotopic fractioning resulting from water phase transitions (precipitation condensation) may be an additional factor for the formation of the isotopic composition of precipitation at the point of its registration.

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