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GLACIERS AND ICE SHEETS

Isotopic Signature of Precipitation in the Elbrus Region

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Abstract—Results of studying isotopic characteristics of precipitation at the foot of the southern slope of Elbrus, in the Caucasus, are presented. The precipitation sampling was organized at Azau station (at an altitude of 2300 m) on an everyday basis. The main precipitation sources for the Elbrus region have been established using the method of HYSPLIT back trajectories. Values of $\delta^{18}O$ of the precipitation reflect a pronounced relation to the temperature of the surface air layer: $\Delta\delta^{18}O/\Delta T = 0.85‰/°C$.

Keywords: oxygen isotope composition, hydrogen isotope composition, precipitation, Caucasus, Elbrus, temperature reconstruction

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INTRODUCTION

High-mountain glaciers accumulate in the composition of ice important climatic information such as air temperature and dustiness and gas composition of the atmosphere. These data represent the climatic signal for middle and low latitudes and complement global climate reconstructions performed by ice cores from Greenland and Antarctic. In comparison with their polar analogs, mountain drilling locations are characterized by comparatively small-scale and complex geometry, the closeness of glaciers to continental sources of air masses, and a complex pattern of precipitation formation. Ice cores in mountains embrace much shorter time intervals when compared with ice covers; however, owing to higher snow accumulation, they allow one to study climatic changes with annual and even seasonal resolution.

Reconstructing air temperatures by oxygen isotope composition of ice oxygen is thought to be an important key of interpreting climate information by ice cores. Despite the global equations of the relation between air temperature and $\delta^{18}O$ of precipitation (Dansgaard, 1964; Rozanski et al., 1992), the character of the relation can change at high altitudes, which is related to both different precipitation sources and the rugged topography of mountain glaciers. A discrepancy between the isotopic record by the core and direct temperature observations occurred at the Alpine glacier Colle Gnifetti (4450 m) due to considerable losses of snow in winter as a result of the wind drift. The negative effect of nonuniform accumulation or losses of a part of precipitation falling on the glacier leads to a interruption of the $\delta^{18}O$–T relation. In some measure, it can be overcome by averaging individual core time series with a duration of 1.5 and 10 years; the coefficients of correlation between $\delta^{18}O$ and T increased from 0.48 to 0.67 and 0.79, respectively (Bohleber et al., 2018). The relation between $\delta^{18}O$, δ^2H, and deuterium excess value ($d_{exc} = \delta^2H - 8 \times \delta^{18}O$) completes the glacier ice temperature record by knowledge about the origin sources and conditions in vapor sources (Ciais and Jouzel, 1994; Vimeux et al., 2001; Stenni et al., 2010) and processes during precipitation, such as subcloud evaporation, as well as processes that occur inside the snow mass and lead to a transformation of the primary isotopic record. Ideally, the interpretation of $\delta^{18}O$ and δ^2H values of ice cores should take into account all these factors, although it is not always possible in practice. Studying precipitations falling either directly at the glacier or at the nearest weather station is considered the first step in this way. Sampling precipitation throughout the year at drilling sites such as the western plateau or the eastern peak (Mikhalenko et al., 2005; Kozachek et al., 2015; Mikhalenko et al., 2015; Kutuzov et al., 2019; Chizhova et al., 2019) is technically impossible. Such work was done at the Azau station at the foot of the southern slope of Elbrus. This work is aimed at studying isotopic characteristics of atmospheric precipitation to establish the dependence of $\delta^{18}O$ values on temperature at the time of precipitation and come closer to understanding the processes forming isotopic characteristics of the snow cover and glacier ice of Elbrus.

MATERIALS AND METHODS

The Elbrus massif is the largest glaciation node of Greater Caucasus. Currently, the area of glaciers is shrinking. During the period from 1999 to 2012, the area of glaciers declined by 4% and, from 1997 to 2017, by 10.8% (Kutuzov et al., 2019). An analysis of long-term changes in air temperature in the region (Kozachek et al., 2015) shows that winter temperatures of air (November–April) are characterized by larger interannual variability than summer temperatures (May–October); current climate changes manifest themselves first and foremost in the summer warming.

To study the relation between the isotopic composition of precipitations and the local temperature of air, precipitation sampling was organized during the period from May 1, 2019, to September 27, 2021, at the Azau station located at the foot of Elbrus at an altitude of 2300 m. The sampling was carried out once a day at 09:00 Moscow time. The air temperature was recorded at the Terskol weather station (Russian meteorological service station no. 4334250). The samples were taken into a sampler; in the case of solid precipitation, the samples were melted, poured into test tubes, and sealed with a parafilm tape. Analysis of the isotopic composition of oxygen and hydrogen was performed in the Climate and Environmental Research Laboratory of the Arctic and Antarctic Research Institute (AARI) on a Picarro L2130-i isotope analyzer. The measurement error was 0.04 and 0.5 for the $\delta^{18}O$ and δ^2H values, respectively. The values were calibrated in the VSMOW–VSLAP scale. In total, 238 samples were analyzed.

To establish the main features of the long-range transport of air and possible sources of water vapor falling in the form of precipitation at Elbrus, the back trajectories of air particles were reconstructed using the NOAA HYSPLIT_4 trajectory model (Draxler and Hess, 1998; Stein et al., 2015) and NCEP/NCAR Reanalysis gridded fields of meteorological parameters with a resolution of 2.5° × 2.5° (Kalnay et al., 1996; Kistler et al., 2001). The back trajectories were reconstructed for 120 h (5 days), which is caused by the average time of the water vapor presence in the atmosphere (Wallace and Hobbs, 2006). The back trajectories were calculated for air particles coming to the Azau station (43.2659° N, 42.4799° E) during the period from January 12, 2019, to September 27, 2021, in all days when precipitation was observed at the station. The calculation was carried out for three 200-m-thick layers centered at levels of 2500, 3500, and 5000 m above sea level or, correspondingly, at heights of 200, 1200, and 2700 m over the Azau station. Within each layer, for each hour of a precipitation day, three trajectories were calculated—for the level itself and for heights of ±100 m from it. For the period under study, an array of 19 756 back trajectories was calculated for each level. Based on the obtained arrays, seasonal fields of the regional probability of air particle transfer P [%] were reconstructed for each level using the technique (Shukurov and Chkhetiani, 2017). The probability characterizes the repeatability of transfer of air masses related to precipitation events at the Azau station (the field resolution is 2.5° × 2.5°).

RESULTS

Values of $\delta^{18}O$ and δ^2H of precipitations vary from 0.52 to −28.22‰ and from 16.3 to −224.1‰, respectively. They exhibit a regular seasonality with high values of $\delta^{18}O$ and δ^2H in summer and low values in winter (Fig. 1). The deuterium excess varies within wide limits from 24.8 to −14.6‰. The minimum $\delta^{18}O$ and δ^2H values of precipitation were recorded in February 2020.

The seasonal variations in values of $\delta^{18}O$ and δ^2H correspond to the annual variations in air temperature at the Terskol station. The relation between the isotopic composition of oxygen and daily average air temperatures on the day of sampling is expressed by the linear equation $\delta^{18}O = 0.825t - 12.7‰$, $R^2 = 0.69$ (Fig. 2). When using ice cores for paleoclimatic reconstructions, it is important to estimate to what extent isotopic parameters of precipitation are related to monthly average air temperatures. When switching to estimating the relation between monthly averaged arithmetic mean $\delta^{18}O$ values of precipitations and monthly average air temperature, the coefficients $\delta^{18}O/T$ remain almost unchanged and the reliability of the linear approximation increases ($\delta^{18}O = 0.85t - 13.3‰$, $R^2 = 0.86$). This means that the relation to the temperature for two years on the whole is represented by the coefficient $\Delta\delta^{18}O/\Delta T = 0.85‰/°C$.

At the same time, meteorological parameters of some seasons varied during the whole observation period; this concerned mainly temperature conditions of winter: the average (−5.2°C) and minimum (−16°C) air temperatures at which precipitations fell in winter 2020 were lower than in winter 2021 (−3.5 and −10°C, respectively). The isotopic parameters of precipitations are also different—the average $\delta^{18}O$ value for winter months from January to March in 2020 was −18‰; the minimum value was −28.2‰. In 2021, the average $\delta^{18}O$ value for winter months was −14.66‰; the minimum value was −23.59‰. The relation between $\delta^{18}O$ of precipitation and air temperature is different for these two seasons (see Fig. 1). Two time intervals are distinguished: the first period lasts from May 2019 to May 2020, the second one from June 2020 to September 2021 (see Fig. 2), and the beginning of the summer season was used as the separator. For the first period, the relationship between $\delta^{18}O$ values and surface air temperatures is expressed by

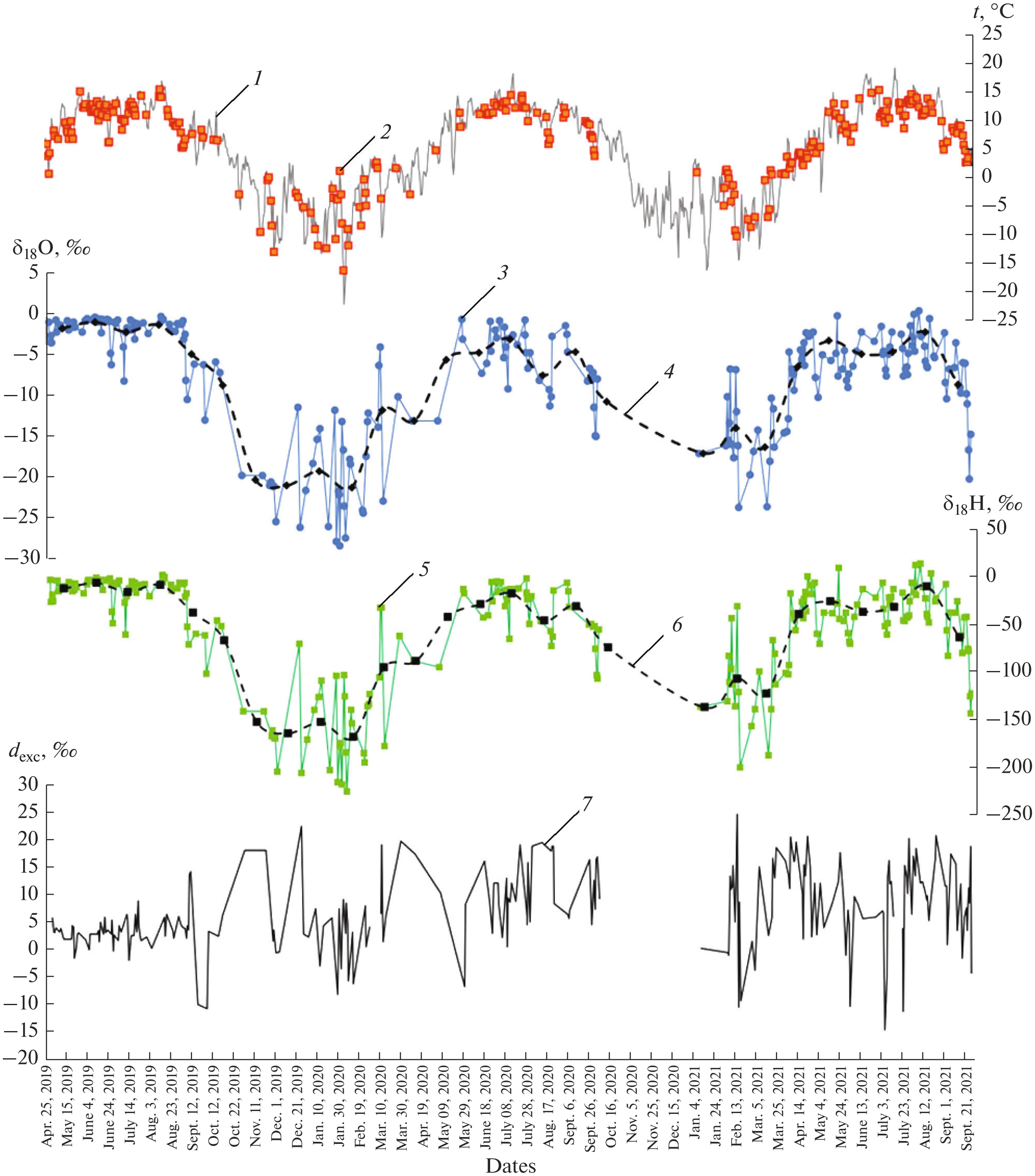

Fig. 1. (a) Variations of air temperature at the Terskol weather station values of (b) δ^{18}O, (c) δ^2H, and (d) d-excess (d) of precipitation sampled at the Azau field for the observation period: (*1*) average daily air temperatures, (*2*) air temperatures on the day of sampling, (*3*) δ^{18}O values of precipitation, (*4*) monthly average δ^{18}O values of precipitation, (*5*) δ^2H values of precipitation, (*6*) monthly average δ^2H values of precipitation, and (*7*) deuterium excess.

the equation $\delta^{18}O = 1.06t - 13.9‰$ ($R^2 = 0.93$) and, for the second period, $\delta^{18}O = 0.64t - 12.05‰$ ($R^2 = 0.84$).

All values of δ^{18}O and δ^2H are approximated by the equation $\delta^2H = 8\ \delta^{18}O + 7.06$ ($R^2 = 0.98$) close to the global meteoric water line. The average value of the deuterium excess over all samples of precipitations amounted to $6.82 \pm 5.99‰$. Earlier, relatively high (>10‰) values of the deuterium excess were observed in snow precipitations and snow cover for the region of

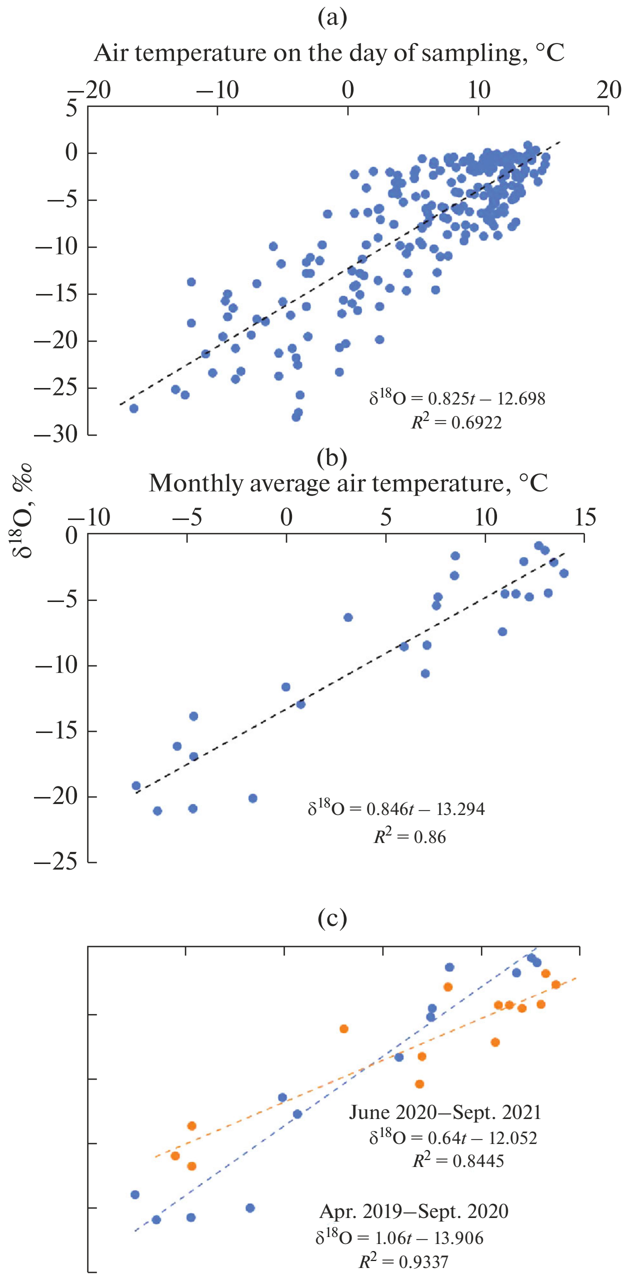

Fig. 2. Relationship between the $\delta^{18}O$ values of precipitation at the Azau station and surface air temperature at the Terskol station for all individual samples of precipitation (a) for the observation period, (b) averaged to monthly averages, and (c) for monthly averages of two periods.

Elbrus and Central Caucasus (Mikhalenko et al., 2005; Vasil'chuk et al., 2020).

The back trajectories characterize general features of the air transfer providing the arrival of moisture-bearing air masses in the Elbrus region. These features exhibit seasonality expressed in the change of the moisture-bearing air mass source from winter to summer and in an increase in the distance from the sources (average length of the air mass trajectory) from summer to winter. In general, an analysis of five-day back trajectories shows that precipitation in Elbrus in winter is related to the prevailing air mass transfer from the Atlantic (Figs. 3a–3c); in summer, it is related to the dominance of the transfer from regions of central Europe and from the Mediterranean and Black seas (see Figs. 3g–3i). The region of the Mediterranean and Black seas is the sourse from where the air transfer to Elbrus is the most probable in all seasons. Despite the fact that the summer season accounts for the largest number of trajectories, the region of transfer at all levels in summer is minimal (see Figs. 3g–3i), which is related to the decrease in the average speed of the air transfer in this season due to weakening of the latitude gradient of air temperature in the Northern Hemisphere. With an increase in the zonal temperature contrast in transition periods and especially in winter, the speed of air particles increases, which is expressed in an increase in the transfer zone in spring (see Figs. 3d–3f), in autumn (see Figs. 3j–3l), and in winter as compared to summer.

RESULTS AND DISCUSSION

Possible Precipitation Sources and Deuterium Excess

One important factor determining the isotopic parameters of atmospheric precipitations is the region of moisture origin. Conditions in the vapor source, such as relative humidity and sea surface temperature, have an effect on the deuterium excess (Pfahl and Sodemann, 2014). The distance from the vapor source to the precipitation location also has an effect on isotopic characteristics of precipitation. In most cases, isotopic parameters of precipitation are formed according to the Rayleigh equation and related to successive depletion of air masses on their way. This is accompanied by a decrease in values of $\delta^{18}O$ and δ^2H of the falling precipitation and an insignificant increase in the deuterium excess (Gat, 2000).

The back trajectories of air masses in summer indicate that the most probable source of precipitations is the center of Europe, regions of the eastern part of the Mediterranean Sea, the basin of the Black Sea, and regions nearest to it. The Mediterranean and Black seas are considered vapor sources for precipitations with high values of the d-excess in southern Europe, the Alps, and the Caucasus (Gat and Carmi, 1970). One more source with high deuterium excess is the recycling of moisture, when the moisture falling in the form of precipitation is reevaporated from the ground. This vapor is mixed with air masses coming to the Elbrus region; as a result, the falling precipitations contain higher values of d_{exc}. Earlier, precipitations with high d_{exc} were observed at Elbrus; most snow pits and shallow cores at the southern slope of Elbrus also contain average values of d_{exc} above 10‰. This is easily seen in the $\delta^{18}O$–δ^2H diagram (Fig. 4), in which the points characterizing the surface snow and ice core

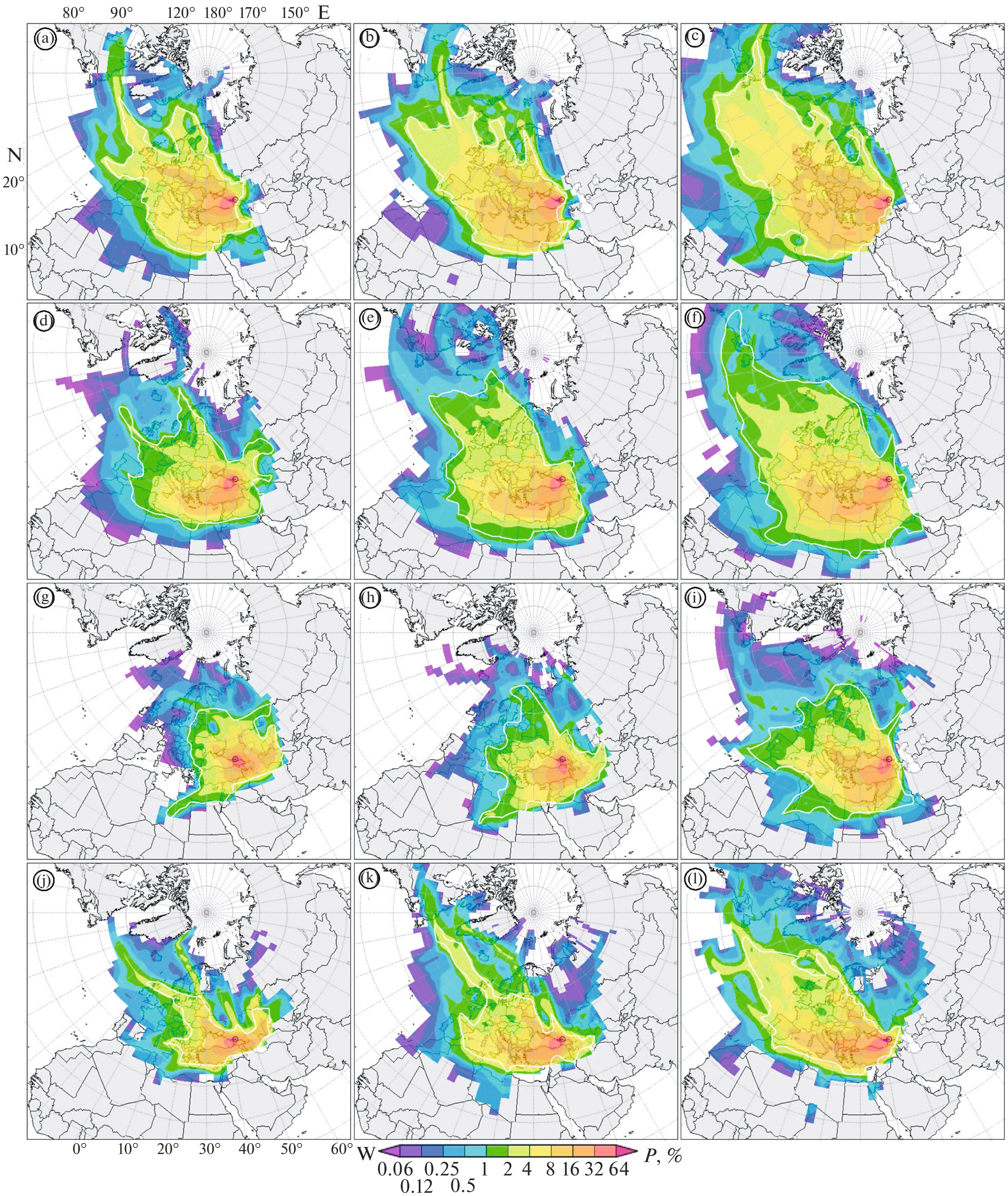

Fig. 3. Average seasonal probability of air particle transfer over the surface (a, b, c) in winter; (d, e, f) in spring; (g, h, i) in summer; and (j, k, l) in autumn at levels of 2500, 3500, and 5000 m (from left to right). The area of cells containing at least 50 independent back trajectories is bounded by a white line.

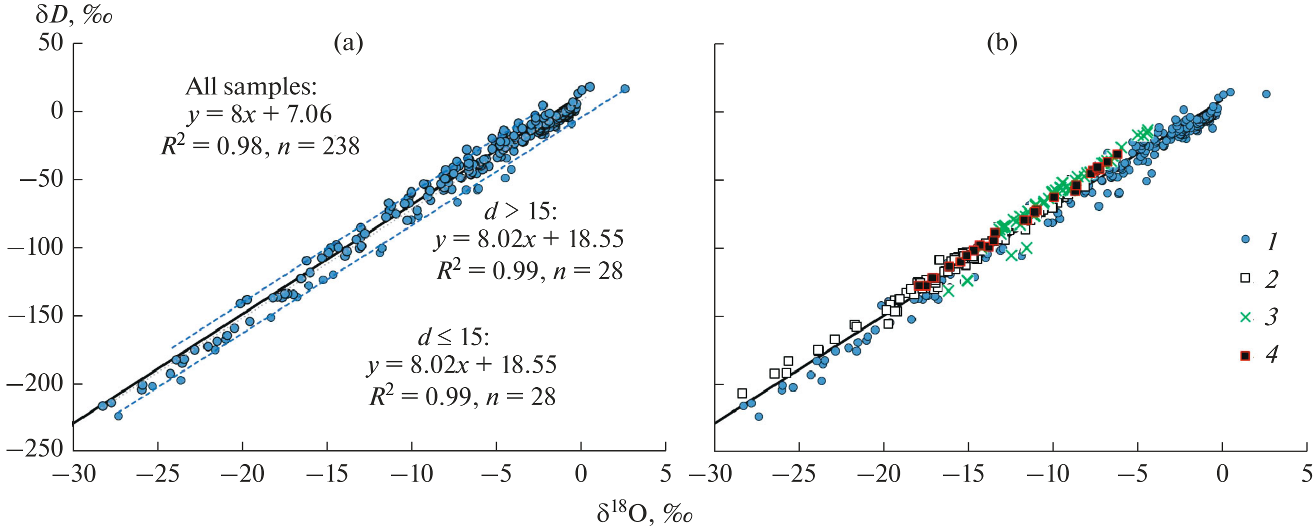

Fig. 4. (a) $\delta^{18}O$–δ^2H relationship for the all precipitation samples at the Azau station and (b) isotope parameters of snow and ice on the Elbrus slope: (*1*) precipitation at the Azau station, (*2*) glacial ice on the Western Plateau of Elbrus, (*3*) fresh snow (Sept. 9–11, 2010) on the southern slope of Elbrus in the altitude range of 3000–4900 m, and (*4*) glacial ice on the eastern peak of Elbrus.

from the western plateau (Mikhalenko et al., 2005) are located above the meteoric water line. In the study, only 30% of precipitation is characterized by d_{exc} above 10‰ (see Fig. 4). The main cause of the decrease in d_{exc} of the precipitation is evaporation occurring either in the cloud or in the subcloud layer until the rain drops reach the ground. Subcloud evaporation can play a major role in summer months, when conditions of low relative humidity and high air temperatures are often observed in the ground air layer.

For individual precipitations at the Azau station, both extremely low and extremely high values of d_{exc} were recorded during the whole observation period disjointedly from the precipitation season. Nevertheless, when averaging all obtained values over the seasons (Table 1), it is seen that values of d_{exc} for winter months are lower than for other months of the year. The general character of the air mass motion for the winter period (see Fig. 4) indicates the prevailing transfer from the Atlantic; the typical values of d_{exc} for this vapor source in winter months are <10‰. At the same time, the intense Rayleigh depletion along the trajectory can lead to an increase in d_{exc} of the precipitation from this source.

The station in Bakuriani (true altitude of 1665 m) at which the isotopic composition of precipitation was systematically observed is the nearest station to the study area. The data at this station from 2008 to 2018 are included into the GNIP database (WMO Code 3752400). The annual average value of $\delta^{18}O$ in precipitations for ten years of observations at this station is −10.4‰ (the monthly average $\delta^{18}O$ values of precipitations vary from −22.03 to 1.73‰) and the annual average value of d_{exc} is 12.8‰. When averaging the $\delta^{18}O$ and δ^2H values of individual precipitation events to monthly average and, then, to annual average values, the $\delta^{18}O$ and d_{exc} values at the field of Azau were −10.8 and 6.4‰, respectively. While the monthly average values of $\delta^{18}O$ and δ^2H in precipitations of the winter period at the Azau field are considerably lower than in Bakuriani, the picture observed in summer is reverse—$\delta^{18}O$ and δ^2H values of precipitations at the Azau field are considerably higher (see Table 1). The deuterium excess at the Azau field is lower than at Bakuriani in all months of the year, with the exception of April. In summer months, high values of d_{exc} of precipitations at the Bakuriani station indicate a local source of moisture. At the Azau field, the precipitations must also contain high d_{exc} due to the local source and contribution of moisture recycling. However, summer precipitations at the Azau station have high $\delta^{18}O$ and relatively low d_{exc}. These features are explained by two processes: vapor origination from regions of the Mediterranean and Black seas and the contribution of moisture recycling, which result in an increase in values of d_{exc} of water vapor; as a result of the following subcloud evaporation, values of $\delta^{18}O$ in rain drops increase and those of d_{exc} decrease.

In winter months, the difference between $\delta^{18}O$ values of precipitations at the Azau field and Bakuriani can indicate the normal height effect (for January–March, −0.3‰/100 m); however, low values of d_{exc} in precipitations of the winter period at the Azau station are still hard to explain. The close location of the Bakuriani station to the exploration area allows one to presuppose common features of the air transfer and origin of precipitations at these stations. The considerable orographic barrier of the Main Caucasian Range and

Table 1. Seasonal and annual average values of $\delta^{18}O$, δ^2H, and d-excess of precipitation at the Azau station and at the nearest GNIP station in Bakuriani (41°43′59.99″ N, 43°31′0″ E)

Indices	December–February	March–May	June–August	September–November	Year
			Azau		
$\delta^{18}O$, ‰	−18.69 ± 1.22	−7.02 ± 4.92	−3.4 ± 0.14	−11.9 ± 5.49	−10.8 ± 6
δ^2H, ‰	−147 ± 10.2	−47.4 ± 37.7	−20.2 ± 1.1	−87 ± 42.5	−79.7 ± 50
d-excess, ‰	2.53 ± 1.2	8.81 ± 6.2	7.17 ± 1.65	8.3 ± 1.6	6.4 ± 3.1
			Bakuriani		
$\delta^{18}O$, ‰	−16.05 ± 0.43	−10.33 ± 1.44	−3.8 ± 0.65	−11.2 ± 2.3	−10.4 ± 4.1
δ^2H, ‰	−116.1 ± 3.36	−71.1 ± 11.2	−20.7 ± 5.3	−76.7 ± 20.4	−71.2 ± 32.2
d-excess, ‰	12.3 ± 1.6	11.2 ± 1.1	12.8 ± 0.3	14.8 ± 1.05	12.8 ± 1.4

different location of the stations in height are treated as the difference. These are probably the factors that play a major role in the formation of precipitation in the Elbrus region.

Half of precipitation events at the Azau station with values $d_{exc} < 0$‰ fall on precipitations of the winter period. Negative values of d_{exc} are also typical for precipitation falling in September 2019, June–July 2021, and February 2021 (from −10.68 to −9.9‰). These precipitations are related to the arrival of air masses from central Europe, regions of the Mediterranean Sea, and (partially) northern Africa. Five-day back trajectories at all levels of air particle motion related to precipitation events with d_{exc} of about −10‰ are characterized by a lower speed of the air particle motion along the trajectories, which manifests itself in a lesser extension of the back trajectories and relatively close location of potential air mass sources (Fig. 5 for 3500 m). In general, trajectories on days with d_{exc} of about −10‰ are localized near the Mediterranean Sea: in the warm season of the year (September 27, 2019; June 3, 2021; and July 6, 2021) over southern Europe and in the cold time of the year over the Mediterranean Sea and the Middle East (February 16, 2021). The back trajectories on days with extremely low d_{exc} during all five days before the arrival at Elbrus were completely located in the continental zone of the transfer and did not reach the Atlantic, which indicates low speeds of the air particles. Thus, precipitations with low values of d_{exc} are related not to sources and routes of the moisture arrival, but to processes occurring upon condensation in a slow-moving air flow.

Atmospheric precipitations at high altitudes have a complex picture of formation. This is related, on the one hand, to the rapid change of air masses and, on the other hand, to complex processes of convection and turbulence arising at mountain slopes (in particular, in diurnal cycles) (Kelsey et al., 2018). There are few described precipitation events with negative values of d_{exc}, and they are related mainly to evaporation of rain drops; however, values $d_{exc} < -10$‰ of water vapor in the air were observed for atmosphere inversion layers with a low content of water vapor and in the boundary layer (Sodemann et al., 2017; Salmon et al., 2019).

The most probable cause of precipitation events with low d_{exc} is the subcloud evaporation of water vapor. To date, there is no possibility to estimate whether the processes of intracloud evaporation and vertical stratification of water vapor took place; that remains beyond the scope of this consideration.

At heights above 3000 m at Elbrus slopes, isolated cases of precipitation events with low values of d_{exc} were also recorded, e.g., snowfall in September 2010 (see Fig. 5). Sampling of the surface fresh snow at different heights showed that the fresh snow was characterized by values of d_{exc} from 12 to 24‰; for four samples, values of d_{exc} were found to be from −2.2 to −7.3‰. The same processes of dynamic charge in isotopic characteristics of water vapor inside the cloud can probably be also observed at high altitudes in individual cases.

These processes can distort the valley–peak relation and deteriorate the accuracy of paleotemperature reconstructions by ice cores.

Temperature Dependence

The high degree of correlation between the average isotopic composition of oxygen in precipitation of temperate climate and annual average air temperature at the sampling location was established for the first time by W. Dansgaard (Dansgaard, 1964). The global dependence of $\delta^{18}O$ values on the annual average surface temperature is expressed as $\delta^{18}O = 0.69T - 13.6$‰. The temperature coefficient $\delta^{18}O/T \approx 0.7$ agrees well with the assumptions made based on experimental and theoretical works and was verified by numerous empirical data for middle and high latitudes (Johnsen et al., 1989; Rozanski et al., 1992; Tian et al., 2003). The relation is strongest in high latitudes and manifests itself more weakly in middle latitudes and equatorial regions (Dansgaard, 1964). It is evident that the temperature coefficient

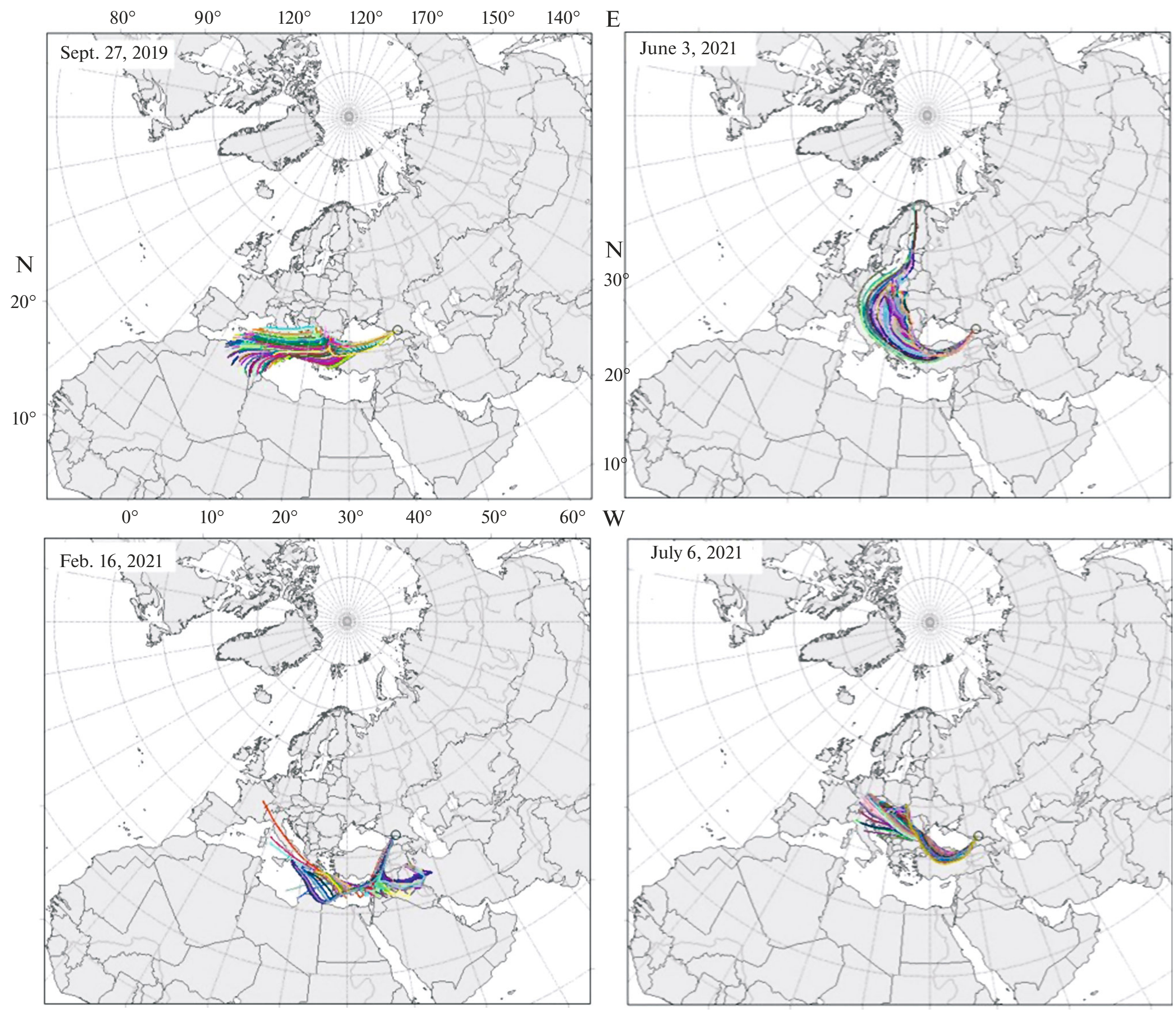

Fig. 5. Reconstructed back trajectories (level of 3500 m) of air masses for precipitation events with $d_{\text{exc}} < -10‰$.

can vary depending on the location of the observation region and some meteorological factors. For correct paleoclimatic reconstructions, it is necessary to estimate this temperature coefficient in a specific region at the time of interest.

Using the dependence $\Delta(\delta^{18}O)/\Delta T$ obtained for precipitations at the Azau station for paleotemperature interpretation of ice core data obtained at true altitudes above 4000 m presupposes introducing a correction for the altitude isotope effect. Direct observations of temperature at the Elbrus slope in 2010 with the use of an automatic weather station showed that the average height gradient of air temperature amounted to 0.4°C/100 m (Toropov et al., 2016). Earlier, the altitude isotope effect was discovered for fresh snow at the Garabashi glacier; it amounted to 0.3‰/100 m on average (Vasil'chuk et al., 2005), which corresponds to a temperature drop with height by 0.4°C per 100 m.

With allowance for this fact, the equation of the $\delta^{18}O-T$ relation obtained for the Azau station is transformed into the equation for the height of 4000 m in the form $\delta^{18}O = 0.85t - 17.8‰$, i.e., the change concerns only the free term in the regression equation. The altitude isotope effect is not always apparent; moreover, mountain slopes are often characterized by the manifestation of the inverse altitude effect (Jing et al., 2022). Therefore, the exact determination of the isotopic shift between precipitations in the valley and at high-mountain drilling sites remains debatable. However, the relation character expressed by the ratio $\Delta(\delta^{18}O)/\Delta T = 0.85‰/°C$ can be used for paleoreconstructions by ice cores of Elbrus. A similar approach was used in studies of the Chongce ice core of the

Tibetan Plateau (Pang et al., 2020). The value $\Delta(\delta^{18}O)/\Delta T = 1.61 \pm 0.22‰/°C$ established for precipitations was used for the reconstruction of temperatures by $\delta^{18}O$ values of the ice core. The quantity $\Delta(\delta^{18}O)/\Delta T$ itself for Chongce is much larger than most of slopes $\Delta(\delta^{18}O)/\Delta T$ observed in regions of middle and high latitudes (0.6–0.7‰/°C) (Dansgaard, 1964; Rozanski et al., 1992), but it is comparable with the data obtained for other ice cores of high-mountain Pamir (Tian et al., 2006). The temperature dependence is influenced by factors such as changes in the seasonal distribution of precipitations, a shift of main sources of moisture, the influence of the local recirculation of moisture, and the different height level of the discharge of air masses. A high coefficient $\Delta(\delta^{18}O)/\Delta T$ equal to 1.7‰/°C was obtained as a result of studying the ice core from Colle Gnifetti in the Alps (Keck, 2001). For the Fiescherhorn glacier in the Bernese Alps, the values $\Delta(\delta^{18}O)/\Delta T = 1.1–1.45‰/°C$ were reported (Rozanski et al., 1997; Schotterer et al., 1997). Cooling of water vapor at the last portions of Rayleigh condensation with an increase in height in mountains and in coefficients of isotope fractionation when passing from the vapor–water system to the vapor–ice system was noted as a hypothesis for explaining high coefficients $\Delta(\delta^{18}O)/\Delta T$ (from the established 1.7 to the possible ~3‰/°C) for high-altitude regions of Alps (Keck, 2001).

The different character of the relation between $\delta^{18}O$ values of precipitations at the Azau station and air temperature, as was established for two periods (the first from May 2019 to May 2020 and the second from June 2020 to September 2021), is caused by differences in air temperature and amount of precipitation (970 and 1518 mm, respectively). In these two periods, a different relation with global circulation processes as the North Atlantic Oscillation (NAO) is observed.

Strong positive phases of the index are related as a rule to temperatures above average throughout northern Europe and to temperatures below average in Greenland and, often, throughout southern Europe and in the Middle East. They are also related to the precipitation amount above average over northern Europe and Scandinavia in winter and to precipitations below average over southern and central Europe. Assuming by convention that the Elbrus region is located in southern Europe, one should expect inverse correlation between the NAO indices and temperatures (precipitation amount) at the Azau station.

In the 2019/2020 season, an inverse correlation between monthly average air temperatures and the NAO index is revealed (Fig. 6c). In the same season, according to the calculated average seasonal probability of transfer P over an array of 7695 back trajectories, the long-range transport of air masses and dominant influence of the Atlantic are observed (see Fig. 6a). In the 2020/2021 season (9505 back trajectories), the influence of the Atlantic is not as pronounced; the air was transported from central regions of Europe, from northern Africa, and from central regions of the European Russia (see Fig. 6b). Such a character of transport and large amount of precipitation resulted in the absence of correlation between monthly average temperatures and NAO index for the 2020/2021 season (see Fig. 6d). In both seasons, no correlation between the index and the precipitation amount is observed.

The obtained coefficient $\Delta(\delta^{18}O)/\Delta T = 1.06‰/°C$ for the period from May 2019 to May 2020 is related to the considerable depletion of air masses by the time they reached Caucasus. Both the lesser precipitation amount during the season and the long range of trajectories of air mass motion (see Fig. 6) are indicative of the increase in the coefficient: when the concentration of water vapor is low, its condensation is accompanied by more pronounced isotopic effects, especially under conditions of negative air temperatures, which leads to higher sensitivity of $\delta^{18}O–T$. The difference in coefficients of the relation $\Delta(\delta^{18}O)/\Delta T$ for the distinguished time periods suggests that the relation character readily responds to changes in meteorological conditions.

Owing to the difference of these two years, the established dependence $\Delta(\delta^{18}O)/\Delta T = 0.85‰/°C$ reflects the averaging performed for periods with different meteorological patterns and, in the first approximation, can be used for paleoreconstructions. Using the established regression equation and solving the inverse problem of calculating the air temperatures by the value of $\delta^{18}O$ of the precipitation, we obtain the average absolute calculation error of 3.2°C and the determination coefficient of 0.67. These are the objective limits of the temperature reconstruction that are caused by breaks of the $\delta^{18}O–T$ relation due to processes accompanying the condensation. Studying the ice cores in which the paleoinformation is averaged to a considerable extent in the natural way, we meet not only problems of temperature reconstruction accuracy, but also the loss of the $\delta^{18}O–T$ relation (Kozachek et al., 2015) due to nonuniform accumulation.

CONCLUSIONS

Values of $\delta^{18}O$ and $\delta^{2}H$ of atmospheric precipitations sampled from May 2019 to September 2021 at the Azau station in the Elbrus region vary from 0.52 to −28.22‰ and from 16.3 to −224.1‰, respectively, and thus reveal a regular seasonality—high values of $\delta^{18}O$ and $\delta^{2}H$ in summer and low values in winter. The deuterium excess varies between very wide limits from 24.8 to −27.4‰. Precipitation in the Elbrus region in winter is related to the prevailing transfer from the Atlantic and, in summer, to the prevalence of the transfer from regions of central Europe and the Mediterranean and Black seas. The Mediterranean Sea in all seasons is considered as a region from which air and moisture are transported to Elbrus.

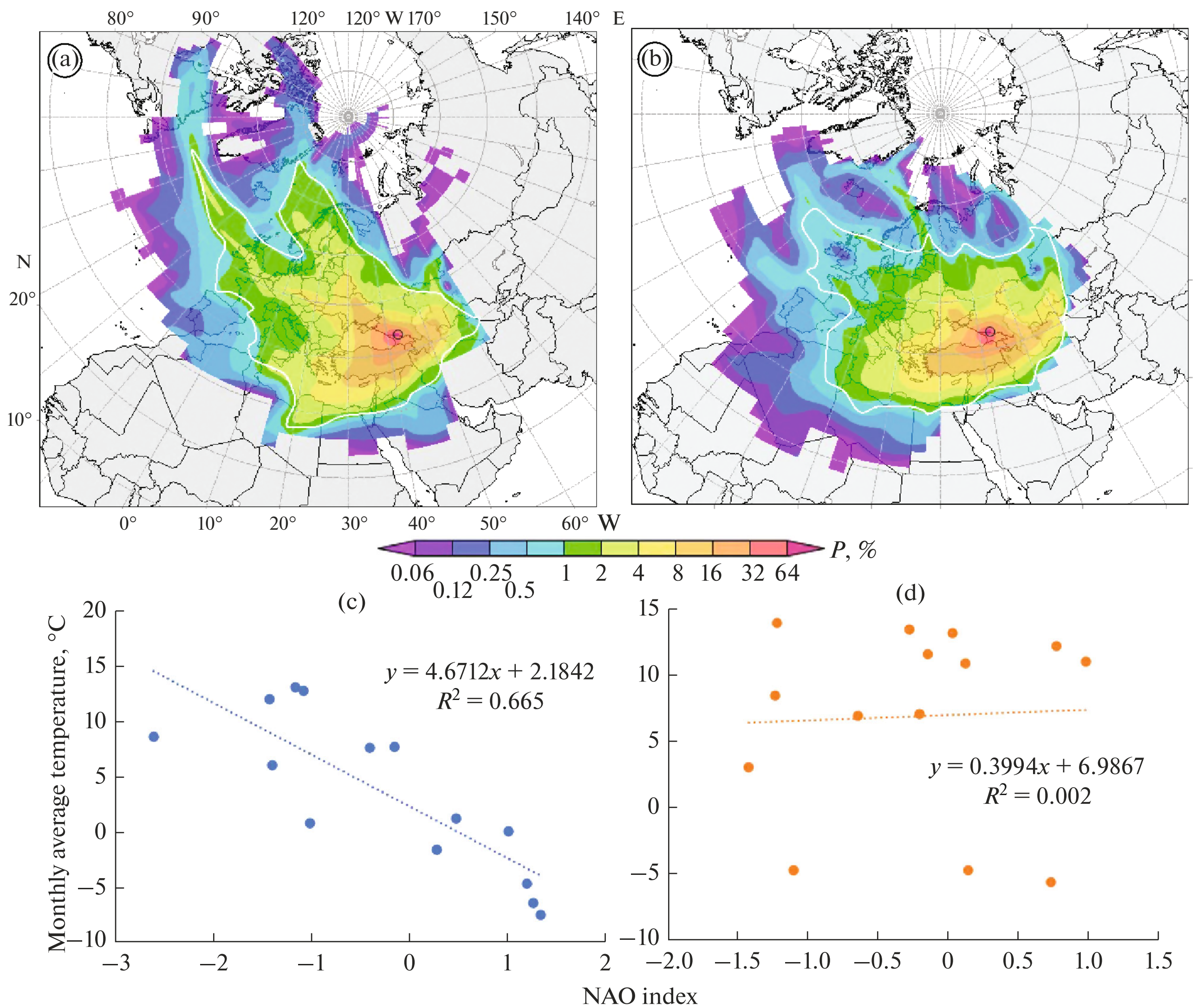

Fig. 6. Average probability of air particle transfer at a level of 2500 m in the period (a) from May 2019 to May 2020 and (b) from June 2020 to Sept. 2021. (c, d) Relationship between air temperature and the North Atlantic Oscillation index for these periods.

All obtained values of $\delta^{18}O$ and δ^2H are approximated by the equation $\delta^2H = 8.02\,\delta^{18}O + 7.0$ ($R^2 = 0.98$) close to the global meteoric water line. The average value of the deuterium excess when averaging over all samples was 6.82 ± 5.99‰.

In general, for two years of observations, the relationship between $\delta^{18}O$ values of precipitation and surface air temperature is expressed by the coefficient $\Delta(\delta^{18}O)/\Delta T = 0.85$‰/°C. With allowance for different meteorological conditions typical for two seasons of observations, the total error of air temperature reconstruction by the $\delta^{18}O$ value of precipitation was ±3.2°C. This is the objective error that is caused by breaks of the $\delta^{18}O$–T relation in view of processes accompanying condensation (intracloud evaporation, orographic precipitation, mixing of different air masses, and different air mass sources). When studying the relation by paleoarchives such as ice cores from the western plateau of Elbrus and the eastern peak, along with taking into account the altitude isotope effect, it is required to search for additional markers for referencing the isotopic record by ice to accumulation seasons. Although seasonal $\delta^{18}O$ or δ^2H variations are still used today for counting annual layers, the search for new additional markers for demarcation summer–winter accumulation layers in the core remains topical.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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