Investigation of a deep ice core from the Elbrus Western Plateau, the Caucasus, Russia

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Abstract

A 182 meter ice core has been recovered from a borehole drilled through the glacier to the bedrock at the Western Plateau of Mt. Elbrus (43°20′53.9″ N, 42°25′36.0″ E; 5115 m a.s.l.), the Caucasus, Russia, in 2009. This is the first ice core in the region which represents a paleoclimate record practically undisturbed by seasonal melting. Relatively high snow accumulation rate at the drilling site enabled analysis of the intra-seasonal climate proxies' variability. Borehole temperatures ranged from −17 °C at 10 meters depth and −2.4 °C at 182 m. A detailed radio-echo sounding survey showed that the glacier thickness ranged from 45 meters near marginal zone of the plateau up to 255 m at the central part. The ice core has been analyzed for stable isotopes ($\delta^{18}O$ and δD), major ions (K^+, Na^+, Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-}, NO_3^-, Cl^-, F^-), succinic acid ($HOOCCH_2COOH$), and tritium content. The mean annual net accumulation rate was estimated from distinct annual oscillations of $\delta^{18}O$, δD, succinic acid, and NH_4^+ and is 1455 mm w.e. for the last 140 years. Using annual layer counting also for the dating of the ice core, a good agreement with the absolute markers of the tritium 1963 bomb test time horizon located at the core depth of 50.7 m w.e. and the sulfate peak of the Katmai eruption (1912) at 87.7 m w.e. was obtained. According to mathematical modeling results, the

bottom ice age at the maximal glacier depth is predicted to be about 660 years BP. As the 2009 borehole was situated downstream of this point, the estimated bottom ice age of the drilling site does not exceed 350–400 years BP. Taking into account the information that we have acquired on the Western Plateau Elbrus glacier and first results of the ice core analysis, these data can be used to reconstruct the atmospheric history of the European region.

1 Introduction

Climate and environmental changes, regional patterns, origin, and prediction are currently among the most important scientific challenges. The functioning of the Earth's climate system has a profound influence on society's development and human prosperity. The discrimination of human-induced and natural climate variability is one of the most urgent tasks and it cannot be solved using only short instrumental meteorological or atmospheric observations and climate-chemistry modeling experiments. Proxy records (lake and marine sediments, ice cores, tree rings, corals) can be used to substitute to some extent the instrumental climatic records. Proxies can reach annual and seasonal resolution, and are useful as large networks covering the areas of continental and even global scale. They can be calibrated against the instrumental data. Such time series are appropriate for the statistical analyses and numerical modeling. At this stage of development of modern paleoclimatology it is essential to have reliable regional reconstructions for the last millennia (Vaughan et al., 2013). The study of chemical impurities in cold glaciers snow and ice permit to reconstruct our changing atmosphere from pre-industrial era to present-day (see Legrand and Mayewski, 1997 for a review).

Ice cores from Polar glaciers (long-term-period of preservation and minimal disturbance by melt/refreeze processes) are presently considered to be the best representation of the paleo-climate and paleoenvironments at hemispheric scales. However, calculations based on observational data trends in the major climatic characteristics show highly pronounced regional variability. Such variability is reproduced by modern climate models and can be projected into the future (AMAP, 2011), but the reliability of the simulations depends on the amount and the quality of existent data and the results are questionable especially for the precipitation rate (Anisimov and Zhil'tsova, 2012).

The need for longer glacier and paleoclimate records has led to the development of numerous reconstructions of annual and seasonal resolution based on instrumental climate data and paleoclimatic proxies. Ice cores from non-polar high mountain glaciers have been used for reconstructing past atmospheric conditions. A number of studies examined climate and environmental changes in various nonpolar areas (Vimeux et al., 2009; Thompson, 2010) including the European Alps (Barbante et al., 2004; Preunkert and Legrand, 2013; Schwikowski, 2004), the continental Siberian Altai (Eichler et al., 2011), and Kamchatka (Kawamura et al., 2012; Sato et al., 2014).

Evidently, the best representation of the climate variability in a region of interest would be from the region itself. Despite the temporal length of the records, the Greenland and the Antarctic ice core data, though not disturbed by melting, is from sites which are very remote from most of the inhabited areas. Therefore, the comparable paleo-climate records derived directly from the glaciers in Europe and Asia are highly valuable. The problem is that the seasonal melting and the water infiltration distort the climate proxies held in firn and ice even at high altitudes of the Andes (Ginot et al., 2010), Himalaya (Hou et al., 2013) and low latitudes of the Arctic islands (Kotlyakov et al., 2004).

The documented conditions (Tushinskii, 1968; Mikhalenko, 2008) near the top of Mt. Elbrus allowed expectation of a reasonably long climatic record in an ice core not affected by melt water infiltration. Relatively high accumulation rate at the site (Mikhalenko et al., 2005) promised a high temporal resolution of the ice core data, apparently showing the seasonality effect on the results of analysis (Werner et al., 2000). Interest to recover records from such natural archive that preserve environmental data associated with atmospheric chemistry, dust deposition, biomass burning, anthropogenic emission and climate change in the Caucasus became a motivation for organizing the drilling campaign at the Western Plateau of Mt. Elbrus (Mikhalenko, 2010). The aim of the Elbrus drilling project is climatic and environmental reconstruction for Caucasian region from the ice core. After giving an overview of the existing geographical, glaciological, meteorological, and climatological knowledge already gained in the past from this region, this paper focuses on the glaciological and glacio-chemical characterization of a new drilling site located on the Western Plateau of Mt. Elbrus. A chronology for a 182 m depth ice core retrieved from this site is elaborated by taking advantage benefit of stable isotopes and glacio-chemical records, as well as a simplified thermo mechanically coupled modeling. Finally, an outlook on the possibilities to develop the high-resolution regional paleoclimate reconstruction with this ice core is given.

2 Previous investigations of the Caucasus and the Mount Elbrus

2.1 Geographical and glaciological characteristics of the Caucasus region

The Caucasus Mountains are situated between the Black and the Caspian seas, and are generally trending east-southeast, with the Greater Caucasus range often considered as the divide between Europe and Asia. The glaciers in the Caucasus cover an area of around 1121±30 km^2 (Kutuzov et al., 2015) (Fig. 1).

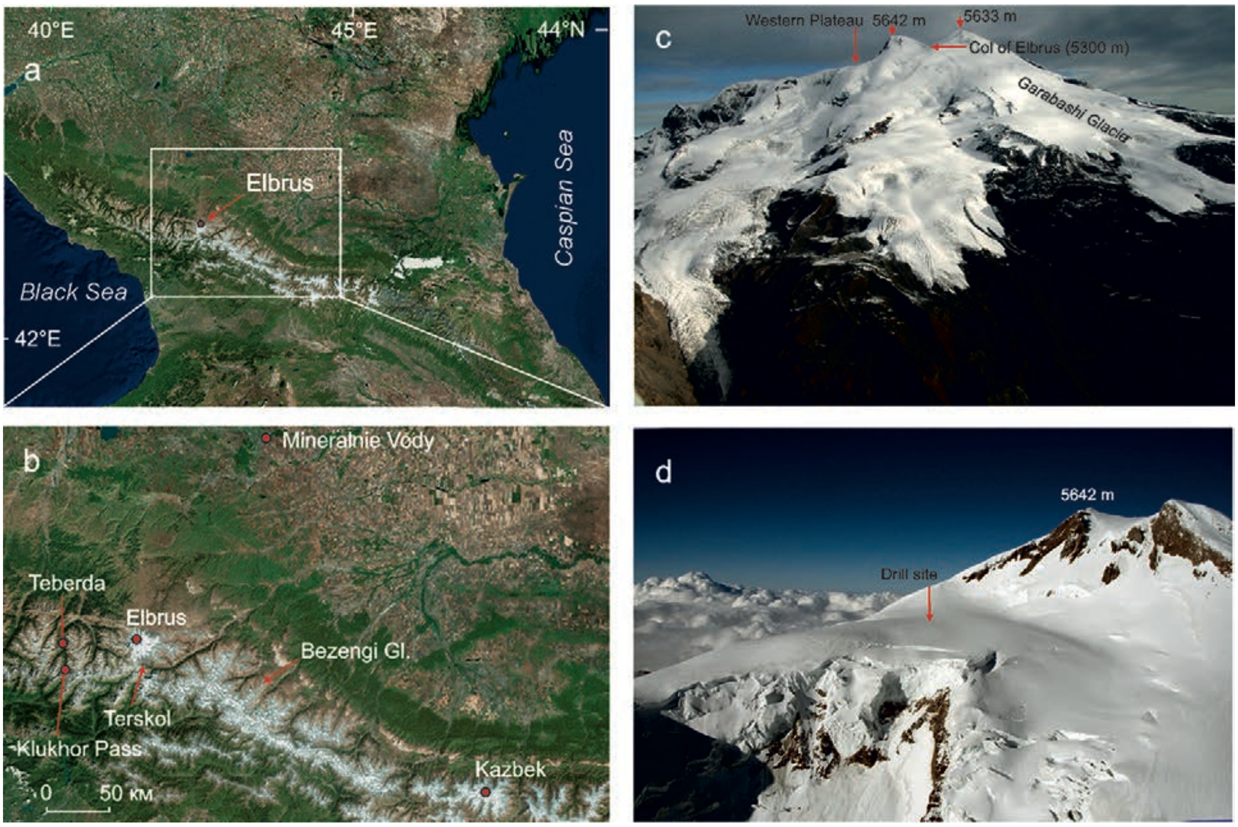

Figure 1. Location of study area: (a) − location of Mt. Elbrus in the Caucasus; (b) − location of glaciers and meteorological stations; (c) − Mt. Elbrus from the south with position of Western Plateau shown; (d) − Western Elbrus Plateau with drill site shown (photos by I. Lavrentiev on September 2009). ArcGIS World Imagery basemap used as a background. Source: DigitalGlobe.

Glacier studies in the Caucasus were begun more than hundred years ago. They were mainly focused on glacier mapping (Pastukhov, 1893; Podozerski, 1911) and reconstruction of glacier position by geomorphological methods (Abich, 1875; Mushketov, 1882; Kovalev, 1961; Serebryannyy at el., 1984). Records of contemporary glaciological processes were obtained during the International Geophysical Year (IGY) in 1957–1959 (Tushinskii, 1968) when the climatic conditions of the glacial zone, accumulation and ablation of the glaciers, glacier runoff, glacier ice formation zones, and snow and firn stratigraphy were investigated. These studies have been conducted mainly on the southern slope of the Mt. Elbrus from the glacier tongues to the summits (see Figure 1b). It has been found that surface snow melting did not occur above 5000 m (Troshkina, 1968). Complex studies of mass, water, and heat balances of glaciers in the Caucasus were started during the International Hydrological Decade (1964–1974) (Golubev et al., 1978; Dyurgerov and Popovnin, 1988; Krenke et al., 1988). A number of studies examined fluctuations of glacier dimensions and volume (Stokes et al., 2006; Kutuzov et al., 2012, 2015; Nosenko et al., 2013, Shahgedanova et al., 2014), glacier mass balance (Rototaeva and Tarasova, 2000) and regional snow chemistry (Kerimov et al., 2011). Characteristics of the mineral dust and its source were investigated using shallow ice cores and snow pits records from Mt. Elbrus (Kutuzov et al., 2013; Shahgedanova et al., 2013).

There is a number of tree-ring based reconstructions representing mean summer air temperature, river run-off and glacier mass balance in the region (Dolgova et al., 2013; Solomina et al., 2012). First lake sediment cores retrieved in 2010, 2012 and 2013 did show a good perspective in using lacustrine records to study long-term climate and glacier history variations (Solomina et al., 2013).

Despite the substantial glacier area in the Caucasus, there is a very limited number of suitable sites for ice core research due to relatively low elevation and considerable melting. High-elevation vast flat parts of the glaciers of Elbrus (5642 m), Kazbek (5033 m), and Bezengi (~5000 m) (see Fig. 1b) are the most promising sites for getting ice-core records. Several shallow and intermediate depth ice cores have been recovered at the Caucasus glaciers (Golubev et al., 1988; Zagorodnov et al., 1992; Bazhev et al., 1998), but they were carried out at sites where considerable melt water percolation smoothed isotopic and geochemical profiles.

2.2 Geographical and glaciological characteristics of Mount Elbrus

Mt. Elbrus, the highest summit of the Caucasus, consists in its upper part from two peaks – the eastern (5621 m a.s.l.) and the western (5642 m a.s.l.) and is covered by glaciers with total area of 120 km^2 (Zolotarev and Kharkovets, 2012) (Fig. 1). Mt. Elbrus is an active volcano but only minor fumarole activity is currently observed (Laverov et al., 2005).

Elbrus glaciers are situated in the altitudinal range from 2800 m to 5642 m. The stratigraphy records display several ice formation zones on Mt. Elbrus (Bazhev and Bazheva, 1964; Psareva, 1964; Troshkina, 1968). The coldest conditions have been observed above 5200 m a.s.l., where the mean summer air temperature does not exceed 0 °C. Part of the Elbrus glaciers above 4700–4900 m falls to the zone with limited surface melting. The alternation of the infiltration ice lenses 30 cm thick with the firn horizons was observed in the sequence of snow-firn pack at 5050 m a.s.l. (Mikhalenko, 2008). Two years (1985 and 1988) measurements at the col of Elbrus (5300 m) (Fig. 1c) provided recorded snow accumulation of 400–600 mm w.e. a^{-1} and considerable wind-driven snow erosion. The snow/firn temperature measured at the col at 6 m depth was −14 °C, indicating absence of melt water runoff from this zone.

Long term (since 1983) mass-balance records of the Garabashi glacier show negative values since 1994. In recent years, a negative trend in these values was discovered, which has been accorded by extremely high summer temperatures and glacier melting. The Garabashi glacier elevation has been decreasing at 3.2 m near the equilibrium line for the last decade (Nosenko et al., 2013).

A 76 m long ice core was recovered in the accumulation area of the Garabashi Glacier at 3950 m a.s.l. in 1988 (Zagorodnov et al., 1992). The firn completely transforms into ice as a result of melt water refreezing and compression at 23–24 m depth after having been deposited over 7–8 years at negative temperatures. Thus, the geochemical profiles obtained from the ice core were smoothed by melt water percolation and could not be used for paleoclimate and environmental reconstruction.

The next ice core was recovered at the Western Plateau of Mt. Elbrus, located at the western slope of Elbrus at 5115 m a.s.l. (Fig. 1). Its area is about 0.5 km^2. The plateau is restricted on south and south-east by two lava ridges, and by a vertical wall of Mt. Elbrus on the east. During the first probe ice core drilling campaign in 4–6 July 2004 a 21.4 m ice core has been recovered, and borehole temperatures and glacier thickness measurements were conducted on the Western Elbrus Plateau (Mikhalenko et al., 2005). The 10-m depth temperature of −17 °C indicated that any meltwater refreezes at some centimeters below the surface and preservation of isotopic and soluble ions profiles is provided. Ice-core records of this first shallow ice core indicated good preserved seasonal stable isotopic ($\delta^{18}O$ and δD) oscillations and mean annual accumulation rate was estimated about 1200 mm w.e.

2.3 Climatology of the Caucasus and the Mount Elbrus

The atmospheric circulation pattern in the Caucasus is determined by the subtropical high pressure in the west and Asian depression in the east dominating in summer time. In winter, it is affected by the western extension of the Siberian high (Volodicheva, 2002). The Caucasus is located in the southern part of the vast Russian Plain permitting unobstructed passage of cold air masses from the north. High elevated ridges on the south prevent and deflect the air flowing from the west and south-west. The influence of the free atmosphere for Elbrus glacier regime is significantly larger than local orographic effects as the glacier accumulation area lies above main ridges.

Most of the annual precipitation occurs in the western part of the Caucasus, reaching 3240 mm a^{-1} at Achishkho weather station (1880 m) and in the southern Greater Caucasus. Precipitation ranges between 2000 and 2500 mm a^{-1} at 2500 m in the west and declines to 800–1150 mm a^{-1} in the east on the northern macroslope of the Caucasus; it ranges eastward from 3000–3200 mm a^{-1} to 1000 mm a^{-1} for the southern macroslope. The proportion of winter precipitation (October–April) also declines eastward from more than 50 % to 35–40 % for the northern Greater Caucasus and from 60–70 % to 50–55 % for the southern slope (Rototaeva et al., 2006). The proportion of solid precipitation increases with altitude and reaches 100 % above 4000–4200 m. Following this continental climate effect, the altitude of the glacier equilibrium line (ELA), tends to increase from 2500–2700 m in the Belaya, Laba and Mzymta river basins in the west to 3700–3950 m in the Samur and Kusurchay basins in the eastern sector of the northern macroslope of the Caucasus.

Mean summer (May–September) air temperature at ELA ranges from west to east from 6–7 °C to 1–2 °C. The ELA is much higher on the glaciers of the northern macroslope, which is distinct in the central Caucasus where ELA on the northern slope of Mt. Elbrus is 1000 m higher than on Svanetia glaciers 80 km southward. The number of high-elevated meteorological stations is very limited in the Caucasus. Figure 2 shows the mean monthly air temperature and precipitation at the Klukhor Pass, Teberda and Terskol meteorological stations in the western and central Caucasus (Figure 1 and Table 1).

Table 1. Meteorological data used in this work (modified from Solomina et al., 2012)

Meteorological station	Geographical coordinates	Altitude, m	Beginning of observation
Klukhor Pass	N 43°15′; E 41°50′	2047	1956
Teberda	N 43°27′; E 41°44′	1313	1956
Terskol	N 43°15′; E 42°30′	2214	1951
Mineralnie Vody	N 44°14′; E 43°04′	316	1955

Air temperatures at these stations are in good agreement and correlate well with lowland stations (r = 0.7–0.9, $p < 0.01$), and this indicates the homogeneity of the temperature regime for investigated area (Solomina et al., 2012). Variation of mean annual and monthly temperature for the Klukhor Pass station for the period of observation (see Table 1) does not display statistically significant trend. A positive trend for mean annual temperature ($r = 0.33$, $p < 0.05$) and slight positive trend for summer temperature was found for the Teberda station. Temperature records from the Terskol station located 7 km southward apart from Elbrus glaciers show a negative mean annual temperature trend for the whole period of observation ($r = -0.35$, $p < 0.05$) (Solomina et al., 2012) but mean summer (May–September) temperatures increased from 11.5 °C in 1987–2001 period to 12.0 °C over the last decade. Winter precipitation increased by 20% over the same period while summer precipitation did not show any change (Nosenko et al., 2013).

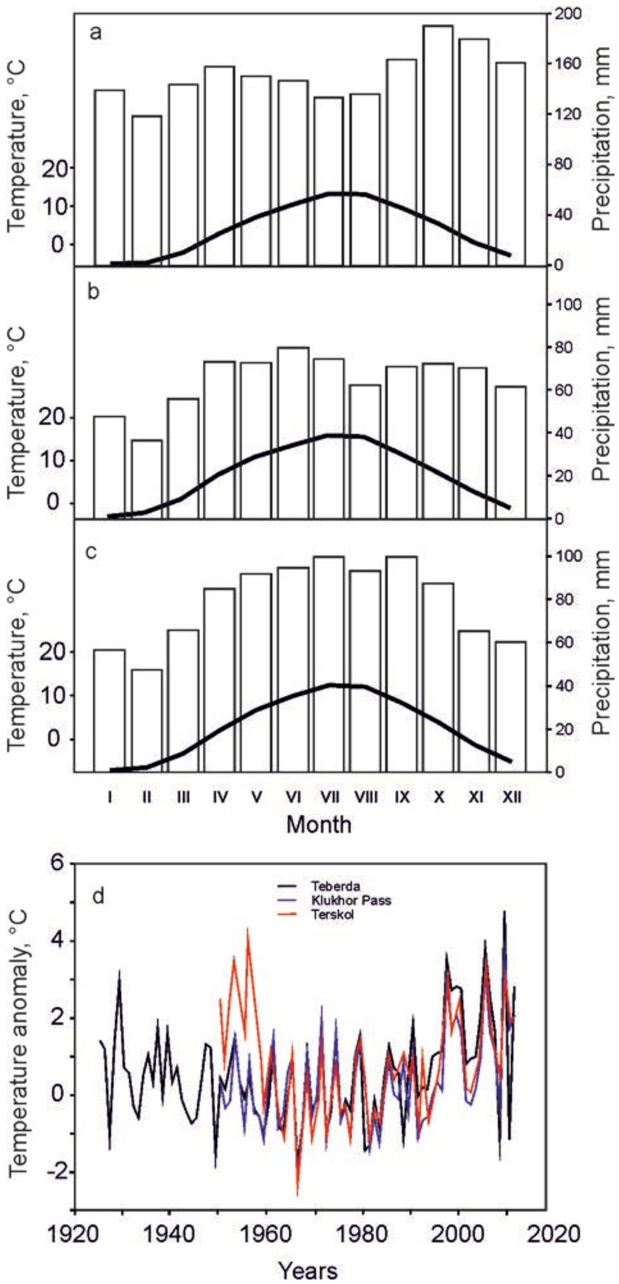

Figure 2. Mean monthly air temperature and precipitation at the Klukhor Pass (a), Teberda (b), and Terskol (c) meteorological stations and (d) anomalies of mean summer temperature, deviations from the average 1961–1990 value.

First meteorological measurements were taken on the Elbrus glaciers in 1934–1935 by the expedition of the Academy of Sciences of the USSR (Baranov and Pokrovskaya, 1936).

Air temperatures, pressure, humidity, wind regime, and incoming solar radiation have been measured at four sites from Terskol at 2214 m to the col of Elbrus at 5300 m. A permanent meteorological station was established near Priyut–9 on the southern slope of the Garabashi Glacier at 4200 m in 1934. According to 1949–1952 data, mean annual air temperature of −9.2 °C was observed. The temperature of the coldest month (January) was −17.1 °C, July temperature was −0.5 °C. The minimum air temperature of −36.1 °C was measured on January 30, 1950, with a maximum of 10.7 °C on August 1, 1950. Annual precipitation rate of 1128 mm was observed for 1949–1952. The summer months (April–October) contribute 75 % of the total precipitation, while the winter months (November–March) account for only 25 % (Matyuhkin, 1960). Maximum wind speed at Priyut–11 station of 56 m s^{-1} was measured in January 1952.

During the IGY (1957–1959) the permanent all-year meteorological station was established on the Glacier Base on the southern slope of the Elbrus near glaciers at 3700 m. Meteorological records from this site include diurnal air pressure and temperature, precipitation, humidity, cloudiness, wind regime and snow cover thickness (Tushinskii, 1968). Heat balance, air temperatures, wind speed were recorded during occasional observations in the col of Mt. Elbrus (5300 m). First accumulation and ablation measurements on the southern slope of Mt. Elbrus were done during the IGY and in 1961–1962 (Bazhev and Bazheva, 1964).

3 The Western Elbrus Plateau glacier archive

In the following section we will present recent meteorological, glaciological and glacio chemical investigations conducted on the Western Elbrus glacier plateau with the aim of obtaining knowledge about the suitability of this site to obtain atmospheric relevant ice core records.

3.1 On site meteorological measurements

An automatic weather station (AWS) of AANDERAA Data Instruments was installed on the Western Elbrus Plateau at 5115 m a.s.l. at the drill site in 2007. The AWS was working between July 30, 2007, and January 11, 2008, but disappeared afterwards under unascertained circumstances. Here we discuss records until the October 12, 2007, only when consistent data without voids was obtained. Air temperature, wind speed and direction, humidity, air pressure, radiation balance, and snow cover thickness have been measured with the time resolution of 1 hour. According to AWS records, mean daily air temperatures were negative during the period of observations. One hour averaged temperature also was negative while the positive instant maximum air temperature was recorded on eight occasions and ranged from 0.1 °C to 3.1 °C. Average wind speed (one hour averaged) on the drilling site of 2.9 m sec^{-1} was measured over the whole period of observation. Wind gusting up to 21.4 m sec^{-1} was observed in frontal passage and cyclone rear, while mean daily maximal wind speed was 6.7 m sec^{-1} in August–September 2007. Our data did not cover the whole year but according to measurements of 1961–1962 the average wind speed was approximately 30% higher in Winter at the southern slope of Elbrus (Tushinskii, 1968). A combination of high snow accumulation and low average wind speed with prevailing westerlies allows us to assume that most of precipitation was deposited at the disposal site and was not scoured by wind.

AWS records were compared with the records of the measurements at the mountain meteorological station Kluhor Pass (2037 m a.s.l.; 50 km westward) and lowland Mineralnie Vody station (316 m a.s.l.; 120 km north–eastward) (Table 1) as well as with the 20th century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, (http://www.esrl.noaa.gov/psd/) (Fig. 3 a, b). Temperature lapse rate of 0.6° per hundred m elevation was observed during the summer months. In winter, however, it decreases due to temperature inversions at the Mineralnie Vody station. There is a good agreement between the temporal variation of mean daily air temperature measured by the AWS at the drill site, 20th Century Reanalysis and meteorological stations data ($r > 0.85$). Therefore the temperature variations at the West Elbrus plateau follow the regional temperature regime.

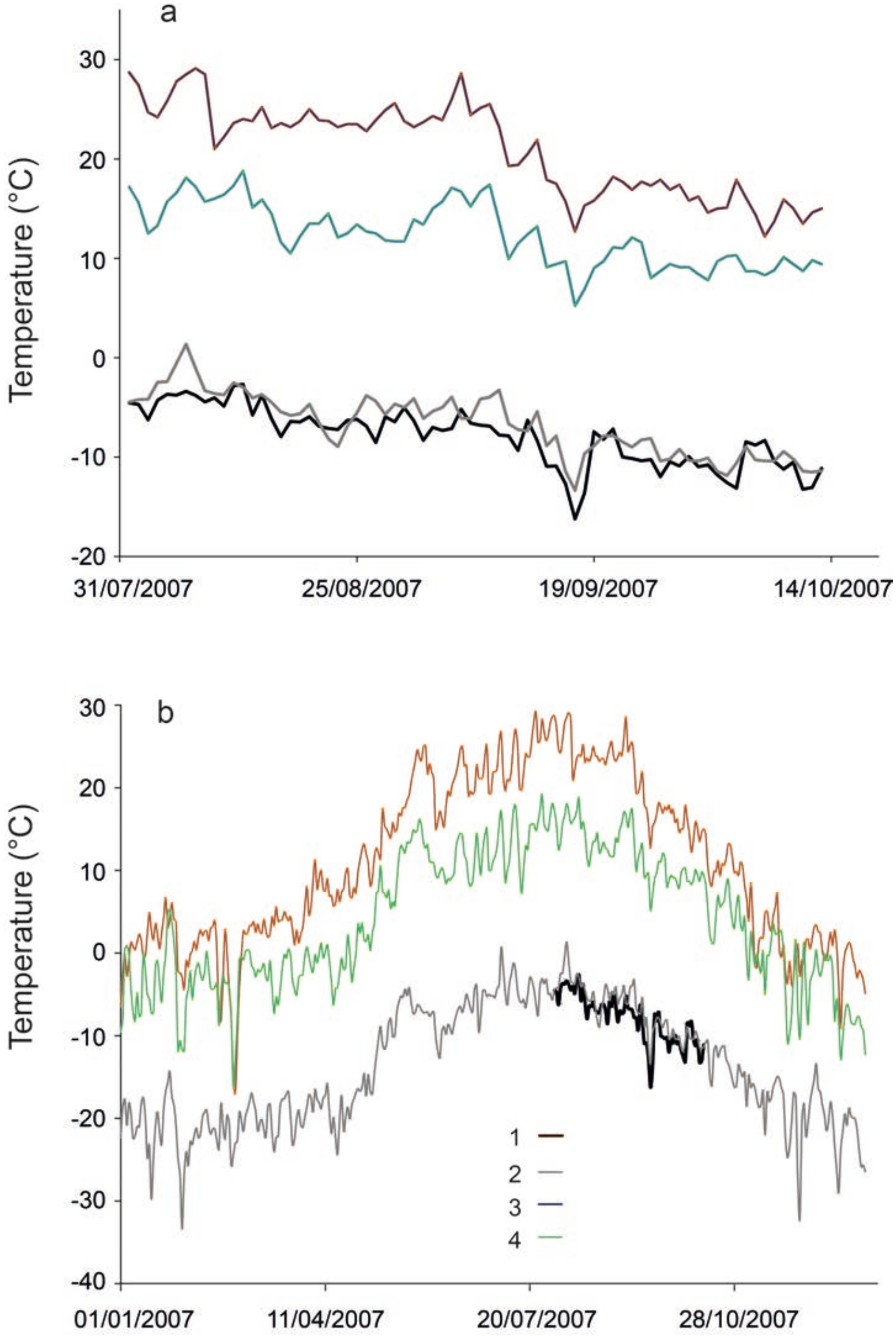

Figure 3. Daily temperature averages (T, °C) for the period of 1 August−12 October 2007 (a) and 1 January–31 December 2007 (b): 1 – AWS at the Western Elbrus Plateau; 2 – 20th Century Reanalysis V2; 3 – Mineralnie Vody meteorological station; 4 – Klukhor pass station.

In June 2013, main meteorological observations with AWS DAVIS Vantage Pro 2 including air temperature, humidity and wind speed at two levels (0.5 and 2.0 m) with 15 min resolution were conducted at the Western Elbrus Plateau near the drilling site of 2009 (see Figure 1 and 4). Along with the estimation of eddy flux of heat and moisture, the fluxes of total, scattered and reflected radiation were measured. Meteorological conditions of the observation period with maximum insolation at the summer solstice were close to mean annual parameters. A level of downward shortwave radiation was varied from 1 to 1.2 kW m^{-2} adding up to 73–88 % from solar constant at the outer boundary of the atmosphere and 78–93 % of total insolation at N 43° latitude at that time of year. Albedo has a dominant role in the short wave balance. Mean albedo values of 0.66 were measured at the plateau in June 2013. First measurements of radiation balance were conducted in Elbrus in 1968–1960 and showed that downward short wave radiation ranged from 1.1 kW m^{-2} at an elevation of 3750 m up to 1.2 kW m^{-2} at 5300 m (Tushinskii, 1968).

Despite the negative air temperatures, the radiation balance was positive except at night time. The mean value of the radiation balance, including short-wave and long-wave balance of 150 W m^{-2} was measured. Apparently, this is just the power that was expended for surface melting and snow recrystallization.

3.2 Ground base survey: surface topography and radar sounding

Detailed measurements of ice thickness were carried out in 2005 and 2007 using monopulse ice penetrating radar VIRL with the central frequency of 20 MHz (Vasilenko et al., 2002, 2003). VIRL ice penetrating radar consists of transmitter, receiver and digital recording system with GPS. For synchronization of transmitter and receiver a special radio channel with repetition rate of 20 MHz was used in 2005. Advanced VIRL–6 radar modification with optical channel for synchronization has been used in 2007 (Berikashvili et al., 2006). The radar allows simultaneous recording and controlling in a real time regime with an interval from 1 to 99 sec to get both radar and navigation data as well as to perform the hardware and program stacking (from 1 to 6192-times) of wave traces.

The average radio wave velocity (RWV) in firn and ice has been used for ice thickness calculation from measured time delay of radar signals reflected from the bedrock. RWV depends on firn/ice density and temperature. We did not measure RWV (V) at the Western Elbrus Plateau, but it has been estimated as a function of glacier depth (z) through measured ice core density ρ_d (z) and borehole temperature T (z) profiles:

$$V(z) = c/[\varepsilon'(\rho_d, T)]^{1/2}, (1)$$

where c = 300 m μs^{-1} – radio wave velocity in air; $\varepsilon'(\rho_d, T)$ – dielectric permeability of snow, firn and ice as a function of density $\rho_d(z)$ and temperature T(z) (Macheret, 2006).

$\varepsilon'(\rho_d)$ was calculated for two component dielectric mixture of ice and air (Looyenga, 1965):

$$\varepsilon'(\rho_d, T) = \{(\rho_d/\rho_i)[\varepsilon'_i(T)^{1/3} - 1] + 1\}^{1/3}, \qquad (2)$$

where ρ_i = 917 kg m^{-3} – density of glacier ice.
$\varepsilon'_i(T)$ was calculated from (Mätzler and Wegmüller, 1987):

$$\varepsilon'_i(T) = 3.1884 + 0.0091\ T. \qquad (3)$$

The average RWV of 180 m μs^{-1} was calculated for 181.8 m (ice thickness at the drilling site). RWV taking into account its depth variations from ρ_d and T has been used for conversion of the measured time delay of radio signal to ice thickness at each point.

Two data sets, 2005 and 2007, have been combined to construct an ice thickness map. In total, the glacier depth was measured at more than 10000 sounding points along 6.5 km profiles with the estimated accuracy of ice thickness measurements of 3% (Lavrentiev et al., 2010). The maximum depth of 255±8 m at the central part of the plateau, minimum values of about 60 m near the edge were found. Radar records and digital elevation model ASTER GDEM averaged for 2000–2009 have been used for bedrock topography mapping (Fig. 4). ASTER GDEM with an error of ±20 m (ASTER…, 2009) is in a good agreement with the 1959 Northern Caucasus topographic map and the 1997 digital orthophotomap of Mt. Elbrus (Zolotarev and Kharkovets, 2000).

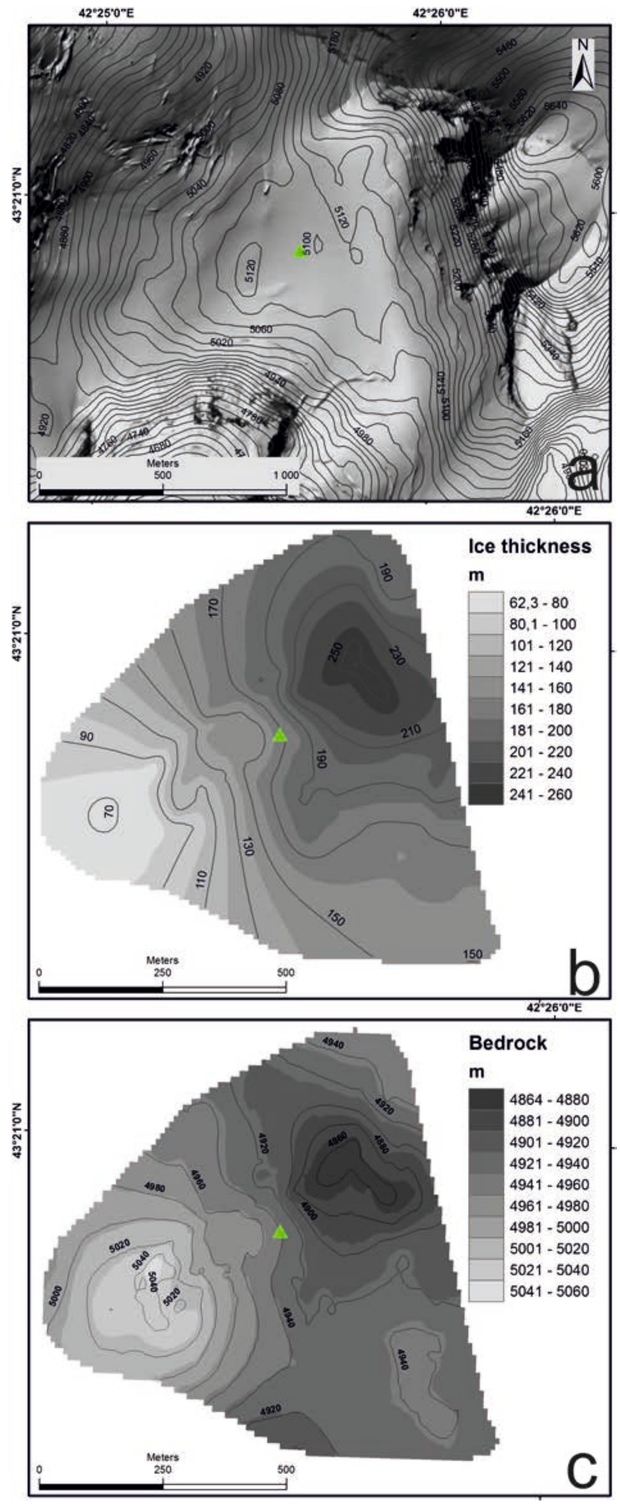

Figure 4. Glacier surface (a), ice thickness (b), and bedrock relief (c) on the Western Elbrus Plateau. The green triangle marks the position of the drilling site.

3.3 Ice core drilling and analysis

3.3.1 Methods

Due to the promising glacier archive conditions obtained from the shallow ice coring in 2004 (see section 2.2), a full-depth ice core drilling was completed on the Western Plateau from 27

August to 6 September 2009 (Mikhalenko, 2010). A bedrock was reached at the depth of 181.80 m. Drilling was done in a dry borehole using the lightweight electromechanical drilling system developed by Geotech Co. Ltd., Nagoya, Japan. Technical details of the drill are described in (Takeuchi et al., 2004). The recovered ice cores were subjected to stratigraphic observations, packed into plastic sleeve and stored in the snow pit under −10 °C. Ice core drilling was accompanied by borehole temperature measurements (using thermistor chains which were left for three days in the borehole and calibrated before and after study with an error of ±0.1 °C), and snow pit sampling 30 m to the south from the drilling site. The ice core was shipped in frozen condition to the cold laboratory of the Lomonosov Moscow State University where detailed stratigraphic descriptions with photographing of each piece of the core and bulk density measurements were done.

In addition to the 2009 ice core subsequent ice core (12 m long) was extracted in June 2012 at the same site to expand the existing ice core sample set from this site to the year 2012. Note that, among others the 2012 ice core was also used for the dust study of Kutuzov et al. (2013). Finally, in June 2013, a 20.36 m depth was recovered at the same location from 27 to 30 June 2013.

Stratigraphic description of the ice core was carried out using transmitted-light illumination. Hereby, stratification depth and thickness of individual horizons were fixed with 1 mm accuracy. Density of firn and ice were measured by 457 individual samples. Figure 5 shows the bulk density distribution with depth. The sharp random outliers from the general profile in both directions, but more often to lower values, could result from uncertainties in estimation of lengths of samples. The uncertainty increases for the denser and smaller samples.

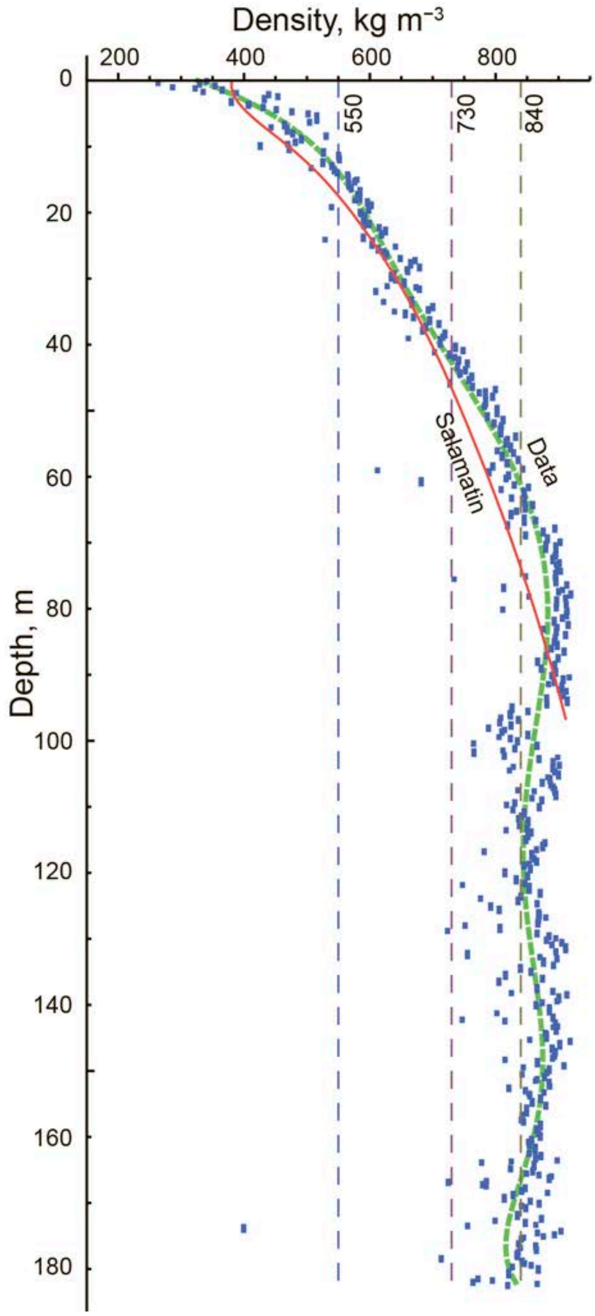

Figure 5. Measured (blue dots) and simulated (red line) ice core density profile, critical densities shown as dashed lines (see 3.3.2.). The green dashed line is a running mean for the measured density values.

Ionic species as ammonium (NH_4^+) succinate ($HOOCCH_2COO^-$, also denoted succinic acid) were investigated along the uppermost 157 m of the Elbrus core (122 m w.e.) with the aim of the ice core dating. Hereby, the analytical protocol previously developed to process Alpine firn and ice samples (Legrand et al., 2007a) was applied. Pieces of firn and ice were decontaminated in a clean air bench located in a cold room using a pre-cleaned electric plane tool. A total of 3350 subsamples were obtained along the 157 m with a depth resolution decreasing from 10 cm at the top to 2 cm at 157 m depth.

For cations (Na^+, K^+, Mg^{2+}, Ca^{2+}, and NH_4^+), a Dionex ICS 1000 chromatograph equipped with a CS12 separator column was deployed. For anions, a Dionex 600 equipped with an AS11 separator column was used with an eluent mixture made on the base of H2O, NaOH at 2.5 and 100 mM and CH3OH. A gradient pump system allows determining inorganic species (F^-, Cl^-, NO_3^-, and SO_4^{2-}) as well as short-chain monocarboxylates (denoted $MonoAc^-$) and dicarboxylates (denoted $DiAc^{2-}$). For all investigated species, ion chromatography and ice core decontamination blanks were found to be insignificant with respect to respective levels found in the ice core samples.

As discussed in Sect. 3.3.5 the search of volcanic horizons in the Elbrus ice cores needs examination of the acidity (or alkalinity) of samples that can be evaluated by checking the ionic balance between anions and cations (concentrations being expressed in micro-equivalents per liter, μEq L^{-1}):

$$[H^+] = ([F^-] + [Cl^-] + [NO_3^-] + [SO_4^{2-}] + [MonoAc^-] + [DiAc^{2-}]) - ([Na^+] + [K^+] + [Mg^{2+}] + [Ca^{2+}] + [NH_4^+]). \qquad (4)$$

Within the present study, we focus (see also section 3.3.4) on the NH_4^+ and succinic acid profiles, in view to (1) define a criterion which allows to separate winter and summer snow depositions, (2) to apply this criterion on the first 157 m of the Elbrus ice core to the establish a depth age relation on the basis of annual layer counting along the NH_4^+ and succinic acid depth profile.

The 2012, 2013 as well as the 2009 ice core (down to 106.7 m) were analyzed for deuterium-hydrogen (D/H) and oxygen ($^{18}O/^{16}O$) isotope ratios using Picarro L1102-*i* instrument in the Climate and Environmental Research Laboratory (CERL), Arctic and Antarctic Research Institute, St. Petersburg, Russia. The instrument was calibrated on a regular basis against isotopic standards V-SMOW, GISP and SLAP provided by the International Atomic Energy Agency (IAEA) for estimating the precision of the measurements and for minimizing the memory effect associated with continuous measurements. The reproducibility of the measurements was ±0.07 ‰ for oxygen isotope ($\delta^{18}O$) and ±0.3 ‰ for deuterium (δD). The CERL laboratory work standard SPB was measured after every 5 samples. The $\delta^{18}O$ and δD values were expressed in ‰ units relative to the V-SMOW value.

3.3.2 Borehole temperatures

Figure 6 shows the vertical profile of the temperature measured along the 181 m long borehole drilled in 2009. Temperatures ranged from −17 °C at 10 meters depth to −2.4 °C at

181.8 m. The temperature profile can be divided into three parts on the base of different gradient of temperature: from the surface down to 10 m, from 10 m to 100 m, and from 100 m to glacier bottom. Upper part of the temperature profile reflects seasonal changes at the surface. The borehole temperature ranges from −17 °C to −12 °C within 10–100 m, and most accurately reflects the past temperature fluctuations. Temperature change is almost rectilinear from 100 m depth to glacier bottom that gives evidence of a steady heat transfer regime. Density of heat flux at the glacier bottom of 0.34 W m^{-2} was calculated from measured temperature gradient and the coefficient of heat conductivity of ice (2.25 W m^{-2}). This value is 4–5 times higher than averaged heat flux density for the Earth surface and higher than the mean value for Central Caucasus, and associated with heat magma chamber of the Elbrus volcano. Fig. 6 also shows the temperature profile measured in the 19-m depth borehole in 2013 and temperature records obtained in 2004 after 22-m depth shallow ice core drilling on the Plateau (Mikhalenko et al., 2005). Good record matching is indicative to stable temperature regime on the Western Elbrus Plateau for the last decade.

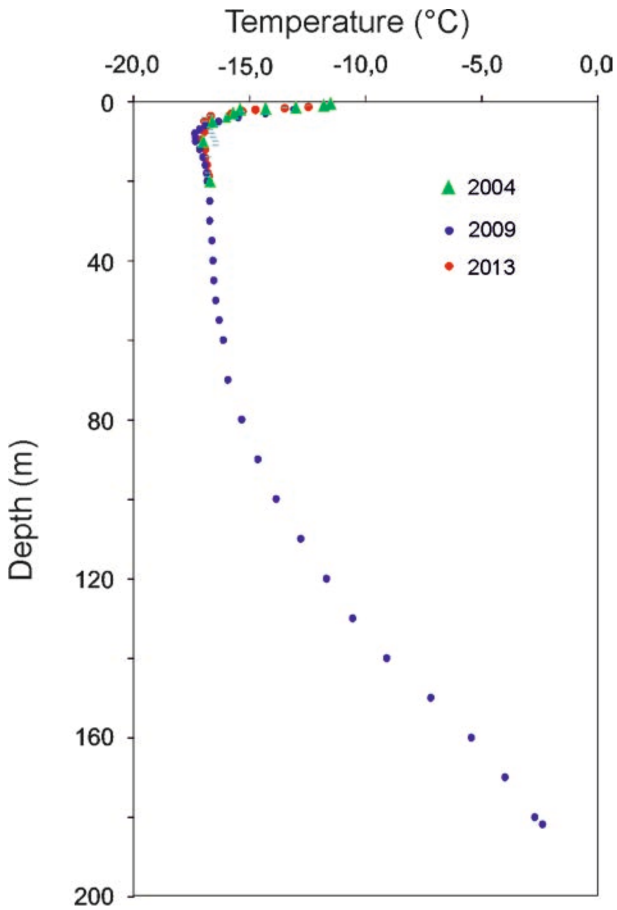

Figure 6. Measured temperature profiles at the Western Elbrus Plateau drill site for different dates: and green triangles – 22 m depth borehole drilled in 2004, blue dots − main 2009 borehole, and red dots – 20 m depth borehole drilled in 2013.

Using the altitude gradient of temperature estimated in section 3.1 on the base of temperature data obtained from the AWS station run at the Western Elbrus Plateau not far from the 2009 drill site and the low elevation station Mineralnie Vody, we estimate the annual mean air temperature at the drill site to be around −19°C. This is close to value of annual mean air temperature of −19.4 °C which was calculated using the general relationship with the ice temperature at the bottom of the active layer (Zagorodnov et al., 2006) and only slightly enhanced compared to the 10 m firn temperatures (see above).

The analysis of measured temperature profile shows that bottom melting can occur under real ice pressure at the deepest part of the glacier. Potential bottom melting has been estimated using mathematical model of temperature regime (Salamatin et al., 2001). Modeling results show that bottom melting occurs under ice thickness more than 220 m and its value does not exceed 10 mm w.e. y^{-1}.

3.3.3 Bulk density and ice core stratigraphy

The bulk density profile suggests a change in densification around the critical densities (Maeno and Ebinuma, 1983) of 550 and 840 kg m^{-3}, and no visible change at 730 kg m^{-3}, which is also the case in some other analyses of density profiles (Hörhold et al., 2011; Ligtenberg et al., 2011). However, the slight trend of a decrease in density at a depth below the maximal values at about 80 m (Fig. 5), close to the critical density over the whole depth interval, is unlikely to be a systematic error in measurements and need further investigation. The research should be based on the ice flow characterization and the possible effects related to the "intervening depth interval" (the alternating of the layers, which have already reached the close-off density, with those which are still permeable) due to seasonal (Bender et al., 1997) or wind induced (seasonal difference in wind speed) snow density variability at high accumulation sites, which are accounted for. Unlike the ice cores from polar ice sheets where such "intervening depth interval" is just a fraction of the whole length of the ice core (Bender et al., 1997), the measured bulk density in the Elbrus ice core remains at a wide interval between 800 kg m^{-3} and 915 kg m^{-3} down to the bottom of the glacier (Figure 5). Elbrus's profile was compared with the results of the Salamatin et al. (2009) densification model. Modelling results show that there has been an increase in the accumulation rate over the past several years. Minimum deviation between simulated and measured ice-core density profiles was marked when the accumulation history was assumed in accordance with the long-term precipitation changes observed at meteorological stations (Nosenko et al., 2013).

According to the morphogenetic classification of stratigraphic features (Arkhipov et al., 2001) two distinct types of layering were observed in the core: firn layers which have not been affected by melting, and ice layers formed by the refreezing of melt water in the surface snow. These features indicate that the thickness of the infiltration ice layers, which do not form every year, does not exceed 10 mm. Ice formation occurs in cold, dry conditions, as already concluded on the basis of borehole and air temperatures at the drill site (see sections 3.1 and 3.3.2). The pore close-off depth at around 55 m, where the air bubbles became separated, was marked. This depth coincides with a measured bulk density of around 840 kg m^{-3}. This is no surprise, since the presence of ice layers will increase the close-off density somewhat above the density close-off value from ice in which no melting occurs (i.e. 830 kg m^{-3}).

3.3.4 Seasonal ice core stratigraphy of stable water isotopes

Seasonal cycle of the isotopic composition is well detectable over the whole measured part of the core (Fig. 7). Mean seasonal values of δD are −200‰ for the winter period and −25 ‰ for the summer period. Values of $\delta^{18}O$ are about −5 to −10 ‰ in summer and −30 ‰ in winter. According to isotopes annual cycles counting 106.7 m of the ice core cover 86 years or the period from 1924 to 2009. Mean accumulation rate for this period based on the dating and taking into account the firn density and layer thinning was 1455 mm w.e. Figure 7 shows results of isotopic measurements of four different ice cores obtained at the Western Elbrus plateau. While 2009, 2012 and 2013 cores were obtained almost at the same location the 2004 core was recovered further 120 m to the south-west. Good agreement in isotopic variations of all cores suggests a relatively homogeneous snow deposition at the plateau.

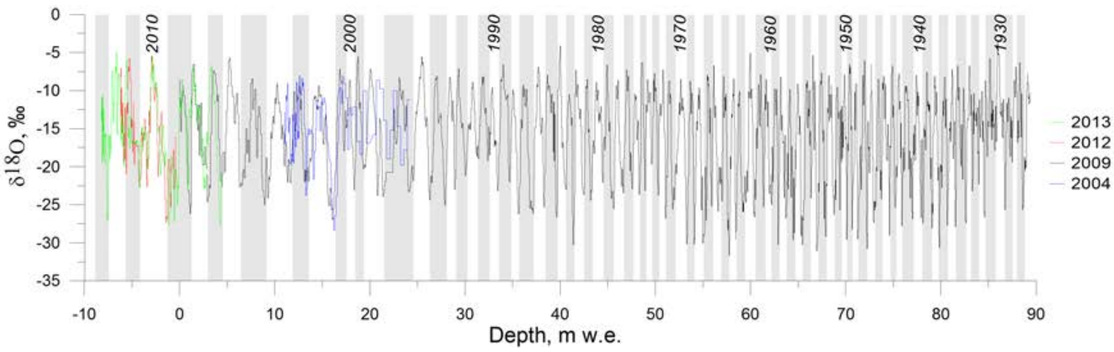

Figure 7. $\delta^{18}O$ profiles in the cores obtained in 2004, 2009, 2012, 2013. 0 m depth corresponds to the surface of 2009. Grey and white boxes depict annual layers.

We used the isotope diffusion model (Johnsen et al., 2000) to estimate the preservation of the isotopic signal in the course of the diffusive smoothing. Although the drilling site is located in a relatively warm place (−17 °C), high snow accumulation rate does not favour a strong diffusion, since any firn layer rapidly sinks and reaches the pore close-off depth in a relatively short time. The maximum “diffusion length” at this depth is estimated as 5 cm in ice equivalent (i.e.). The effective diffusion length could be even smaller if we take into account ice lenses in the firn that prevent vertical travelling of the water molecules.

Such a diffusion length means that all the oscillations shorter than 13 cm i.e. will be completely erased due to the diffusion, the oscillations between 13 and 70 cm i.e. will survive but will be damped to some extent, and the cycles longer than 70 cm (e.g., the annual cycle) i.e. will not be affected by the diffusion. Thus, if during a single snowfall a 35-cm snow layer precipitates (that corresponds to 13 cm in i.e.), the isotopic signal of this layer will survive during the diffusion processes and will be seen in the ice core.

Deeper than the pore close-off depth the diffusion takes place in ice but much slower than the in firn. The final diffusion length solely depends on the time and temperature of the firn-ice thickness. Even if we take a maximum possible temperature (−2.4 °C) and age estimate (few hundred years), the additional diffusion in ice will still be very small.

This leads us to an important conclusion: we may expect to obtain the seasonal cycles in the isotope profile down to the very bottom of the core, and our ability to detect the annual cycle in the core will be dependent on the sampling resolution, as well as on such basal processes as layers folding and mixing.

3.3.5 Seasonal ice core stratigraphy of chemical parameters and ice core dating on the base of annual layer counting

A dating attempt was made by counting annual layers on the basis of chemical ice core stratigraphical records, as previously successfully applied to mid-latitude Alpine ice cores (Preunkert et al., 2000). As done in Alpine ice core studies, we examine the NH_4^+ signal. Since this specie experiences a strong maximum of emissions in phase with the summer strengthened of upward transport of air masses, a particularly well-pronounced seasonal cycle is expected, as observed at the Col du Dôme Alpine site (Preunkert et al., 2000; Fagerli et al., 2007). However, it appears that the NH_4^+ seasonal cycle at Elbrus is less pronounced than in the Alps. Whereas recent summer NH_4^+ levels are comparable at both sites, recent winter concentrations at Elbrus are significantly higher than at Col du Dôme.

A first study on the seasonality of the Elbrus snow accumulation was made by Kutuzov et al. (2013) along a short firn core spanning the years 2012–2009. Based on the dust layer stratigraphy of absolute dated dust events and the stable isotope record of the firn core the authors showed that the annual deposition at Elbrus has a mean $\delta^{18}O$ signature of −15 ‰ and is built up by nearly equal deposition amounts from the warm season (45 % of total accumulation), for which $\delta^{18}O$ values varying between −5.5 ‰ and −10 ‰, and from the cold season (55 % of total accumulation), for which values vary between −17 ‰ and −27 ‰, respectively.

Therefore, the concentration distribution of NH_4^+ values was inspected in recent firn layers (0–12 m w.e.), and the 50 % concentration limit of 100 ppb was taken as a first approach to separate snow depositions arriving from summer and winter precipitation at Elbrus. However this criterion will be not conservative in time since the NH_4^+ sources are mainly anthropogenic in origin, and a trend in summer as well as in winter are expected over the last 100 years. Therefore, a second criterion was used to confirm our winter snow selection. This criterion used succinic acid, a light dicarboxylic acid for which a strong summer maximum and a quasi-nul winter level can be observed in the present-day atmosphere in Europe (Legrand et al., 2007b), the very low winter levels being related to the absence of source at that season for this species mainly photochemically produced from biogenic precursors. The concentration distribution of succinate values was inspected in recent firn layers (0–12 m w.e.), and the 50 % concentration limit of 5 ppb was taken to separate snow depositions arriving from summer and winter precipitation at Elbrus. Winter snow and ice layers were identified when both ammonium and succinate criteria were fulfilled for more than 2 successive samples.

Figure 8 a, c shows the result of this data dissection over the uppermost 12 m w.e. along with the $\delta^{18}O$ record (Fig. 8 e). The mean $\delta^{18}O$ level of hereby selected winter data is −19.6 ‰, and as it could be detected in Fig. 8 a, c from ammonium and succinate selected winter sections match quite well with winter sections deduced from the $\delta^{18}O$ profile. However it might appear that sometimes the spring season or even the beginning of the summer season might be included. For an application as the dating by annual layer counting this shortcoming is not critical, however if an inspection of the data set in seasonal resolution is envisaged this might be a handicap. In this case a stronger criteria (NH_4^+ <50 ppb and succinate < 3 ppb) might be applied in addition to assure that only depositions corresponding to winter precipitation under atmospheric background conditions are selected within the winter period. The mean $\delta^{18}O$ level of hereby selected winter data is –21.1 ‰. On the other hand, as seen in Figure 8 a, c, and e some winter sections might be omitted.

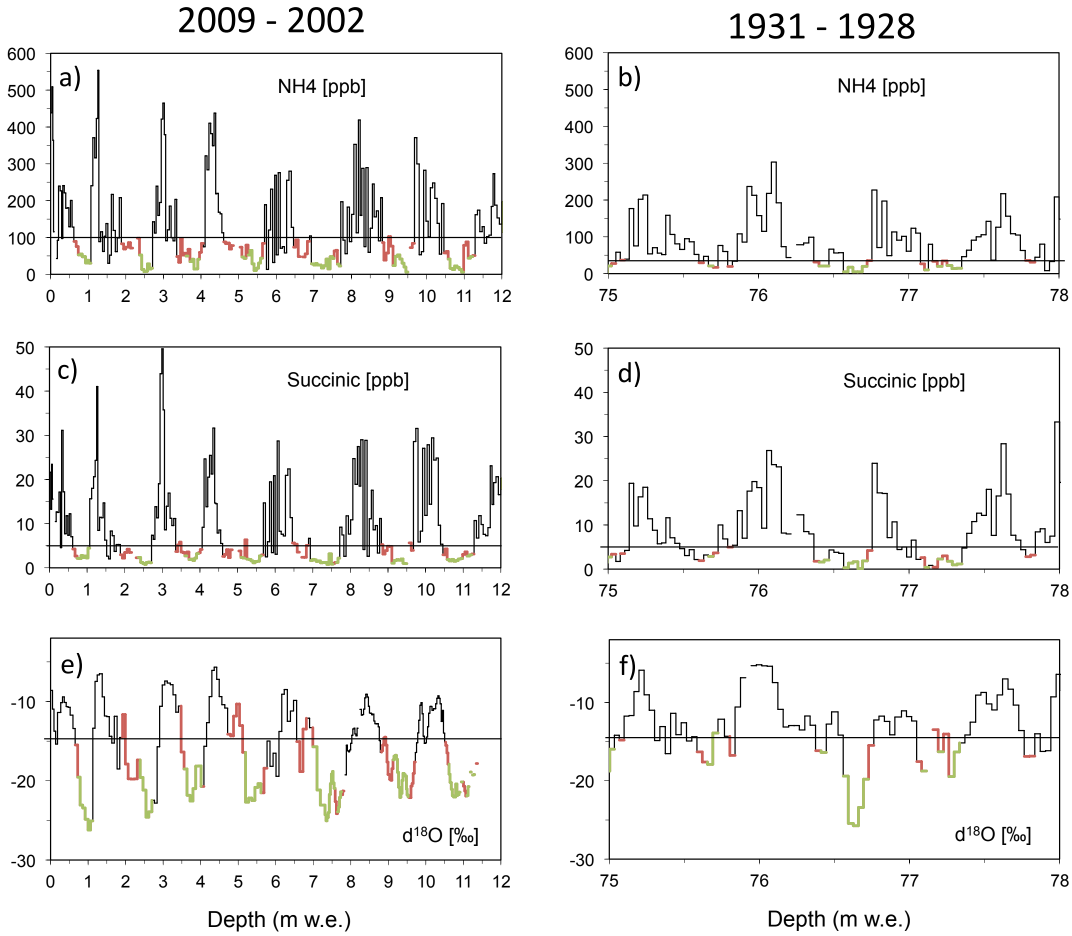

Figure 8. Seasonal course of $NH4^{+}$ (a, b), succinic acid (c, d), and $\delta^{18}O$ (e, f) signals at to different sections of the Elbrus ice core. Red marked sections assigned samples selected with the winter criterion: Succinic acid smaller than 5 ppb, NH_4^+ smaller than 100 ppb for recent years and smaller than 50 ppb prior to 1950; green marked sections correspond to the winter-background criterion: Succinic acid smaller than 3 ppb, NH_4^+ smaller than 50 ppb for recent years and smaller than 20 ppb prior to 1950. Black bars in ionic plots refer to the winter criteria. The black bars in the $\delta^{18}O$ plots refer to the respective mean value.

Examination of NH_4^+ and succinate minimum below 12 m depth showed that in contrast to what was seen in the Alps, the NH_4^+ winter level decreases significantly from near the surface to around 70 m w.e. depth (see Fig. 8). Therefore, the NH_4^+ winter and background criteria had been adjusted, using a winter (background) threshold of 50 ppb (30 ppb) form 52 – 62 m w.e. of the core and 30 ppb (20 ppb) core down of 62 m w.e. In contrast, the succinate winter levels did not change and the 5 ppb criterion applied in recent times was also applied in deeper layers. Fig. 8 b, d, and f showed a comparison of NH_4^+, succinate with the $\delta^{18}O$ record between 75 and 78 m w.e. (i.e. from 1931–1928). As observed for recent times, the winter criteria matches very good with winter deposition as deduced from the stable isotope content, although the latter record tends to be already a bit smoothed compared to the uppermost firn layers. As observed for the uppermost core section, it could not be excluded that the winter criteria includes parts of the intermediate season, whereas the background criteria selects only depositions arriving from the coldest precipitations.

Figure 9 shows the result of the dating of the Elbrus ice core. In addition to model calculations which are detailed in section 3.4, the depth age scale obtained by annual layer counting using the NH_4^+ – succinate criteria is reported down to 122 m w.e. Annual layer counting was achieved as described above down to 85 m w.e. Further down, winter levels became rather thin, due to annual layer thinning but probably also to upstream effects as commonly encountered on such small-scale glaciers (Preunkert et al., 2000). Therefore, below 85 m w.e. ice core layers in which less than 3 samples have reached the winter criteria were considered as winter seasons, and from 113 to 122 m w.e. winter layers were also assigned when only one of the two criteria was fulfilled for at least one sample while the other one showed only a relative minima (exceeding sometimes the fixed threshold). This could be either due to the fact that winter sections become smaller than our depth resolution of 2–3 cm applied core down of 90 m w.e., and/or be the result of an incomplete precipitation preservation due to wind erosion upstream the borehole as already observed on small-scale Alpine glacier sites (see e.g. Preunkert et al., 2000). In this latter case a systematic lack of winter snow accumulation would occur in deeper ice core layers.

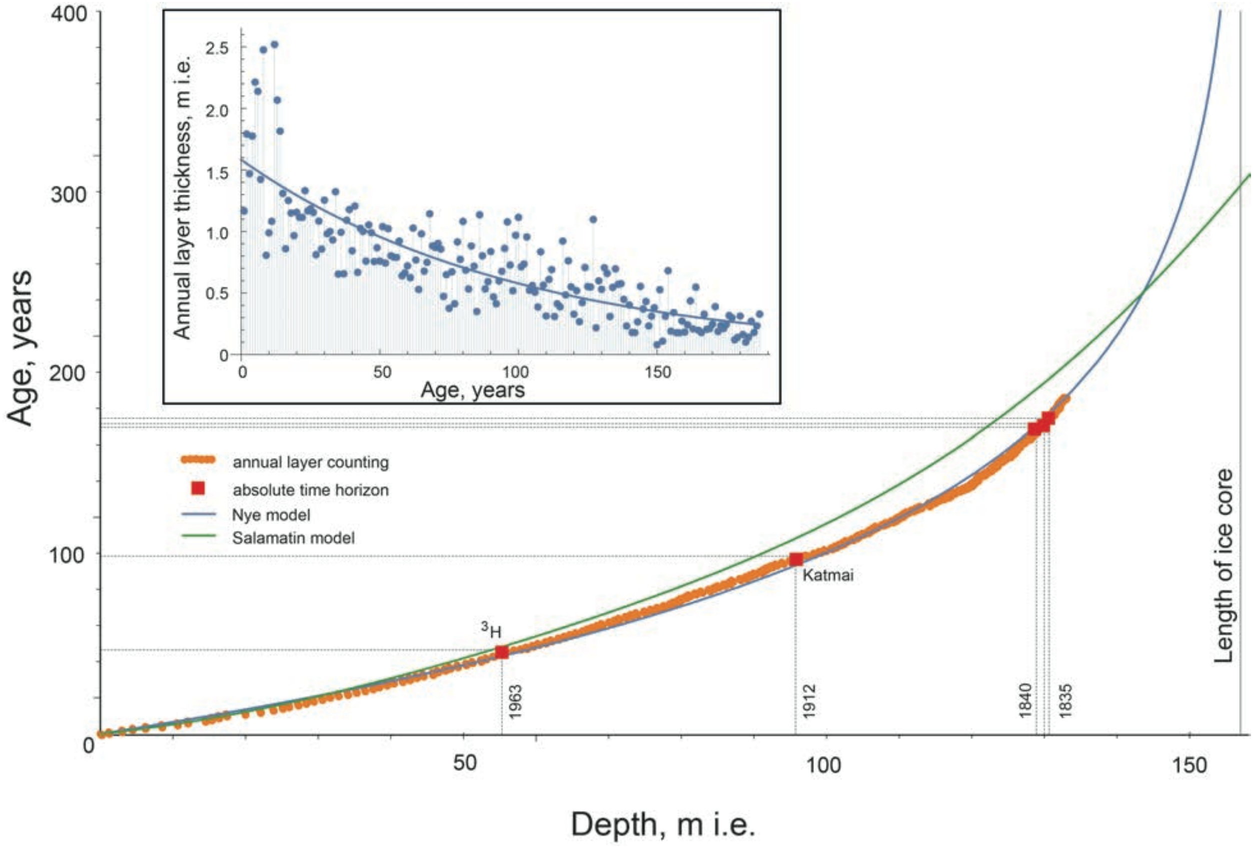

Figure 9. Depth (in m of ice equivalent)/age relation established for the Elbrus ice core by annual layer counting along the depth profile of ionic species (orange dots), and applying the ice flow models: Nye (blue line), Salamatin (green line). The inset represents the annual layers thickness (in m of ice equivalent) and the "Nye" least square fit (see text).

Dating based on annual layer counting of the chemical stratigraphy is in a fairly good agreement with the tritium 1963 time horizon that is located at the core depth of 50.7 m w.e. (dated at 1965 using the ammonium stratigraphy, Fig. 10a). In addition it fits very well with the dating achieved so far (i.e. core down to 106.7 m) on the base of the seasonal stratigraphy of the stable isotope profile. Whereas stable isotopes predict the year 1924 at a core depth of 106.7 m, the chemical stratigraphy leads to estimate the year 1926 in this depth.

To anchor the depth age relation with further absolute time horizons, a first inspection of the sulfate profile was made in view to identify volcanic horizons as found in other northern hemisphere ice cores between 1912 (Katmai) and 1783 (Laki eruption) in Greenland (Legrand et al., 1997; Clausen et al., 1997) and at Colle Gnifetti (Bohleber 2008). However since the Elbrus is an in active volcanic crater, it is sometimes difficult to attribute a peak either to a well-known global eruption or to a local event. Furthermore, numerous sulphate peaks in the Elbrus ice core originate from terrestrial inputs as suggested by the presence of concomitant calcium peaks. So far, the Katmai eruption in 1912 could be clearly identified at

87.7 m w.e. (dated at 1911 using the ammonium stratigraphy) with several neighboured samples showing relatively high sulfate levels (up to 1200 ppb, i.e. 25 μEq L^{-1}) compared to those seen in sulphate peaks generally present in summer layers of the early 20th century. Furthermore, as seen in Fig. 10b, in contrast to neighboured summer sulphate peaks located at 87.2, 87.4, 88.0, and 89.3 m w.e., that are alkaline (see Fig. 10b), the acidity of samples of the 87.7 m w.e. sulphate peak reaches 8 μEq L^{-1} at the bottom part of the sulphate peak. Furthermore, samples located of the top part of the 87.7 m w.e. sulfate peak remains neutral in spite of a large presence of calcium (similar to those seen in neighboured summer sulphate peaks). As seen in Figure 11 it appears that within one-year uncertainty this horizon is in excellent agreement with our annual counting.

Below 88 m w.e., we were still able to easily proceed annual counting down to 113 (1860), whereas further down the dating become more uncertain (see the green line in Fig. 9). Below 88 m w.e., 7 significant potential volcano horizons can be suspected on the basis of the ionic balance and sulfate levels (not shown), from which however at least 1 are of local origin (as suggested by small stones with size of up to 1–2 mm were found in the corresponding layer). Nevertheless, a series of 3 narrow spikes was located at 118–120 m w.e. (dated at around 1840–1833) among which two that are characterized by an increase of sulphate and acidity (up to 7.8 μEq L^{-1}, not shown) may be related to the well-known eruptions observed in Greenland in a time distance of 2 years around 1840 (one of them being possibly due to the Coseguina eruption in 1835) (Legrand et al., 1997).

The depth / age relation was obtained from the annual layers counting along the depth (Fig. 9). Despite high variability in the annual layers' thickness the data represents evident thinning of the layers with depth related to the ice flow. Applying the form of the thickness/age relationship as developed by Nye (Dansgaard & Johnsen, 1969) to the actual annual layers data (see inlet at Fig. 9) provides the mean accumulation over the whole time period covered by the studied part of the ice core to be 1.583 m in ice equivalent. The "Nye" curve, shown at Fig. 9, corresponds to the depth/age relationship from the Nye model with such "best fit" (constant over time) accumulation rate and the glacier thickness as at the drilling site. The blue line is the depth/age relation as suggested by Salamatin's model (Salamatin et al., 2000) with the same "best fit to Nye" accumulation rate and the bed and surface descriptions as at the drilling site.

Dating based on annual layer counting of the chemical stratigraphy is in a fairly good agreement with the tritium 1963 time horizon that is located at the core depth of 50.7 m w.e. (dated at 1965 using the ammonium stratigraphy, Fig. 10a). In addition it fits very well with the dating achieved so far (i.e. core down to 106.7 m) on the base of the seasonal stratigraphy of the stable isotope profile. Whereas stable isotopes predict the year 1924 at a core depth of 106.7 m, the chemical stratigraphy leads to estimate the year 1926 in this depth.

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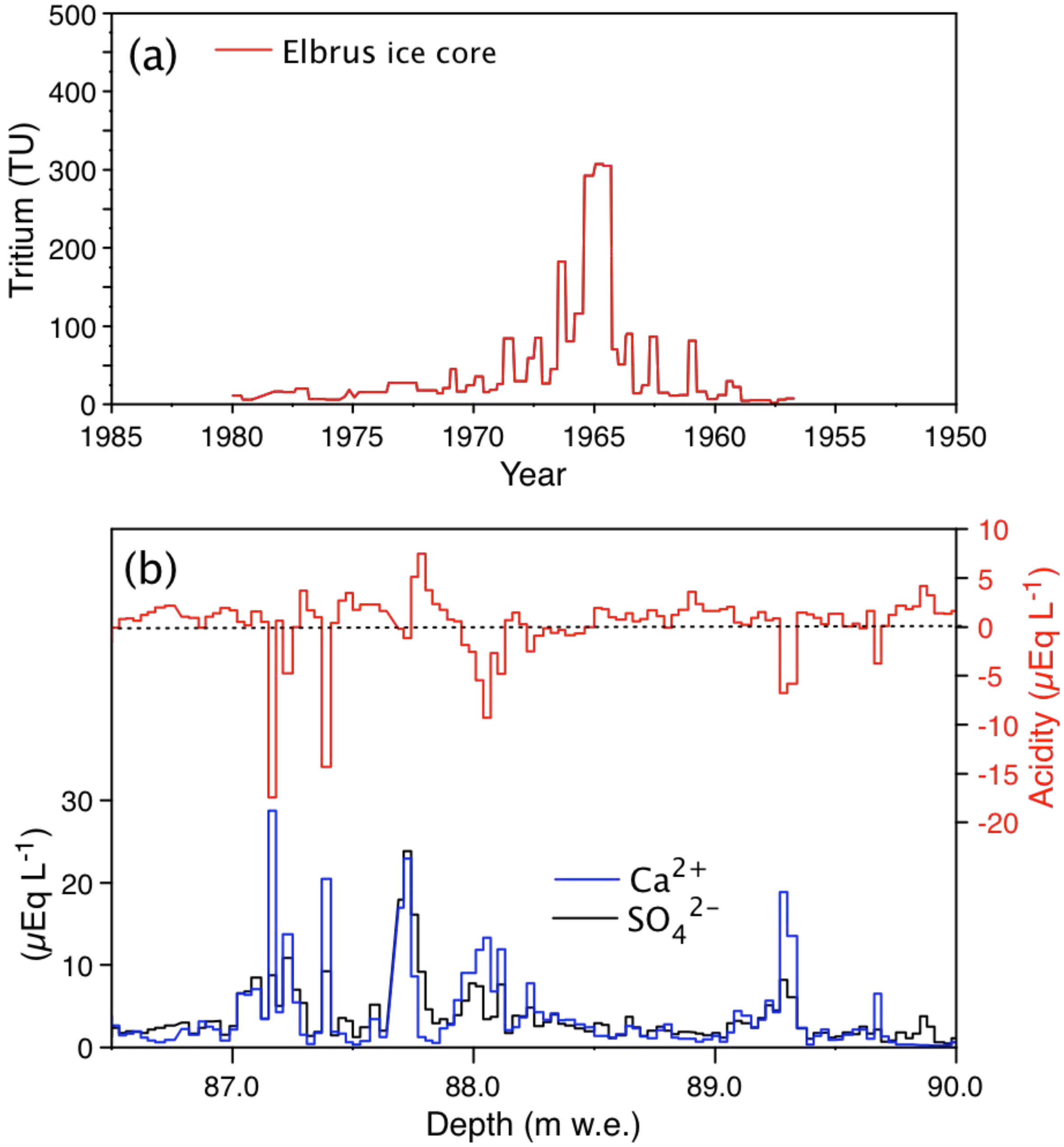

Figure 10. Absolute time horizons: (a) Tritium measurements made on Elbrus ice core samples (data were converted to 2009 with regard to the half-life time of tritium, $T_{1/2}$ = 12.32 year). The dates reported in the tritium curve are derived from the ammonium stratigraphy. (b) Calculated acidity (top, see Sect. 3.3.1), calcium and sulfate (bottom) in ice layers located between 86.5 and 90 m w.e.

Below 88 m w.e., we were still able to easily proceed annual counting down to 113 (1860), whereas further down the dating become more uncertain (see the green line in Fig. 9). Below 88 m w.e., 7 significant potential volcano horizons can be suspected on the basis of the ionic balance and sulfate levels (not shown), from which however at least 1 are of local origin (as suggested by small stones with size of up to 1–2 mm were found in the corresponding layer). Nevertheless, a series of 3 narrow spikes was located at 118–120 m w.e. (dated at around 1840–1833) among which two that are characterized by an increase of sulphate and acidity (up to 7.8 μEq L^{-1}, not shown) may be related to the well-known eruptions observed in Greenland in a time distance of 2 years around 1840 (one of them being possibly due to the Coseguina eruption in 1835) (Legrand et al., 1997).

3.4 Modelled ice flow and ice core dating

From the thermodynamic point of view mountain glaciers filling volcano craters present a special type. Relatively high crater depth and limited ice flux over the crater rims form flat glacier surface result in small surface ice velocity. Intensive volcanic heat flux could result in bottom melting and removal of the oldest basal layers. A simplified thermo mechanically coupled model for simulating ice flow along a fixed flow tube and heat transfer in ice caps filling volcanic craters has been developed by Salamatin et al. (2000). Model description and ice-flow and heat-transfer equations are given in Salamatin et al. (2000). The model takes into account surface and bedrock topography and snow-firn densification parameters (see section 3.3.2), the distribution of the relative bottom melt rate (see section 3.3.1) and normalized by the present day accumulation rate. We calculated depth/age relationship for the Western Elbrus Plateau on the basis of recent accumulation rate of 1200 mm w.e. The ice melt rate at the glacier bedrock is negligible and comprises less than 10 mm w.e y^{-1} (see section 3.3.1) in the deepest part at current accumulation rate limit. Figure 11 shows the cross section of the Elbrus Western Plateau along a reference flow line. Predicted ice particle paths are shown by arrowed lines, isochrones are designated by numbers, which specify the ice age in years.

The depth age relation calculated for the 2009 ice core is also given in Figure 9. It fits well/fairly well with the dating on the annual layer counting. According to the modelling results, the bottom ice age at the maximal depth is predicted to be about 660 years before 2009 AD and is close to the maximal age in the crater. A 2009 borehole was situated below and the estimated bottom ice age does not exceed 350–400 years before 2009 AD.

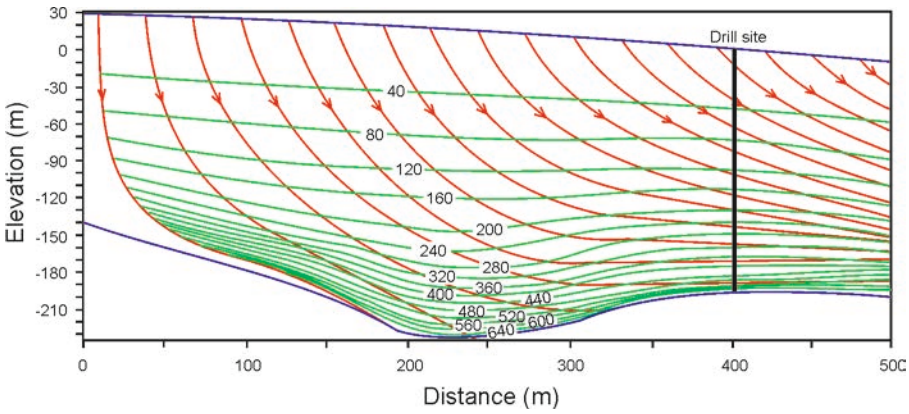

Figure 11. Vertical transect of the Western Elbrus Plateau glacier along a reference flow line. Predicted ice-particle paths (lines with arrows) and isochrones are shown.

4. Conclusions

Paleoclimatological records for southern and eastern Europe are based on geomorphological, palinological, limnological, and dendrochronological data. Ice core records have not been taken into account as a source of paleoclimate and environmental information for this area due to rapid glacier mass exchange rate and significant surface melting, causing isotope and chemical profile smooth in the glacier depositions. The analysis of the ice core derived in 2009 on the Mt. Elbrus at 5115 m provides new evidence for significant regional-scale multiproxy climatic implications. The negative ice temperature of the glacier at the drilling site secures an undisturbed incoming climate signal. The considerable snow accumulation rate of 1455 mm w.e. coupled with a great body of analyzed samples allow us to separate snow depositions from summer and winter precipitation. Annual layering was made on the basis of seasonal oscillations of NH_4^+, succinic acid, and $\delta^{18}O$. Annual layer counting was secured down to 85 m w.e. The ice flow model shows that the near bedrock ice age at the maximal glacier depth of 255 m can reach more than 600 years. But the 2009 drilling site was situated downstream and where the bottom ice age does not exceed 350–400 years. An essential difference between reported depth-age scale constructed on the base of layer counting and modeled one demands the inspection of model algorithm and development of a reliable ice flow model. Annual layer counting was confirmed by the well-known reference horizons of the 1963 nuclear tests and the 1912 Katmai volcanic eruption. The comparison of Mt. Elbrus ice core records with ice core records from Alpine glaciers (Col du Dôme and Colle Gnifetti) will allow us to estimate the tendency of climatic changes over Europe for the last centuries, and to obtain high resolution multiproxy reconstructions of the dustiness of the atmosphere, air temperature and precipitation oscillations, black carbon pollution, and atmospheric circulation change.

Combining the different glacio-chemical features of the Western Elbrus Plateau detailed in this study, we conclude that this high elevation glacier archive offers the possibility to extract atmospheric relevant information from long-term ice core records. Ongoing works are therefore dedicated to reconstructing several key aspects of the changing atmosphere of this central European region, in particular for various components of aerosol (sulfate, ammonium, terrigenous matter, and carbonaceous compounds or fractions) and species related to the nitrogen cycle (nitrate).

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References

Abich, H.: Geologische Beobachtungen auf Reisen im Kaukasus im Jahre 1873, Bulletin de la Société impériale des naturalistes de Moscou, 48(2), 278–342 + 1 Karte, 1874a.

Abich, H.: Geologische Beobachtungen auf Reisen im Kaukasus im Jahre 1873 (Fortsetzung), Bulletin de la Société impériale des naturalistes de Moscou, 48(3), 63–107, 1874b.

Abich, H.: Geologische Beobachtungen auf Reisen im Kaukasus im Jahre 1873 (Schluss), Bulletin de la Société impériale des naturalistes de Moscou, 48(4), 243–272, 1874c.

AMAP: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere, Arctic Monitoring and Assessment Programme (AMAP), Oslo, 538 pp., 2011.

Anisimov, O.A. and Zhil'tsova, E.L.: Climate change estimates for the regions of Russia in the 20th century and in the beginning of the 21st century based on the observational data, Rus. Meteorol. Hydrol., 37(6), 421–429, doi:10.3103/S1068373912060106, 2012.

Arkhipov, S.M., Mikhalenko, V.N., Thompson, L.G., Zagorodnov, V.S., Kunakhovich, M.G., Smirnov, K.E., Makarov, A.V., and Kuznetsov, M.P.: Stratigrafiya deyatelnogo sloya lednikovogo kupola Vetreniy na ostrove Graham Bell, Zemlya Frantsa Iosifa (Stratigraphy of the active layer of the Vetreny Ice Cap, Graham Bell Island, Franz Josef Land), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (90), 169–186, 2001 (in Russian with English summary).

ASTER GDEM Validation Team: ASTER Global DEM Validation Summary Report, Sioux Falls, USA, 28 pp., 2009.

Baranov, S. and Pokrovskaya, T.: Rabota meteorologicheskoi gruppy EKNE 1935 (Investigations of the Meteorological team of the Elbrus Complex Scientific Expedition), in: Trudy Elbrusskoi ekspeditsii Akademii nauk SSSR i VIEM 1934 i 1935 gg.; Trudy komissii po izucheniyu stratosfery, t. 2 (Elbrus expedition of the Academy of Sciences and of the Institute of Experimental Medicine of the USSR, 1934 and 1935; Proceedings of the commission of the stratosphere investigations, v. 2), resp. ed.: Vavilov, S.I., Academy of Sciences Press, Moscow, Leningrad, 199–209, 1936 (in Russian with English summary).

Barbante, C., Schwikowski, M., Ring, T., Gäggeler, H.W., Schotterer, U., Tobler, L., Van de Velde, K., Ferrari, C., Cozzi, G., Turetta, A., Rosman, K., Bolshov, M., Capodaglio, G., Cescon, P., and Bourton, C.: Historical record of European emissions of heavy metals to the atmosphere since the 1650s from Alpine snow/ice cores drilled near Monte Rosa, Environ. Sci. Technol., 38(15), 4085–4090, doi:10.1021/es049759r, 2004.

Bazhev, A.B. and Bazheva, V.Ya.: Stroenie firnovo-ledyanoy tolschi na Elbruse (Structure and firn-ice layer at the south slope of Elbrus), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (10), 94–100, 1964 (in Russian with English summary).

Bazhev, A.B., Rototaeva, O., Heitzenberg, J., Stenberg, M., and Pinglot, J.F.: Physical and chemical studies in the region of the southern slope of Mount Elbrus, Caucasus, J. Glaciol., 44(147), 214–222, 1998.

Bender, M. Sowers, T., and Brook, E.: Gases in ice cores, P. Natl. Acad. Sci. USA, 94(16), 8343–8349, doi:10.1073/pnas.94.16.8343, 1997.

Berikashvili, V.Sh., Vasilenko, E.V., Macheret, Yu.Ya., and Sokolov, V.G.: Odnoimpulsniy radar dlya zondirovaniya lednikov s opticheskim kanalom sinkhronizatsii (Monopulse radar for glacier sounding with optical channel for synchronization and digital signal processing), Radiotekhnika (Radio technics), (9), 52–57, 2006 (in Russian with English summary).

Bohleber, P.: Age distribution and δ^{18}O variability in a low accumulation Alpine ice core: Perspective for paleoclimate studies, Diploma thesis, Fakultät für Physik und Astronomie, Ruprecht-Karls-Universität, Heidelberg, 147 pp., 2008.

Clausen, H.B., Hammer, C.U., Hvidberg C.D., Dahl-Jensen, D., Kipfstuhl, J., and Legrand, M.: A comparison of the volcanic records over the past 4000 years from the Greenland Ice Core Project and Dye 3 Greenland ice cores, J. Geophys. Res., 102(C12), 26707–26723, doi:10.1029/97JC00587, 1997.

Dansgaard, W., Johnsen, S.J. A flow model and a time scale for the ice core from Camp Century, Greenland, J. Glaciol., 8(53), 215–223, 1969.

Dolgova E.A., Matskovskiy V.V., Solomina O.N., Rototarva O.V., Nosenko G.A., and Khmelevskoy I.F.: Rekonstruktsiya balansa massy lednika Garabashi (1800–2005) po dendrokhronologicheskim dannim (Reconstructing mass balance of Grabashi Glacier (1800–2005) using dendrochronological data), Led i Sneg (Ice and Snow), 53(1), 34–42, doi:10.15356/2076-6734-2013-1-34-42, 2013 (in Russian with English summary).

Dyurgerov, M.B. and Popovnin, V.V.: Rekonstruktysiya balansa massy, prostranstvennogo polozheniya I zhidkogo stoka lednika Dhzankuat so vtoroi poloviny 19 veka (Reconstruction of mass balance, spatial position, and liquid discharge of Dzhankuat Glacier since the second half of the 19th century), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (40), 111–126, 1988 (in Russian with English summary).

Eichler, A., Tinner, W., Brusch, S., Olivier, S., Papina, T., and Schwikowski, M.: An ice-core based history of Siberian forest fires since AD 1250, Quaternary Sci. Rev., 30(9–10), 1027–1034, doi:10.1016/j.quascirev.2011.02.007, 2011.

Fagerli H., Legrand, M., Preunkert, S., Vestreng, V., Simpson, D., and Cerquera, M.: Modeling historical long-term trends of sulfate, ammonium, and elemental carbon over Europe: A comparison with ice core records in the Alps. J. Geophys. Res., 112(D23), D23S13: 1–16, doi:10.1029/2006JD008044, 2007.

Ginot, P., Schotterer, U., Stichler, W., Godoi, M. A., Francou, B., and Schwikowski, M.: Influence of the Tungurahua eruption on the ice core records of Chimborazo, Ecuador, The Cryosphere, 4(4), 561–568, doi:10.5194/tc-4-561-2010, 2010.

Golubev, G.N., Dyurgerov, M.B., Markin, V.A., Berry, B.L., Sukhanov, L.A., Zolotarev, E.A., Danilina, A.V., and Arutunov, Yu.G.: Lednik Dzhankuat (Tsentralniy Kavkaz) (Water-ice and heat balances of Jankuat Glacier (Central Caucasus)), edited by: Byarski, I,Ya., Hydrometeoizdat Press, Leningrad, 184 pp., 1978 (in Russian with English summary).

Golubev, V.N., Mikhalenko, V.N., Serebrennikov, A.V., and Gvozdik, O.A.: Strukturnye issledovaniya ledyanogo kerna Dzhantuganskogo firnovogo plato na Tsentral’nom Kavkaze (Structural studies of the ice core obtained from the Djantugan Firn Plateau in the Central Caucasus), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (64), 25–33, 1988 (in Russian with English summary).

Hörhold, M.W., Kipfstuhl, S., Wilhelms, F., Freitag, J., and Frenzel, A.: The densification of layered polar firn, J. Geophys. Res., 116(F1), F01001: 1–15, doi:10.1029/2009JF001630, 2011.

Hou, S., Chappellaz, J., Raynaud, D., Masson-Delmotte, V., Jouzel, J., Bousquet P., and Hauglustaine D.: A new Himalayan ice core CH_4 record: possible hints at the preindustrial latitudinal gradient, Clim. Past, 9(6), 2549–2554, doi:10.5194/cp-9-2549-2013, 2013.

Johnsen, S., Clausen, H.B., Cuffey, K.M., Hoffmann, G., Schwander, J., and Creyts, T.: Diffusion of stable isotopes in polar firn and ice: the isotope effect in firn diffusion, in: Physics of Ice Core Records, edited by Hondoh, T., Hokkaido University Press, Sapporo, 121–140, doi:10.7916/D8KW5D4X, 2000.

Kawamura, K., Izawa, Y., Mochida, M., and Shiraiwa, T.: Ice core records of biomass burning tracers (levoglucosan and de-hydroabietic, vanillic and p-hydroxybenzoic acids) and total organic carbon for past 300 years in the Kamchatka Peninsula, Northeast Asia, Geochim. Cosmochim. Ac., 99, 317–329, doi:10.1016/j.gca.2012.08.006, 2012.

Kerimov, A.M., Rototaeva, O.V., and Khmelevskoy, I.F.: Raspredelenie tyazhelykh metallov v poverkhnostnykh sloyakh snezhno-firnovoi tolshchi na yuzhnom sklone Elbrusa (Distribution of heavy metals in the surface layers of snow-firn mass on the southern slope of Mount Elbrus), Led i Sneg (Ice and Snow), 51(2), 24–34, doi:10.15356/2076-6734-2011-2-24-34, 2011 (in Russian with English summary).

Kotlyakov, V.M., Arkhipov, S.M., Henderson, K.A., and Nagornov, O.V.: Deep drilling of glaciers in Eurasian Arctic as a source of paleoclimatic records, Quaternary Sci. Rev., 23(11–13), 1371–1390, doi:10.1016/j.quascirev.2003.12.013, 2004.

Kovalev P.V.: Sovremennoe oledenenie basseina reki Baksan (Recent glaciation of the Baksan River basin), in: Materialy Kavkazskoi ekspeditsii (po programme Mezhdunarodnogo geofizicheskogo goda) (Proc. of the Caucasus expedition (by the programme of the International Geophysical Year)), v. 2, edited by: Dubinskii G.P., Khar’kov University, Khar’kov, 3–106, 1961 (in Russian).

Krenke, A.N., Menshutin, V.V., Voloshina, A.P., Panov, V.D., Bazhev, A.B., Bazheva, V.Ja., Balaeva, V.A., Vinogradov, O.N., Voronina, L.S., Garelik. I.S., Davidovich, N.V., Dubinskaya, N.M., Macheret, Yu.Ya., Moiseeva, G.P., Psareva, T.V., Tyulina, T.Yu., Freidlin, V.S., Khmelevskoy, I.F., Chernova, L.P., and Shadrina, O.V.: Lednik Marukh (Zapadniy Kavkaz) (Marukh Glacier (Western Caucasus)), edited by: Kotlyakov, V.M., Hydrometeoizdat Press, Leningrad, 254, 1988 (in Russian with English summary).

Kutuzov S., Lavrentiev, I. I., Macheret, Yu, Ya., and Petrakov, D. A.: Izmenenie lednika Marukh s 1945 po 2011 (Changes of Marukh Glacier from 1945 to 2011), Led i Sneg (Ice and Snow), 52(1), 123–127, doi:10.15356/2076-6734-2012-1-123-127, 2012 (in Russian with English summary)

Kutuzov S.S., Lavrentiev I.I., Vasilenko E.V., Macheret Y.Y., Petrakov D.A., and Popov G.V.: Otsenka obiema lednikov Bolshogo Kavkaza po dannym radiozondirovania i modelirovania (Estimation of the Greater Caucasus glaciers volume, using radio-echo sounding data and modelling), Kriosfera Zemli (Earth's Cryosphere), 19(1), 78–88, 2015 (in Russian with English summary)

Kutuzov, S., Shahgedanova, M., Mikhalenko, V., Lavrentiev, I, and Kemp, S.: Desert dust deposition on Mt. Elbrus, Caucasus Mountains, Russia in 2009–2012 as recorded in snow and shallow ice core: high-resolution "provenancing", transport patterns, physical properties and soluble ionic composition, The Cryosphere, 7(5), 1481–1498, doi:10.5194/tc-7-1481-2013, 2013.

Laverov, N.P., Dobretsov, N.L., Bogatikov, O.A., Bondur, V.G., Gurbanov, A.G., Karamurzov, B.S., Kovalenko, V.I., Melekestsev, I,V., Nechaev, Yu.V., Ponomareva, V.V., Rogozhin, E.A., Sobisevich, A.L., Sobisevich, L.E., Fodotov, S.A., Khrenov, A.P., and Yarmolyuk, V.V.: Noveyshiy i sovremenniy vulkanizm na territorii Rossii (Modern and Holocene volcanism in Russia), Nauka, Moscow, 604 pp., 2005 (in Russian with English summary).

Lavrentiev, I.I., Mikhalenko, V.N., and Kutuzov, S.S.: Tolshchina l'da i podlednyi rel'ef Zapadnogo lednikovogo plato Elbrusa (Ice thickness and subglacial relief of the Western Ice Plateau of Elbrus), Led i Sneg (Ice and Snow), 50(2), 12–18, doi:10.15356/2076-6734-2010-2-12-18, 2010 (in Russian with English summary).

Legrand M., C. Hammer, M. De Angelis, J. Savarino, R. Delmas, H. Clausen, and S.J. Johnson, Sulphur containing species (MSA and SO_4) over the last climatic cycle in the GRIP (central Greenland) ice core, J. Geophys. Res., 102(C12), 26663–26679, doi:10.1029/97JC01436, 1997.

Legrand, M. and Mayewski, P.: Glaciochemistry of polar ice cores: A review, Rev. Geophys.,

35(3), 219–243, doi:10.1029/96RG03527, 1997.
Legrand, M., Preunkert, S., Schock, M., Cerqueira, M., Kasper-Giebl, A., Afonso, J., Pio, C., Gelencsér, A. and Dombrowski-Etchevers, I.: Major 20th century changes of carbonaceous aerosol components (EC, WinOC, DOC, HULIS, carboxylic acids, and cellulose) derived from Alpine ice cores, J. Geophys. Res., 112(D23), D23S11, doi:10.1029/2006JD008080, 2007a.
Legrand, M., S. Preunkert, Oliveira, T., Pio, C.A., Hammer, S., Gelencsér, A., Kasper-Giebl, A., and Laj, P.: Origin of C_2–C_5 dicarboxylic acids in the European atmosphere inferred from year-round aerosol study conducted at a west-east transect, J. Geophys. Res., 112(D23), D23S07, doi:10.1029/2006JD008019, 2007b.
Ligtenberg, S.R.M., Helsen, M.M., and van den Broeke, M.R.: An improved semi-empirical model for the densification of Antarctic firn, The Cryosphere, 5(4), 809–819, doi:10.5194/tc-5-809-2011, 2011.
Looyenga, M.: Dielectric constant of heterogeneous mixtures, Physica, 31(3), 401–406, doi:10.1016/0031-8914(65)90045-5, 1965.
Macheret, Yu.Ya.: Radiozondirovanie lednikov (Radio-echo sounding of glaciers), Scientific World Publishers, Moscow, 392 pp., 2006 (in Russian with English summary).
Maeno, N. and Ebinuma, T.: Pressure sintering of ice and its implication to the densification of snow at polar glaciers and ice sheets, J. Phys. Chem., 87(21), 4103–4110, doi:10.1021/j100244a023, 1983.
Matyukhin, G.D.: Klimaticheskie dannye po vysotnym poyasam yuzhnogo sklona Elbrusa (Climatic data for the southern slope of Elbrus), in: Informatsionnyi sbornik o rabotakh po Mezhdunarodnomu geofizicheskomu godu (Information collection on the investigations in International Geophysical Year), 5, Faculty of Geography, Moscow State University, Moscow, 130–194, 1960 (in Russian).
Mätzler, C. and Wegmüller, U.: Dielectric properties of fresh-water ice at microwave frequencies, J. Phys. D Appl. Phys., 20(12), 1623–1630, doi:10.1088/0022-3727/20/12/013, 1987.
Mikhalenko, V.N., Kuruzov, S.S., Lavrentiev, I.I., Kunakhovich, M.G., and Thompson, L.G.: Issledovanie zapadnogo lednikovogo plato Elbrusa: rezul'taty i perspektivy (Western Elbrus Plateau studies: results and perspectives), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (99), 185–190, 2005 (in Russian with English summary)
Mikhalenko, V.N.: Glubinnoe stroenie lednikov tropicheskikh i umerennikh shirot (Inner structure of glaciers in non-polar regions), LKI Publishers, Moscow, 320 pp., 2008 (in Russian with English summary).

Mikhalenko, V.N.: Glubokoe burenie l'la bliz vershiny Elbrusa (Deep ice core drilling near summit of Mt. Elbrus), Led i Sneg (Ice and Snow), 50(1), 123–126, doi:10.15356/2076-6734-2010-1-123-126, 2010 (in Russian with English summary).

Mushketov, I.V.: Geologicheskaya poezdka na Kavkaz v 1881 (Geological excursion to the Caucasus in 1881), Izvestiya Imperatorskogo Russkogo geograficheskogo obshchestva (Proc. Rus. Geogr. Soc.), 18(2), 106–119, 1882 (in Russian).

Nosenko, G.A., Khromova, T.E., Rototaeva, O.V., and Shahgedanova, M.: Reaktsiya lednikov Tsentralnogo Kavkaza v 2001–2010 na izmeneniya temperatury i kolichestva osadkov (Glacier reaction to temperature and precipitation change in Central Caucasus), 2001–2010, Led i Sneg (Ice and Snow), 53(1), 26–33, doi:10.15356/2076-6734-2013-1-26-33, 2013 (in Russian with English summary).

Pastukhov, A.V.: Poseshchenie Elbrusa 13 iyulya 1890 (Ascending to Elbrus on 13 July, 1890), Zapiski Kavkazskogo otdela Imperatorskogo Russkogo geograficheskogo obshchestva (Mem. Cauc. branch Imperial Rus. Geogr. Soc.), 15, 22–37, 1893 (in Russian).

Podozerski, K.I.: Ledniki Kavkazskogo khrebta (Glaciers of the Caucasus Range), Zapiski Kavkazskogo otdela Imteratorskogo Russkogo geograficheskogo obschestva (Mem. Cauc. branch Imperial Rus. Geogr. Soc.), 29(1), 200 pp., 1911 (in Russian).

Preunkert, S. and Legrand, M.: Towards a quasi-complete reconstruction of past atmospheric aerosol load and composition (organic and inorganic) over Europe since 1920 inferred from Alpine ice cores, Clim. Past, 9(4), 1403–1416, doi:10.5194/cp-9-1403-2013, 2013.

Preunkert, S., Wagenbach, D., Legrand, M., and Vincent, C.: Col du Dôme (Mt Blanc Massif, French Alps) suitability for ice-core studies in relation with past atmospheric chemistry over Europe, Tellus, 52B(3), 993–1012, doi:10.1034/j.1600-0889.2000.d01-8.x, 2000.

Psareva, T.V.: Preobrazovanie snezhno-firnovoi tolshchi i tipy l'doobrazovaniya na Elbruse (Transformation of snow-firn thickness and types of ice formation on Elbrus), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (10), 79–86, 1964 (in Russian with English summary).

Rototaeva, O.V. and Tarasova, L.N.: Rekonstruktsiya balansa massi lednika Garabashi za poslednee stoletie (Reconstruction of the Garabashi Glacier mass balance in the last century), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (88), 16–26, 2000 (in Russian with English summary).

Rototaeva, O.V., Nosenko, G.A., Tarasova, L.N., and Khmelevskoy, I.F.: obschaya kharakteristika oledeneniya severnogo sklona Bolshogo Kavkaza (General characteristics of glacierization of the north slope of the Gteater Caucasus), in: Sovremennoe oledenenie

Severnoi i Tsentralnoi Evrazii (Glaciation in North and Central Eurasia at present time), edited by: Kotlakov, V.M., Nauka Press, Moscow, 141–144, 2006 (in Russian).

Salamatin, A.N., Lipenkov, V.Ya., Barnola, J.-M., Hori, A., Duval, P., and Hondoh T.: Snow/firn densification in polar ice sheets, in: Physics of Ice Core Records II: Papers collected after the 2nd International Workshop on Physics of Ice Core Records, held in Sapporo, Japan, 2–6 February 2007 (Low Temperature Science; 68(Suppl.)), edited by: Hondoh, T., Sapporo, Institute of Low Temperature Science, Hokkaido University, 195–222, 2009.

Salamatin, A.N., Murav'yev, Y.D., Shiraiwa, T., and Matsuoka, K.: Modelling dynamics of glaciers in volcanic cratrs, J. Glaciol., 46(153), 177–187, doi:10.3189/172756500781832990, 2000.

Salamatin, A.N., Shiraiwa, T., Muravyev, Y.D., Kameda, T., Silantiyeva, E., and Ziganshin, M.: Dynamics and borehole temperature memory of Gorshkov Ice Cap on the summit of Ushkovsky Volcano, Kamchtka Peninsula, Proceedings of the International Symposium on the Atmosphere-Ocean-Cryosphere Interaction in the Sea of Okhotsk and the Surrounding Environments held at Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, December 12–15, 2000, 120–121, 2001.

Sato, T., Shiraiwa, T., Greve, R., Seddik, H., Edelmann, E., and Zwinger, T.: Accumulation reconstruction and water isotope analysis for 1736–1997 of an ice core from the Ushkovsky volcano, Kamchatka, and their relationships to North Pacific climate records, Clim. Past, 10(1), 393–404, doi:10.5194/cp-10-393-2014, 2014.

Schwikowski, M.: Reconstruction of European air pollution from Alpine ice cores, in: Earth Paleoenvironments: Records Preserved in Mid- and Low-Latitude Glaciers, edited by: DeWayne Cecil, L., Green, J.R., Thompson, L.G., Developments in Paleoenvironmental Research, 9, Kluwer Academic Publishers, 95–119, doi:10.1007/1-4020-2146-1_6, 2004.

Serebryannyy, L.R., Golodkovskaya, N.A., Orlov, A.V., Malyasova, E.S., and Il'ves, E.O.: Kolebaniya lednikov I protsessy morenonakopleniya na Tsentralnom Kavkaze (Glacier variations and moraine accumulation: processes in Central Caucasus), Nauka, Moscow, 216 pp., 1984 (in Russian with English summary).

Shahgedanova M., Nosenko G., Kutuzov S., Rototaeva O., and Khromova T.: Deglaciation of the Caucasus Mountains, Russia/Georgia, in the 21st century observed with ASTER satellite imagery and aerial photography, The Cryosphere, 8(6), 2367–2379, doi:10.5194/tc-8-2367-2014, 2014.

Shahgedanova, M., Kutuzov, S., White, K., and Nosenko, G.: Using the significant dust deposition event on the glaciers of Mt. Elbrus, Caucasus Mountains, Russia on 5 May 2009 to develop a method for dating and provenancing of desert dust events recorded in snow pack, Atmos. Chem. Phys., 13(4), 1797–1808, doi:10.5194/acp-13-1797-2013, 2013.

Solomina O.N., Kalugin, I.A., Aleksandrin, M.Yu., Bushueva, I.S., Darin, A.V., Dolgova, E.A., Jomelli, V., Ivanov, M.N., Matskovsky, V.V., Ovchinnikov, D.V., Pavlova, I.O., Razumovsky, L.V., and Chepurnaya, A.A.: Burenie osadkov ozera Kara-Kel' (dolina reki Teberdy) I perspektivy rekonstruktsii istorii oledeneniya i klamata golotsena na Kavkaze (Coring of Karakel' Lake sediments (Teberda River valley) and prospects for reconstruction of glaciation and Holocene climate history in the Caucasus), Led i Sneg (Ice and Snow), 53(2), 102–111, doi:10.15356/2076-6734-2013-2-102-111, 2013 (in Russian with English summary).

Solomina, O.N., Dolgova, E.A., and Maximova, O.E.: Rekonstruktsiya gidrometeorologicheskikh uslovii poslednikh stoletii na severnom Kavkaze, v Krymu i na Tyan' Shane po dendrokhronologicheskim dannym (Tree-ring based hydrometeorological reconstructions in the Crimea, the Caucasus and Tien-Shan), Nestor History Press, Moscow, St. Petersburg, 232 pp., 2012 (in Russian with English summary).

Stokes, C.R., Gurney, S.D., Shahgedanova, M, and Popovnin, V.: Late-20th-century changes in glacier extent in the Caucasus Mountains, Russia/Georgia, J. Glaciol., 52(176), 99–109, doi:10.3189/172756506781828827, 2006.

Takeuchi, N., Takahashi, A., Uetake, J., Yamazaki, T., Aizen, V. B., Joswiak, D., Surazakov, A. and Nikitin, S.: A report on ice core drilling on the western plateau of Mt. Belukha in the Russian Altai Mountains in 2003, Polar Meteorol. Glaciol., 18, 121–133, 2004.

Thompson, L.G.: Understanding Global Climate Change: Paleoclimate Perspective from the World's Highest Mountains, Proc. Amer. Phil. Soc., 154(2), 133–157, 2010.

Troshkina, E.S.: Stratigrafiya snazhno-firnovogo pokrova v oblasti pitaniya (Snow and firn stratigraphy in the accumulation zone of the Mt. Elbrus), in: Oledenenie Elbrusa (Elbrus Glaciation), edited by Tushinski, G.K., Moscow University Press, Moscow, 213–222, 1968 (in Russian).

Tushinskii, G.K. (ed.): Oledenenie Elbrusa (Glaciation of the El'brus Mountain), Moscow University Press, Moscow, 346 pp., 1968 (in Russian)

Vasilenko, E.V., Glazovsky, A.F., Macheret, Yu.Ya., Navarro, F., Sokolov, V.G., and Shiraiwa, T.: Georadar VIRL dlya zondirovaniya lednikov (Georadar VIRL for glacier sounding), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (94), 225–234, 2003 (in Russian with English summary).

Vasilenko, E.V., Sokolov, V.A., Macheret, Y., Glazovsky, A.F., Cuadrado, M.L., and Navarro, F.J.: A digital recording system for radioglaciological studies, Bull. R. Soc. N. Z., 35, 611–617, 2002.

Vaughan, D.G., Comiso, J.C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T.: Observations: Cryosphere, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317–382, 2013.

Vimeux, F., Ginot, P., Schwikowski, M., Vuille, M., Hoffmann, G., Thompson, L. G., and Schotterer, U.: Climate variability during the last 1000 years inferred from Andean ice cores: A review of methodology and recent results, Palaeogeogr., Palaeoclimatol., Palaeoecol., 281(3–4), 229–241, doi:10.1016/j.palaeo.2008.03.054, 2009.

Volodicheva, N.: The Caucasus, in: The Physical geography of Northern Eurasia, edited by: Shahgedanova, M., Oxford University Press, Oxford, 350–376, 2002.

Werner, M., Mikolajewicz, U., Heimann, M., and Hoffmann, G.: Borehole versus isotope temperatures on Greenland: Seasonality does matter, Geophys. Res. Lett., 27(5), 723–726, doi:10.1029/1999GL006075, 2000.

Zagorodnov, V.S., Arkhipov, S.M., Bazhev, A.B., Vostokova, T.A., Korolev, P.A., Rototaeva, O.V., Sinkevich, S.A., and Khmelevskoy, I.F.: Stroenie, sostav i gidrotermichaskiy rezhim lednika Garabashi na Elbruse (Structure, state and hydrothermal regime of the Garabashi Glacier), the Elbrus area, Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (73), 109–117, 1992 (in Russian with English summary).

Zagorodnov, V.S., Nagornov, O.V., and Thompson, L.G.: 2006. Influence of air temperature on a glacier's active-layer temperature. Ann. Glaciol., 43, 285–287, doi:10.3189/172756406781812203, 2006.

Zolotarev, E.A.: Evolutsiya oledeneniya Elbrusa: katrografo-aerokosmicheskie tekhnologii glyatsiologicheskogo monitoringa (Evolution of Elbrus glaciers: Cartographic-aerospace technologies of glacier monitoring), Nauchnyi Mir, Moscow, 238 pp., 2009 (in Russian).

Zolotarev, E.A. and Kharkovets, E.G.: Oledenenie Elbrusa v kontse XX veka: tsifrovaya ortofotokarta Elbrusa na 1997 (Glaciation of Elbrus at the end of XX century (digital orthophotomap of Elbrus for 1997)), Materialy glyatsiologicheskikh issledovanii (Data Glaciol. Stud.), (89), 175–191, 2000 (in Russian with English summary).

Zolotarev, E.A. and Kharkovets, E.G.: Evolutsiya oledeneniya Elbrusa posle malogo lednikovogo perioda (Development of glaciers of Mount Elbrus after the Little Ice Age), Led i Sneg (Ice and Snow), 52(2), 15–22, doi:10.15356/2076-6734-2012-2-15-22, 2012 (in Russian with English summary).