We would like to thank three anonymous reviewers for their comments. The answers to the questions raised in the reviews provided below. The comments of reviewers are highlighted in *italic* and the corrections in the paper are in **bold**. Figures that are used for the answers only are inserted into the text; updated figures from the paper and the supplement are at the end of the document.

Reviewer 1

The most critical point is separating the record into a warm a cold season part. This is conducted by implementing a threshold (average d18O value of -15.5‰ for the entire record), thereby inherently presuming a d18O-temperature relationship and the absence of a trend.

We agree that the dating section should be revised to make the dating procedure clearer as was pointed by all the three reviewers. However, we think that the proposed method of dating when the border between warm and cold seasons is the 100-years mean value is the best one for this very ice core.
Accumulation at the drilling site has been investigated sporadically (see review in Mikhalenko et al., 2015). We cannot use the meteorological observations from the nearest weather stations as these stations situated at sufficiently lower elevation and belong to two different groups as discussed in section 3.1. The ice core is the only source for the information about the seasonal cycle of this parameter.
We think that the annual cycle of the isotopic composition is influenced by local temperature while interannual variations depend on the other factors. In order to better illustrate the dating methodology we will add the ammonium concentration and dust concentration profiles to Fig. 3. Layers with the high dust concentration have been precisely dated by Kutuzov et al. (2013) for the 2012 ice core. Their results show that the separation of the core into a warm and cold season part using the average value of δ18O is appropriate for this drilling site at least for the period from 2009 till 2012 that was investigated in the paper. Also, to show correlation between temperature and isotopic composition on annual scale, we will add temperature data to the GNIP data graphs on Fig. 7.
As for the linear trend that can cause errors in the dating, we also tried separation into warm and cold seasons using linear trend of δ18O. The result is shown on Fig. below. The difference between this method of separation and ours is about 0.5 per mil which is comparable with the δ18O measurement precision and is negligible given the high accumulation rate at the drilling site.

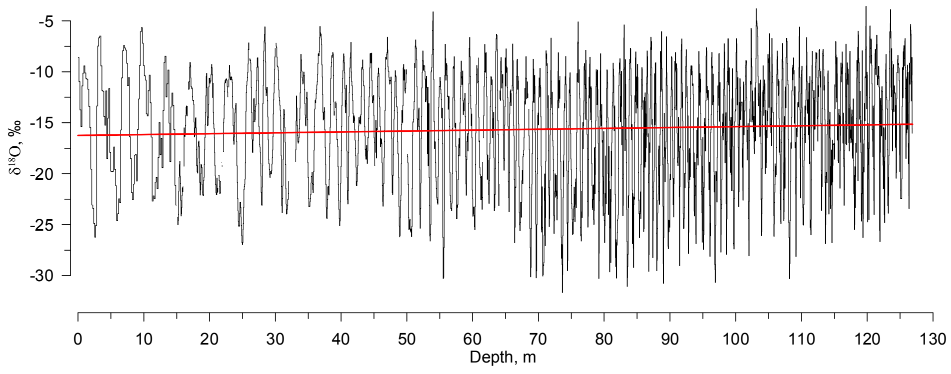


Fig. Vertical profile of δ18O with the linear trend.

2.1.4 Dating

The chronology is based on the identification of annual layers. These are prominent in $\delta^{18}O$ with the average seasonal amplitude of 20 ‰. As there is no trend in the $\delta^{18}O$ record. we used the mean value of the $\delta^{18}O$ of the whole dataset (-15.5 ‰) as a threshold to separate between the warm and cold seasons. For equivocal situations, we also used additional data: melt layers and dust layers (used to identify the warm season) (Kutuzov et al., 2013) as well as ammonium and succinic acid concentration data that also have seasonal variations (Mikhalenko et al., 2015). Layers with the high dust concentration have been precisely dated by Kutuzov et al. (2013) for the 2012 ice core. Their results show that the separation of the core into a warm and cold season part using the average value of $\delta^{18}O$ is appropriate for this drilling site at least for the period from 2009 till 2012 that was investigated by Kutuzov et al. (2013).

So, the question is if you could investigate a longer time period (potentially showing a trend in temperature) and longer term averages to smooth the effect of year-to-year shifts in precipitation/accumulation.

Investigation of a sufficiently longer period is not feasible because of huge dating uncertainties. We will discuss them elsewhere.

Also, we tried 3-, 5-, and 7-years running means for the correlation analysis but obtained the same result. We can add these results as well.

At the bottom part of the core the isotopic composition cycles are less prominent and cannot be used for dating, consequently the dating uncertainty is sufficiently higher. The isotopic composition of that part of the core will be discussed elsewhere.

We also repeated our linear correlation analysis using precipitation weighted temperature, and obtained the same results. We didn't find any statistically significant correlations when compared 3-, 5-, 7-years running means of these parameters.

One other point is the dating uncertainty and how you deal with that for correlation analysis with meteorological data. You specify +/- 1 year uncertainty, whereas the first publication on this ice core (Mikhalenko et al., 2015) shows a 2-years difference between annual layer counting of the stable isotope signal and the chemical stratigraphy at 106.7 m. What is correct and how to you consider this in the correlation analysis?

We agree with the comment and will correct the uncertainty as stated by Mikhalenko et al (2015). In the correlation analysis we used the dating obtained using the isotopic composition annual cycles counting. We will add this point to the text of the paper.

The discrepancy between two independent chronologies is 2 years at a depth of 126 m. We used the dating based on the isotopic composition data in this paper. This dating is also best fit for the correlation analysis with the meteorological data.

Obviously this is not the first publication about that ice core which is not a problem if you present other data or new analyses. Here this is not so clear and you should state it and reference it where results were already presented before. Examples are the diffusion of stable isotopes, the AWS data from the ice core site, the overlap with the shallow cores, the precision of the stable isotope analysis (0.06‰ for d18O here and 0.07‰ in Mikhalenko et al. (2015)).

The paper of Mikhalenko et al (2015) presented the ice core and the analysis done. Now we are discussing the isotopic profile of the core. Of course, some replications are inevitable in this case. We will add this point to the discussion section as well as citations of Mikhalenko et al (2015) to the data and methods section. The analytical precision is slightly different as now we are discussing a bigger part of the core.

The methods of the isotopic measurements have been partially discussed in (Mikhalenko et al., 2015).

Our calculation showed that the seasonal amplitude of $\delta^{18}O$ variations could be 10-20% less because of the diffusion (Mikhalenko et al., 2015).

At our drilling site, an automatic weather station (AWS) provided in situ measurements for the period from August 2007 till January 2008. The day to day variations of temperature at low elevation weather stations and at the AWS are coherent for the whole period of the AWS work (Mikhalenko et al., 2015).

I wonder how the entire stable isotope record looks like. In the manuscript only the part down to 126 m out of 182 m is shown, whereas it is stated that the entire core was analysed. Why do you not focus on a longer period, for example back to 1815, since the Tambora volcanic layer gives a nice time marker, detected in most of the ice core records.

We are not going to discuss the bottom part of the core as the isotopic cycle is less prominent there and cannot be used for the dating purpose. The dating using the volcanic layers at Elbrus is complicated as Elbrus is a volcano itself. The dating of the bottom part of the core and the properties of this part like isotopic composition, chemical composition, and dust concentration will be discussed elsewhere. We focused on 100 years period because it is covered by weather observations in the region and we can obtain ice core data with annual resolution.

Hereafter, we focus our analysis on one century, from 1914 till 2013, which corresponds to the upper 126 m of the core. This period has been chosen because of relatively small dating uncertainty and the availability of other records such as local meteorological observations. At the bottom part of the core the isotopic composition cycles are less prominent and cannot be used for dating, consequently the dating uncertainty is sufficiently higher. The isotopic composition of that part of the core will be discussed elsewhere.

In the introduction you state that water stable isotopes are more sensitive to distortion because of seasonality than aerosol concentrations, which is not correct. The seasonality of aerosol-related species and the isotope signal are comparable, but the anthropogenic aerosol trend exceeds by far any temperature-driven water isotope increase during the Holocene (Wagenbach et al., 2012).

We removed this statement as it is unimportant for the further discussion.

Explain why there are gaps in the data (fig. 2 and 3) and how you treated them for calculating annual averages.

The gaps came from the technical problems during the drilling operations and the analysis process. The drilling problems are thoroughly described in (Mikhalenko et al., 2015). We used the values from the duplicate core obtained in 2004 for the gap between 31.3 and 32.1 m. In case of one sample missing we considered its isotopic value to be the average between the two neighbor samples. We will add this explanation to the paper.

There some gaps in the isotopic composition data that came from the technical problems during the drilling operations and the analysis process. The drilling problems are described in (Mikhalenko et al., 2015). We used the values from the duplicate core obtained in 2004 for the gap between 31.3 and 32.1 m. In case of one sample missing we considered its isotopic value to be the average between the two neighbor samples.

Table 4: Include number of points n or time period for correlation analysis when they are different for the different parameters as for temperature and precipitation.

Ok, we will do this

Table 2: Correlation coefficients between meteorological data and indices of large-scale modes of variability (statistically significant coefficients at p < 0.05 are highlighted in bold). The period of calculation for each coefficient is shown in brackets.

	SUMMER			WINTER		
	Temperature	P south*	P north*	Temperature	P south*	P north*
NAO	-0.47 (100)	0.23 (45)	-0.03 (45)	-0.41 (100)	0.04 (45)	0.26 (45)
AO	-0.11 (63)	0.08 (45)	-0.14 (45)	-0.40 (63)	0.14 (45)	0.37 (45)
AMO	0.24 (100)	0.01 (45)	-0.02 (45)	0.07 (100)	0.27 (45)	0.25 (45)
NCP	-0.50 (65)	0.34 (45)	0.18 (45)	-0.77 (65)	0.25 (45)	0.33 (45)

***P south – precipitation rate at the weather stations to the South from the Caucasus, P north – precipitation rate at the weather stations to the North from the Caucasus.**

Table 4. Correlation coefficients between ice core data, meteorological data and indices of large-scale modes of variability (statistically significant coefficients at p < 0.05 are highlighted in bold). The period of calculation for each coefficient is shown in brackets.

Summer	δ18O	Accumulation	*d*	NAO	AO	NCP
***T.* °C**	**0.13 (100)**	**0.09 (100)**	**0.21 (100)**	**–0.48 (100)**	**–0.10 (63)**	**–0.51 (65)**
P north	**0.07 (45)**	**0.24 (45)**	**0.11 (45)**	**–0.03 (45)**	**–0.14 (45)**	**0.18 (45)**
P south	**–0.12 (45)**	**0.44 (45)**	**–0.04 (45)**	**0.23 (45)**	**0.08 (45)**	**0.34 (45)**
δ18O		**–0.17 (100)**	**–0.11 (100)**	**0.06 (100)**	**0.23 (63)**	**–0.04 (65)**
Accumulation			**0.27 (100)**	**–0.25 (100)**	**0.05 (63)**	**0.07 (65)**
d				**–0.17 (100)**	**0.00 (63)**	**–0.18 (65)**
Winter	**δ18O**	**Accumulation**	***d***	**NAO**	**AO**	**NCP**
***T.* °C**	**–0.02 (100)**	**0.31 (100)**	**–0.08 (100)**	**–0.42 (100)**	**–0.45 (63)**	**–0.79 (65)**
P north	**0.25 (45)**	**0.13 (45)**	**–0.01 (45)**	**0.26 (45)**	**0.37 (45)**	**0.23 (45)**
P south	**–0.09 (45)**	**0.44 (45)**	**–0.06 (45)**	**0.04 (45)**	**0.14 (45)**	**0.25 (45)**
δ18O		**–0.05 (100)**	**–0.04 (100)**	**0.42 (100)**	**0.34 (63)**	**0.08 (65)**
Accumulation			**0.04 (100)**	**–0.34 (100)**	**–0.35 (63)**	**0.05 (65)**
d				**0.05 (100)**	**–0.09 (63)**	**0.04 (65)**

***P south – precipitation rate at the weather stations to the South from the Caucasus, P north – precipitation rate at the weather stations to the North from the Caucasus.**

Reviewer 2

Seasonal d18O data. The division of the data as shown in Fig 3 is largely unmotivated, except that there appears to be an annual cycle in the data. How is the distribution of seasonal accumulation? We don't know and it seems the authors have not investigated this. I suggest that a similar approach as Vinther et al. (2010) is made. I.e. investigating the proportion of the yearly accumulation to be assigned to either summer or winter depending on the coherency with meteorological observations, be it either temperature or circulation indecies. I think that before a properly motivated division of the seasons is made the effort of discussing the outcome of the analysis is not really relevant.

We will broaden the dating section as pointed before. See the answer to the reviewer 1.

In the introduction in general I miss a stronger representation of similar work done for Greenland although Greenland is mentioned. Many of the research questions are similar as well as the connection to atmospheric circulation patterns. See e.g. Vinther et al. 2003, Vinther et al. 2010 and Ortega et al. 2014.

We will add this to the introduction.

Connection of Greenland ice cores isotopic composition with the atmospheric circulation patterns was studied by Vinther et al. (2003 and 2010). The strong influence of the NAO pattern on the Greenland ice cores isotopic composition has been discovered and the possibility to use the ice cores data for the past NAO changes reconstruction was proved (Vinther et al., 2003). The authors also revealed the importance of the seasonally resolved ice cores records study rather than annual records as there are different factors governing formation of the isotopic composition of precipitation in warm and in cold seasons (Vinther et al., 2010).

L57-63 here a lot of detailed processes are mention, but there are no reference to literature. Why not refer to the early isotope work by Willi Dansgaard and e.g Persson et al. 2011 on intermittency of snowfall.

We will add these references to the paper.

Water stable isotope records are in mid to high latitudes physically related to condensation temperature through distillation processes (Dansgaard, 1964), but the climate signal is archived through the snowfall deposition and post-deposition processes. One important artefact lies in the intermittency of precipitation, and the covariance between condensation temperature and precipitation, which may bias the climate record towards one season, or towards one particular weather regime, challenging an interpretation in terms of annual mean temperature (Persson et al., 2011).

L169-176 I can't follow this section easily. I suppose the point you want to make is that you think diffusion has little influence on the isotope values. Did you calculate the variation of amplitude of the d18O annual cycle from top to bottom? It might "look" like there is no decease in amplitude, but what are the numbers? Another way to test if diffusion plays a role is the d-excess. Since the diffusivity of HDO and H2-18O is different there will be a phase change of d-excess with the diffusion often shifting the d-excess peak earlier in the year (depending on the annual cycle of the d-excess).

Yes, exactly, we think that the diffusion of stable isotopes does not influence the isotopic profile significantly at the part of the core that is discussed in the paper. We will add description of the calculation procedure to the section. Investigation of d-excess in this case will not add any information as the seasonal cycle of this parameter is not observed (Fig. 2).

2.1.5 Diffusion of stable isotopes

We calculated the potential influense of diffusion on the stable isotopes record according to (Johnsen, 2000) model. We used the following parameters for the calculation: Our calculation showed that the seasonal amplitude of $\delta^{18}O$ variations could be 10-20% less because of the diffusion (Mikhalenko et al., 2015). If it was the case we would observe a decreasing of $\delta^{18}O$ maxima and increasing of minima with depth. Moreover we would find a positive correlation between accumulation rate and seasonal amplitude of $\delta^{18}O$. These features have not been found in the ice core data. The correlation coefficient between seasonal amplitude and accumulation rate is -0.10 and is statistically insignificant. There is also no statistically significant trend in the seasonal amplitude; the seasonal amplitude varies stochastically from 10 to 25 ‰. The maximum value observed on 1984 and the minimum in 1925. We therefore consider that the diffusion does not influence sufficientely the isotopic composition record in the upper 126 m of the ice core. At the bottom part of the core (e.g. at a depth of 180 m) the annual cycle of $\delta^{18}O$ should have an amplitude of 4 ‰ which is detectable but the length of the cycle should be less then 1 cm. As the *d* annual cycle is not prominent we cannot used the method based on the discrepancy between the $\delta^{18}O$ and *d* cycles. Thus, for obtaining climatic information from the bottom part of the core very high sampling resolution is required.

Reviewer 3

1. If possible, it would be better to draw a dividing line in Fig.1 to separate the regions with and without a distinct seasonal variation of precipitation. This can help readers to understand some discussions in the paper.

Ok, we will add it

2. The dating is very important for the ice core study. In the section of dating, i.e. 2.1.4, authors used the mean value of the d18O of the whole dataset (-15.5 ‰ as a threshold to separate between the warm and cold seasons. This suggestion should be verified and/or confirmed by the data of d18O in precipitation at the GNIP stations around the ice core drilling site. Another way to test the effectiveness of the division of seasons in ice core is to discern if there is a consistency between the ratio of warm *season accumulation rate to cold season accumulation rate (in table 3) and that of precipitation at the adjacent meteorological stations (this method was used by Wang et al (2002, Annals of Glaciology, Vol.35, 273-277) in a Himalayan ice core). Authors also mentioned that the other parameters with seasonal variational characteristics, such as dust and ammonium concentrations, were used to identify the warm/cold season in the ice core profile. It would be better to display the variations of these parameters in the Fig. 3.*

The discussion of the dating methodology will be expanded. Also we will add the dust and ammonium concentration profiles to the fig. 3. See the answer to the reviewer 1.

3. Authors calculated the correlation between temperature and d18O in the Lines 329-332 of the text using the 11-year running means for the different periods, and found that the correlations changes with time. If possible, authors can do this by a sliding window method used by Wang et al. (2003, Geophysical Research Letters. Vol.30, No.22, doi: 10.1029/2003GL018188) in a Tibetan ice core. Another issue is that the data series used in the paper ended in 2013, why their 11-year running means also ended in 2013 (shown in Fig. 11)?

We will reconsider these calculations according to the reviewer's suggestions. We added the sliding window correlation graph to the fig.11. We would like to note that the periods for comparison on fog. 11 refer to the periods in the unsmoothed data. So it seems that the running means ended in 2013. Actually, the number of points is less than it would be if we used the full record.

(see fig. 11 for the correlation plot and regression equations as well as for the sliding window correlation plot). The 10-years sliding window correlation shows the same result, i.e. sharp changes of the correlation between these parameters with predominant negative correlation.

4. The significance test in the paper should be paid much attention, especially for the datasets of 11-year and 20-year running means. The degree of freedom can be reduced sharply for the running mean datasets. For example, as for the 11-year mean data sets over the period of 1994-2013, their degree of freedom is only 2 (20/11 is about 2).

We agree with the comment and will broaden the discussion of the statistical methods used for the calculations. In the example of the reviewer the degree of freedom (N – 2n – 2, where N is number of data points and n – smoothing period) are 35 – 22 – 2 = 11 for the period from 1914 to 1928 and from 1994 to 2013, and 65 – 22 – 2 = 41. In this case the correlations discussed in the paper are still statistically significant with $p<0.05$.

2.3 Statistical methods

For the correlation analysis we used Pearson correlation coefficient. Statistical significance was estimated with the Student significance test. When compared running means records we calculated the degrees of freedom as N – 2n – 2, where N is number of data points and n – smoothing period.

5. In the paragraph, Lines 343-346, authors should present the results of the seasonal cycle of precipitation isotopic composition calculated by using the LMDZiso model, and compare that with the ice core record in one chart.

Ok, we will add it

Calculation of the seasonal cycle of precipitation isotopic composition using the LMDZiso model (Risi et al., 2010) do not correspond to the results obtained from the ice core in absolute values or in amplitude (Fig. S5). This can be explained by a complicated relief of the region that influences strongly the isotopic composition, but it is not taken into account in the model. Also in summer Elbrus is in a local convective precipitation system that is not included in the model.

6. When discussing the variations of δ18O in precipitation in lines 362-365, the continental effect should be considered.

Ok, we will add the discussion of the continental recycling to the section

It is also the continental recycling of moisture (Eltahir and Bras, 1996) that influences the water isotopic composition. Due to this process the δ18O values became lower while *d* values increase (Aemisegger et al., 2014) which is observed in our ice core data.

7. In Tables 2 and 4, the period of calculation should be presented.

Ok, we will add it. See the answer to the reviewer 1.

8. Line 321, "in the Alps by (Bohleber et al., 2013)" should be "in the Alps by Bohleber et al. (2013)".

Ok, we will correct it

Another research performed in the Alps by Bohleber et al. (2013)

9. Line 327, "the methods described by (Bohleber et al., 2013)" should be "the methods described by Bohleber et al. (2013)".

Ok, we will correct it

the methods described by Bohleber et al. (2013) because of the relatively short and sparse original datasets.

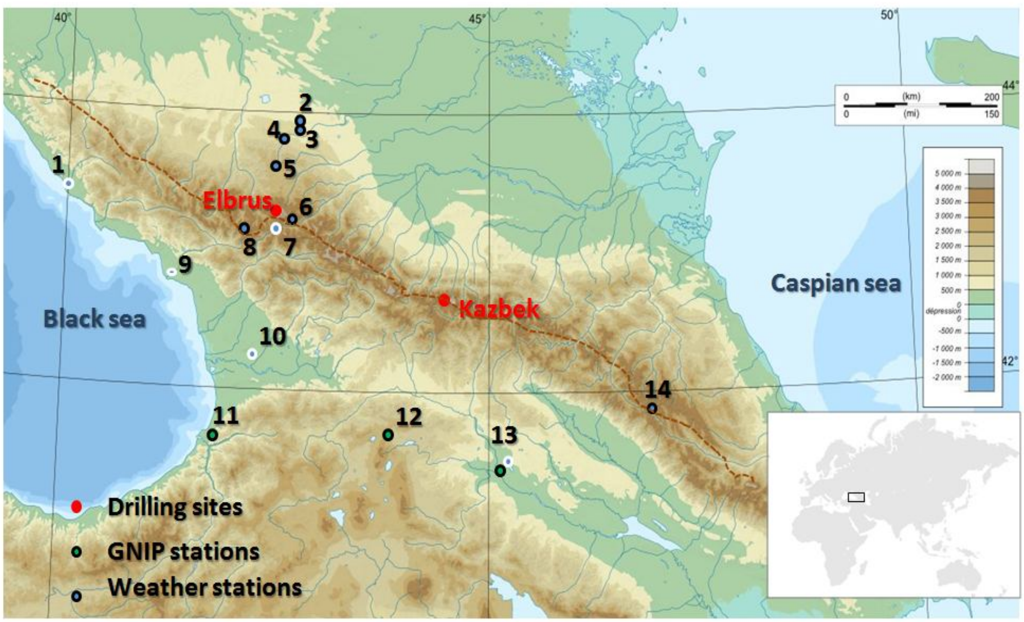


Fig. 1: Map showing the region around Elbrus (black rectangle in the world's map in the lower right corner), with shading indicating elevation (m above sea level). Drilling sites are indicated with red filled circles, GNIP stations as green filled circles, and meteorological stations as blue dots. Stations situated to the south of the Main Caucasus Ridge according to the precipitation cycle pattern are shown using a blue dot with white outside circle and the stations situated to the north are displayed with black outside circle (see text for the details). The brown dotted line

shows the border between two types of precipitation seasonal cycles. The number of the various stations refers to Table 1 for their detailed description.

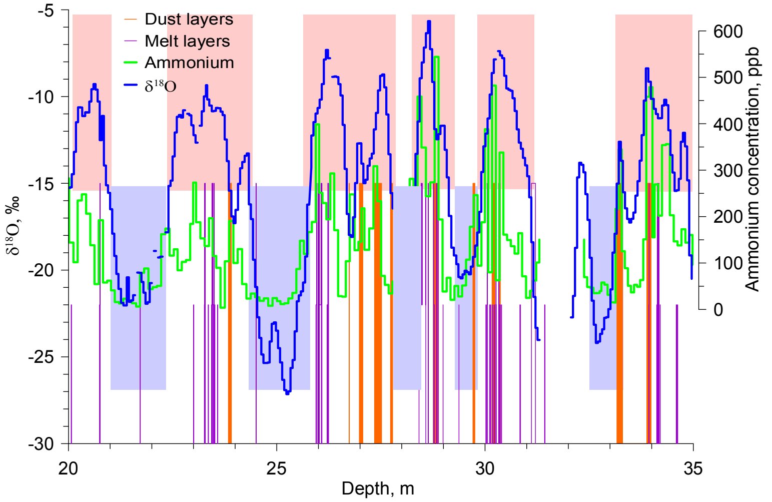
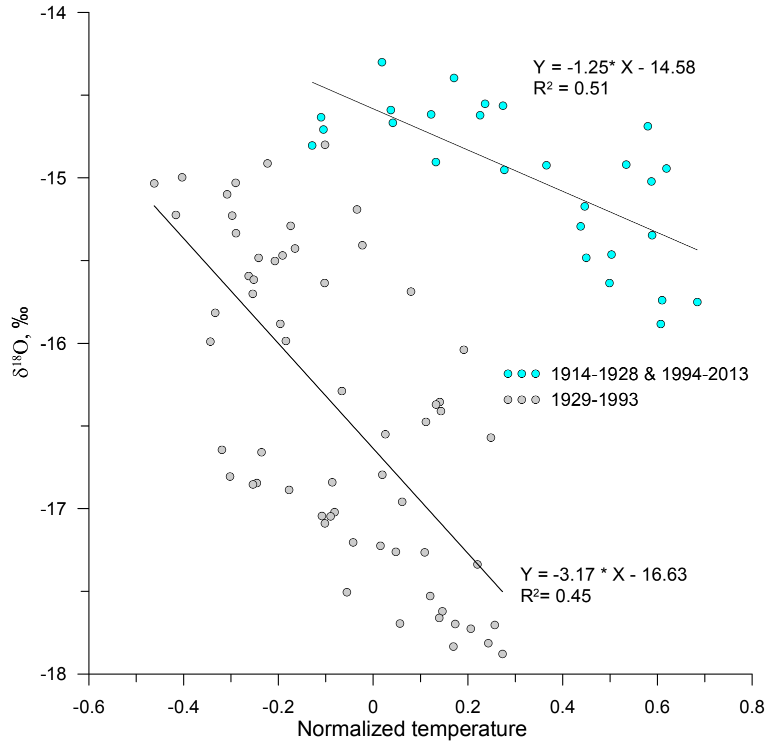


Fig. 3: Illustration of the scheme used to identify warm and cold half-years (respectively indicated by the light red and light blue shaded areas) based on the deviation of the mean $\delta^{18}O$ values from the long-term average value. The purple lines depict the melt layers observed in the core, dust layers are shown in orange and ammonium concentration graph (Mikhalenko et al., 2015) is in green.


Y = -1.25* X - 14.58
R² = 0.51
Y = -3.17 * X - 16.63
R²= 0.45
1914-1928 & 1994-2013
1929-1993
δ18O, ‰
Normalized temperature
-14
-15
-16
-17
-18
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8

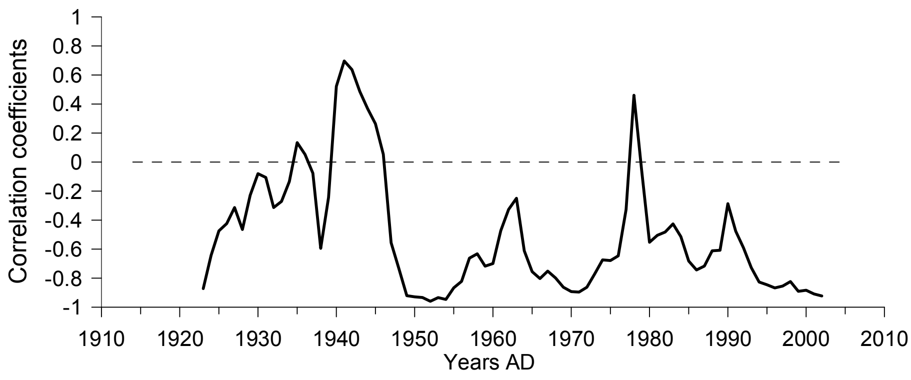

Correlation coefficients
Years AD
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Fig. 11. Correlation plot and regression lines for the 11-year running means of the annual local temperature and annual $\delta^{18}O$ (upper panel) and 10-years sliding window correlation coefficients of the same parameters .

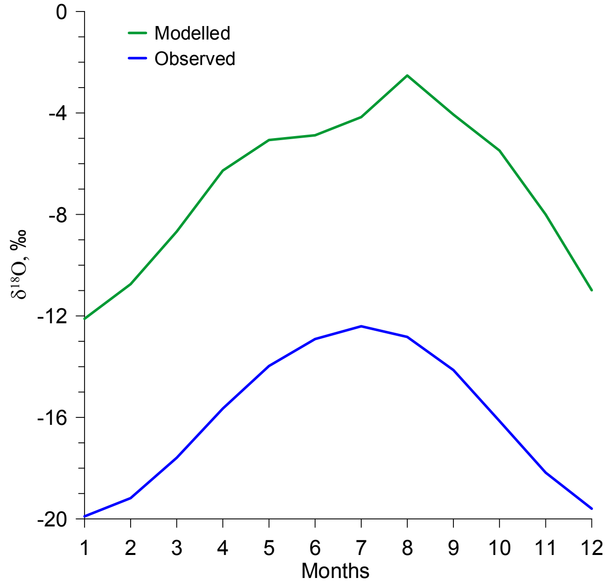


Fig. S5. Comparison of the precipitation isotopic composition seasonal cycle at the Elbrus Western Plateau: derived from the ice core data (blue line) and calculated in LMDZiso (Risi et al., 2010) model (green line).

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Large-scale drivers of Caucasus climate variability in meteorological records and Mt Elbrus ice cores

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Abstract

A 181.8 m ice core was recovered from a borehole drilled into bedrock on the western plateau of Mt. Elbrus (43°20'53.9'' N, 42◦25'36.0'' E; 5115 m a.s.l.) in the Caucasus, Russia, in 2009 (Mikhalenko et al., 2015). Here, we report on the results of the water stable isotope composition from this ice core in comparison with results from shallow ice cores. There is a distinct seasonal cycle of the isotopic composition which allowed dating by annual layer counting. Dating has been performed for the upper 126 m of the deep core combined with shallow cores data. The whole record covers one century from 2013 back to 1914. Due to the high accumulation rate (1380 mm w.e. per year) and limited melting we obtained the isotopic composition and accumulation rate records with seasonal resolution. These values were compared with available meteorological data from 13 weather stations in the region, and also with atmosphere circulation indices, back-trajectories calculations and GNIP data in order to decipher the drivers of accumulation and ice core isotopic composition in the Caucasus region. In the summer season the isotopic composition depends on the local temperature, while in winter, the atmospheric circulation is the predominant driver of the ice core isotopic composition. The snow accumulation rate correlates well with the precipitation rate in the region all year round, this made it possible to reconstruct and expand the precipitation record at the Caucasus highlands from 1914 till 1966 when the reliable meteorological observations of precipitation at high elevation began.

1 Introduction

Large scale modes of variability such as the NAO (North Atlantic Oscillation) and AMO (Atlantic Multidecadal Oscillation) are known to influence European climate variability (see review in Panagiotopulos et al., 2002). However, most studies of large-scale drivers of European climate change have been focused on low elevation instrumental records from weather stations, and there is very limited information about climate variability at high altitudes, and about differences in climate variability and trends at different elevations (EDW research group, 2015). Such differences were calculated in many mountain regions (EDW research group, 2015), except for the Caucasus, due to the lack of high elevation instrumental observations in this region.

The Caucasus is located southwards of the East European Plain. It is a high mountain region, with typical elevations of 3200-3500 m a.s.l., and with the highest point reaching 5642 m for Elbrus. The Main Caucasus Ridge acts as a barrier between subtropical and temperate mid-latitude climates, as observed for other high mountain regions such as the Himalaya. As in other mountain regions, there is a lack of high elevation meteorological records in the Caucasus. Moreover, existing records are relatively short: for example, reliable Caucasus precipitation measurements started only in 1966. An improved spatio-temporal coverage is required to investigate internal variability, to explore trends and spatial differences, and to evaluate the skills of atmospheric models providing atmospheric analysis products where no meteorological data are assimilated.

Measurements of the stable isotope composition of water, and annual accumulation rates in mid to high latitude ice cores are widely used proxies to estimate past temperature and precipitation rate changes. In many high mountain regions such as the Caucasus, and for elevations situated above the tree line, ice core data provides the only source of detailed information to document past climate changes, complementing punctual information retrieved from changes in glacier extent and recent glacier mass balance. For example study of the water stable isotope composition of several ice cores obtained in the Alps was recently conducted by Mariani et al. (2014) and the same research in Alaska was performed by Tsushima et al. (2015). The authors explored the links between the ice cores isotopic composition, local climate and large-scale circulation patterns. They found that in mountain regions isotopic composition of the ice cores governed both by the local meteorological conditions and by the regional and global factors. However, ice core records are complex. For instance, even in areas without any seasonal melt, accumulation is the net effect of precipitation, sublimation, and wind erosion processes, and may significantly differ from precipitation. Water stable isotope records are in mid to high latitudes physically related to condensation temperature through distillation processes (Dansgaard, 1964), but the climate signal is archived through the snowfall deposition and post-deposition processes. One important artefact lies in the intermittency of precipitation, and the covariance between condensation temperature and precipitation, which may bias the climate record towards one season, or towards one particular weather regime, challenging an interpretation in terms of annual mean temperature (Persson et al., 2011). ~~The water isotope content is more sensitive to distortion because of seasonality than the other ice core properties like aerosol concentration (Wagenbach et al., 2012).~~ Moreover, water stable isotopes are integrated tracers of all phase changes occurring from evaporation to mountain condensation, and are also affected by non-local processes related to evaporation characteristics, or shifts in initial moisture sources. Such processes have the potential to alter the validity of an interpretation of the proxy record in terms of local, annual mean, or precipitation-weighted temperature. In some region, isotopic records are more related to hydrological cycles, recycling, rainout (Aemisegger et al., 2014). Finally, the condensation temperature may also strongly differ from surface air temperature~~,~~; depending on elevation shifts in e.g. planetary boundary layer or convective activity (see Ekaykin and Lipenkov, 2009 for a review). While these processes make the interpretation of ice core records complex, they conversely open the possibility that the ice core proxy record may be in fact more sensitive to large-scale climate variability than punctual precipitation amounts. For instance, Casado et al (2014) have evidenced a strong fingerprint of the NAO in water stable isotope records from central ~~w~~Western Europe and Greenland, either in long instrumental records based on precipitation sampling, in seasonal ice core records, or in atmospheric models including water stable isotopes. Connection of Greenland ice cores isotopic composition with the atmospheric circulation patterns was studied by Vinther et al. (2003 and 2010). The strong influence of the NAO pattern on the Greenland ice cores isotopic composition has been discovered and the possibility to use the ice cores data for the past NAO changes reconstruction was proved (Vinther et al., 2003). The authors also revealed the importance of the seasonally resolved ice cores records study rather than annual records as there are different factors governing formation of the isotopic composition of precipitation in warm and in cold seasons (Vinther et al., 2010).

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We will now briefly review earlier studies performed on climate variability in the Caucasus area, and which have already explored the relationships between regional climate, glacier expansion, and large-scale modes of variability: the NAO (North Atlantic Oscillation), AO (Arctic Oscillation), AMO (Atlantic Meridional Oscillation) and NCP (North Sea – Caspian Pattern). For example, Shahgedanova et al. (2005) monitored the mass balance of the Djankuat glacier, situated at an altitude between 2700 and 3900 m a.s.l. While no significant correlation was identified between accumulation rate and the winter NAO index, the years of high accumulation systematically occurred during winters with a very negative NAO index. Brunetti et al. (2011) explored the influence of the NCP mode on climate in Europe and around the Mediterranean region. They evidenced a negative correlation coefficient of -0.50 between temperature in the Caucasus and the NCP index. Baldini et al. (2008) investigated records of precipitation isotopic composition in Europe from the IAEA/GNIP stations, extrapolating a significant negative correlation between winter precipitation $\delta^{18}O$ in the Caucasus region and the NAO index ($R = -0.50$). Casado et al (2013) studied the influence of precipitation intermittency on the relationships between precipitation $\delta^{18}O$, temperature, and the NAO. The influence of the NAO index on European climate and precipitation $\delta^{18}O$ appeared more prominent in winter than in summer (Comas-Bru et al., 2016).

Here, we take advantage of the new Elbrus deep ice cores (Mikhalenko et al., 2015), and produce the first analysis of water stable isotope and accumulation records. Section 2 introduces the data and methods, with a description of the ice core analyses and age scale, an overview of regional meteorological information, as well as the source of information for indices of modes of variability. Section 3 presents the results of the comparison and statistical analyses of the relationships between regional climate parameters (temperature and precipitation), Elbrus ice core records, and modes of variability. In section 4, we finally summarize our key findings and the next steps envisaged to strengthen the climatic interpretation of the Caucasus ice core records.

2 Data and methods

2.1 Ice core data

2.1.1 Drilling site and drilling campaigns

Here, we report on results from the new, deepest ice core from Mt Elbrus, in comparison with results from shallow ice cores. Deep drilling was performed on the Western Plateau (43°20'53.9" N, 42°25'36.0" E; 5115 m a.s.l.) of Mt Elbrus (fig. 1) in September 2009, allowing recovery of a 181.8 m long ice core, down to bedrock. The drilling site and the drilling operations are thoroughly described in Mikhalenko et al. (2015).

In order to update the ice core records towards the present-day, and enable a comparison of the measurements with local meteorological monitoring data, surface drilling operations were repeated at the same place in 2012 (11.5 m long) and in 2013 (20.5 m long). Results are also compared here with previously published isotopic composition data measured along the 22 m shallow ice core drilled at the same place in 2004 which covered the period from 1998 till 2004. (Mikhalenko et al, 2005).

In 2014, drilling operations were also successful at the Maili Plateau (Mt. Kazbek), at the altitude of 4500 m a.s.l. in 200 km eastwards from Elbrus (fig. 1), delivering a 20-m ice core. The Kazbek core is shown for the comparison only. Its detailed description will be published elsewhere.

2.1.2 Sampling process and sampling resolution

For the upper and the lower parts of the deep core (0-106 m and 158-181.8 m) and for the shallow firn cores drilled in 2012 and 2013, sampling was performed using classical cutting-melting procedures. For the other depth intervals, melted samples were extracted from the continuous flow analysis system of LGGE (Grenoble, France), automatically sub-sampled, frozen and stored in vials for subsequent isotopic analysis. The description of the CFA system will be published elsewhere.

The sampling resolution was 15 cm for the upper 16 m of the deep core (see the sketch of the sampling resolution in fig. 2c). It was then increased to 5 cm in order to achieve better resolution, from 16 to 70 m depth and in the bottom part of the core (158-182 m depth). To ensure 15-20 samples per year, the sampling resolution was increased to 4 cm in the depth range from 70 to 106 m, similar to the sampling resolution of the CFA system (3.7 cm).

Samples from the shallow cores drilled in 2012 and 2013 were cut with a resolution of 10 and 5 cm, respectively.

2.1.3 Isotopic measurements

The methods of the isotopic measurements have been partially discussed in (Mikhalenko et al., 2015). Water stable isotope ratios ($\delta^{18}O$ and δD) were measured at the Climate and Environmental Research Laboratory (CERL) of Arctic and Antarctic research Institute (St Petersburg, Russia), using a Picarro L2120-i analyzer. Each sample was measured once. Sequences of measurements included the injection of 5 samples, followed by the injection of an internal laboratory standard with an isotopic value close to that of the samples. We also repeated the measurements of about 10% of all the samples in order to calculate the analytical precision: 0.06‰ for $\delta^{18}O$ and 0.30‰ for δD. The depth profile of $\delta^{18}O$ (Mikhalenko et al., 2015; Kozachek et al., 2015) and of the deuterium excess ($d = \delta D - 8*\delta^{18}O$) are shown in fig. 2.

Moreover, 600 samples from the depth interval from 23 to 35 m were measured in the Laboratory of Isotope Hydrology of the IAEA (Vienna, Austria). The two records are highly correlated ($r=0.99$, $p < 0.05$) for both isotopes (Figure S2b) with a systematic offset of 0.2 ‰ for $\delta^{18}O$ and 1 ‰ for δD. The records of the second order parameter deuterium excess are also significantly correlated ($r=0.65$, $p < 0.05$) without any specific trend or systematic offset. This inter-laboratory comparison demonstrates the high quality of the isotopic measurements performed in CERL.

We also stress the close overlap of the upper part of the profiles of the water stable isotope records versus depth from the different cores drilled in 2009, 2012 and 2013 (Fig. S2a). Based on this close agreement within the different shallow firn cores, we decided to calculate a stack record for the period from 1914 till 2013 which is used hereafter for the dating.

In the depth interval from 100 to 106 m depth, we also have an overlap of samples obtained with classical cutting method and CFA method described above, without any significant difference (Fig. S2c), again allowing us to combine the two records into one stack record.

2.1.4 Dating

The chronology is based on the identification of annual layers. These are prominent in $\delta^{18}O$ with the average seasonal amplitude of 20 ‰. As there is no trend in the $\delta^{18}O$ record. ~~W~~we used the mean value of the $\delta^{18}O$ of the whole dataset (-15.5 ‰) as a threshold to separate between the warm and cold seasons. For equivocal situations, we also used additional data: melt layers and dust layers (used to identify the warm season) (Kutuzov et al., 2013) as well as ammonium and succinic acid concentration data that also have seasonal variations (Mikhalenko et al., 2015). Layers with the high dust concentration have been precisely dated by Kutuzov et al. (2013) for the 2012 ice core. Their results show that the separation of the core into a warm and cold season part using the average value of $\delta^{18}O$ is appropriate for this drilling site at least for the period from 2009 till 2012 that was investigated by Kutuzov et al. (2013). We compared annual layers counting performed independently using the seasonal cycles in the isotopic composition and the ammonium concentration. The discrepancy between two independent chronologies is ~~±1~~2 years at a depth of 126 m. We used the dating based on the isotopic composition data in this paper. This dating is also best fit for the correlation analysis with the meteorological data. Hereafter, we focus our analysis on one century, from 1914 till 2013, which corresponds to the upper 126 m of the core. This period has been chosen because of relatively small dating uncertainty ~~(±1 year)~~ and the availability of other records such as local meteorological observations. At the bottom part of the core the isotopic composition cycles are less prominent and cannot be used for dating, consequently the dating uncertainty is sufficiently higher. The isotopic composition of that part of the core will be discussed elsewhere. Figure 3 illustrates the identification of years using the isotopic composition seasonal cycle.

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There some gaps in the isotopic composition data that came from the technical problems during the drilling operations and the analysis process. The drilling problems are described in (Mikhalenko et al., 2015). We used the values from the duplicate core obtained in 2004 for the gap between 31.3 and 32.1 m. In case of one sample missing we considered its isotopic value to be the average between the two neighbor samples. ~~-~~For a detailed description of the raw isotopic data and annual layers allocation for the upper 106 m of the core, please refer to Mikhalenko et al. (2015). Mean seasonal values of $\delta^{18}O$ and *d* obtained as a result of the dating are shown in fig. 5 and 6 respectively.

The annual accumulation rate is calculated as the thickness of the seasonal layer, multiplied by the layer density using the density profile from Mikhalenko et al. (2015), and corrected for layer thinning using the Dansgaard-Johnsen model (Dansgaard and Johnsen, 1969), with the following parameters: accumulation rate 1.583 m of ice equivalent, pore close-off depth = 55 m (Mikhalenko et al., 2015).

2.1.5 Diffusion of stable isotopes

We calculated the potential influense of diffusion on the stable isotopes record according to (Johnsen, 2000) model. We used the following parameters for the calculation: Our calculation showed that the seasonal amplitude of $\delta^{18}O$ variations could be 10-20% less because of the diffusion (Mikhalenko et al., 2015). If it was the case we would observe a decreasing of $\delta^{18}O$ maxima and increasing of minima with depth. Moreover we would find a positive correlation between accumulation rate and seasonal amplitude of $\delta^{18}O$. These features have not been found in the ice core data. The correlation coefficient between seasonal amplitude and accumulation rate is -0.10 and is statistically insignificant. There is also no statistically significant trend in the seasonal amplitude; the seasonal amplitude varies stochastically from 10 to 25 ‰. The maximum value observed on 1984 and the minimum in 1925. We therefore ~~concider~~consider that the diffusion does not influence sufficientely the isotopic composition record in the upper 126 m of the ice core. At the bottom part of the core (e.g. at a depth of 180 m) the annual cycle of $\delta^{18}O$ should have an amplitude of 4 ‰ which is detectable but the length of the cycle should be less then 1 cm. As the *d* annual cycle is not prominent we cannot used the method based on the discrepancy between the $\delta^{18}O$ and *d* cycles. Thus, for obtaining climatic information from the bottom part of the core very high sampling resolution is required.

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2.2 Meteorological data

We used the daily meteorological data (precipitation rate and mean daily temperature) from several weather stations around the drilling site (see map in Fig. 1 and Table 1) for comparison with the ice core data. We also investigated records of precipitation isotopic composition based on monthly sampling, performed at three stations to the south of Caucasus within the WMO-IAEA Global Network of Isotopes in Precipitation (GNIP) program (Table 1).

For comparison we used the NCEP/NCAR reanalysis temperature data (Kalnay et al., 1996) for the 500 mbar level which corresponds to the drilling site altitude. Two different models were used to calculate back trajectories: FLEXPART (Forster et al., 2007, Stohl et al., 2009), HYSPLIT (Draxler, 1999, Stein et al., 2015, Rolph, 2016). The LMDZiso model was used to estimate the precipitation isotopic composition at the drilling site (Risi et al., 2010).

2.3 Statistical methods

For the correlation analysis we used Pearson correlation coefficient. Statistical significance was estimated with the Student significance test. When compared running means records we calculated the degrees of freedom as N – 2n – 2, where N is number of data points and n – smoothing period.

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3 Results

3.1 Regional climate

The main peculiarity of the drilling site is its location on the border between subtropical and temperate climatic zones (Volodicheva, 2004). Back-trajectory calculations show that the drilling site is characterized by remarkable seasonal differences in moisture sources locations. In winter, the origin of air masses varies from the Mediterranean to the North Atlantic. In summer, local moisture sources from the surrounding continents or from the Black Sea are predominant (see fig. S1 for examples).

Meteorological data depict large regional variations in the seasonal cycle of precipitation. To the south of the Caucasus, there is no distinct seasonal cycle (Fig. 4a), showing the climatology for the Klukhorsky Pereval station. In fact, the Klukhorsky Pereval station is situated north of the Main ridge, but in terms of the seasonal cycle of precipitation it undoubtedly belongs to the southern group. But we are nevertheless using this station as an example because of the uninterrupted record of temperature and precipitation for the 1966-1990 period. By contrast, the north of the Caucasus is marked by a distinct seasonality in precipitation amounts, which are maximum in summer and minimum in winter (Fig. 4b), showing the climatology for the Mineralnye Vody station. Moreover, the annual precipitation rate to the south of the Caucasus is much higher than to the north. For example, the typical annual precipitation rate to the north of the Caucasus at the altitude close to the sea level is 500 mm per year, while to the south of the Caucasus at the same altitude it is about 1500 mm. The amount of precipitation in the region is affected by the altitude and the distance from the sea shore.

The seasonal changes of temperature appear uniform all over the region surrounding Caucasus, with warmest conditions observed in summer and coldest conditions observed in winter. The seasonal amplitude depends on the distance from the sea and the mean annual temperature depends on the altitude. The average regional lapse rate was calculated using the available meteorological data. It is minimum in winter (2.3°C per 1000 m) and maximum (5.2 °C per 1000 m) in summer (Fig. S3).

Based on the coherency of temperature variability at all the weather stations in this region, we calculated a regional stack temperature record. Normalized temperature time series were calculated for each station for each season or for the whole year, and results were then averaged (see Fig. 8a and 8b for seasonal stack records). For precipitation data, available in this region since 1966, we considered two different stacks (fig. S4), separating the stations with a distinct seasonal cycle from those where no seasonal cycle was identified for precipitation rates. We coherently used the reference period from 1966 to 1990 for normalization for both precipitation rate and temperature.

At our drilling site, an automatic weather station (AWS) provided in situ measurements for the period from August 2007 till January 2008. The day to day variations of temperature at low elevation weather stations and at the AWS are coherent for the whole period of the AWS work (Mikhalenko et al., 2015).

We also compared the data from meteorological stations with the NCEP reanalysis (Kalnay et al., 1996) outputs (not shown) for the 500 mbar level. Despite difference in absolute values on the daily scale when compared with the AWS data (the difference is random and varies from -1 to 1 °C), the observed regional data and reanalysis data have the same month to month variability. The maximum daily mean temperature at the drilling site according to the reanalysis data was -1.3 °C for the whole dataset. The temperature in the glacier at 10m depth, which correspond to the annual mean temperature at the drilling altitude, is -17 °C (Mikhalenko et al., 2015), the annual mean temperature at the drilling altitude from the NCEP reanalysis is -14 °C, and the same value calculated from meteorological observations and corrected for the lapse rate is -11 °C.

Hereafter in the meteorological data, we considered the cold season or winter of a given year to range from November of the previous year till April of the current year, and the warm season or summer from May till October.

We then investigated long-term trends in the composite meteorological records. It is evident that last 20 years in summer season were the warmest for the whole observation period (fig. 8), while in winter the recent warming is not unprecedented. For example, winters in the 1960s – 1970s were even warmer (fig. 8). Multi-decadal patterns of temperature variations also differ in the late 19^{th} Century, where negative anomalies are identified in winter temperature (Fig. 8) but not in summer temperature (Fig 8). On the other hand in winter temperatures we can observe lower temperatures at the end of 19^{th} century that can be impact of the volcanic eruptions (Stoffel et al., 2015). We also noted the high temperature values in the 1910s - 1920s that is not completely understood. We did not find any trends in the precipitation rate for neither of the groups of stations (fig. S4).

A significant anti-correlation is observed between temperature and the NAO index, both in winter and summer (Table 2, the information about the time series used for the correlation analysis can be found in Table 1). Stronger anti-correlations are identified between temperature and the NCP index, especially in winter, as also reported by Brunetti et al. (2011). A weak positive correlation is identified between AMO and summer temperature. Relationships with indices of large scale modes of variability are systematically weaker for precipitation, with contradictory results for the south\north Caucasus stack; they appear significant for the NCP in summer and winter (Table 2).

GNIP data are only available at low elevation stations. They show a rather uniform distribution of the isotopic composition of precipitation in the region during summer, as well as a gradual depletion of $\delta^{18}O$ at higher altitudes in winter.

GNIP records are too short and intermittent (one-two years with gaps) to investigate the variability and relationships with the local temperature on interannual scale. We therefore restrict discussion of GNIP data to seasonal variations. The $\delta^{18}O$ and δD

in precipitation have a distinct seasonal cycle with maximum values observed in warm season (JJA) and minimum values observed in cold season (DJF). As an example we show the seasonal cycle of $\delta^{18}O$ and *d* for Bakuriani station in 2009 (fig. 7). This station is the only one in the region for which the whole uninterrupted dataset for one annual cycle is available. The seasonal amplitude of $\delta^{18}O$ is about 10 ‰. The *d* variations show no seasonal cycle varying randomly between 10 ‰ and 25 ‰. We found no significant correlation between $\delta^{18}O$ and *d*.

Climate variability as a driver for glacier variations in the Caucasus has recently been explored by several authors. Elizbarashvili et al. (2013) found the increased frequency of extremely hot months during the 20th century, especially over Eastern Georgia, whereas number of extremely cold months decreased faster in the Eastern than in the Western region. In addition, highest rates for positive trends of annual mean air temperature can be observed in the Caucasus Mountains. Shahgedanova et al. (2014) evidenced significant glacier recession at the northern slopes of the Caucasus, consistent with increasing air temperature of the ablation season. They report that the most recent decade (2001-2010) was 0.7 – 0.8 °C warmer than in 1960-1986 at Terskol and Klukhorskiy Pereval stations (see Table 1 for information on stations). However, the warmest decade for JJA was 1951-1960 (Shahgedanova et al., 2014). Tielidze (2016) reports recent increase of the annual mean temperatures at different elevations in the Georgian Caucasus. The region experienced glacier area loss over the 20th century at an average annual rate of 0.4% with a higher rate in eastern Caucasus than in the central and western sections. The analysis of temperature and radiation regime of glaciers at the ablation period has been performed at Elbrus vicinities recently (Toropov et al., 2016). The authors prove that the observed waning of glaciers can not be explaned by increase of temperature during the ablation period because of increase of precipitation during the accumulation period. They concluded that the main driver of glacier retreat if increase of the solar radiation balance for 4% for the 2001-2010 period which corresponds to increase of ablation for 140 mm per ablation season (Toropov et al., 2016).

3.2 Ice core records

The comparison of the four cores obtained at the Western Plateau of Elbrus shows similar variations during overlap periods (see Fig. 2S). We therefore calculate a stack record for each season, based on the average value of individual ice cores for the overlapping seasons. The inter-core disagreement is almost negligible (fig. 2S) and can be explained by different sampling resolution.

We note that the shallow ice core from the Maili plateau of Kazbek shows the same mean values of $\delta^{18}O$ as the Elbrus ice cores during their overlap period. This is a surprise, given the difference in elevation (500 m) and continentality (200 km distance).

The inter-annual variability in isotopic composition is about twice larger in winter than in summer for $\delta^{18}O$. Different patterns of inter-annual to multi-decadal variations appear in the instrumental temperature data (see section 3.1) and ice core $\delta^{18}O$ records (Fig 5) emerge for winter versus summer. Consequently, we do not investigate annual mean results, and focus on each season.

The δD and $\delta^{18}O$ values are highly correlated (r = 0.99) on sample to sample scale so hereafter we use the $\delta^{18}O$ information for the dating and comparison with the other parameters. The slope between $\delta^{18}O$ and δD is 8.03 on sample to sample scale and 7.9 on seasonal scale without any significant difference between the two seasons.
No significant (R squared is insignificant at $p<0.05$) centennial trend is identified in winter / summer $\delta^{18}O$, nor in winter / summer accumulation rate or deuterium excess. We observe large variations in $\delta^{18}O$ with high and variable values early 20th century, lower and more stable values in the 1940s-1960s, and a step increase in the 1970s with another level. These variations are coherent in both seasons but are not reflected in the meteorological observations. There is also an increase of $\delta^{18}O$ in the last two decades in both seasons in regard to the 1970s-1980s values but the absolute values of $\delta^{18}O$ are close to the multiannual seasonal averages (Table 3). The highest decadal values of $\delta^{18}O$ in both summer and winter are observed in 1912-1920. While a recent warming trend is observed in the regional meteorological data (in summer), it is much less prominent in the ice core $\delta^{18}O$ record, suggesting a divergence between $\delta^{18}O$ and regional temperature. One of the possible explanations for this feature is the post-depositional change of the isotopic composition. But we do not expect a significant influence of the post-depositional processes because of high snow accumulation rate. The highest $\delta^{18}O$ values for a single year correspond to the summer periods of 1984 and 1928, two years for which no unusual feature is identified from meteorological observations. The highest snow accumulation rate (fig. 9) is observed in both seasons of 2010, in coherence with the meteorological precipitation data, and also corresponding with a record low winter NAO index.
Our deuterium excess record (fig. 2b) does not depict any robust seasonal variation. Moreover, the distribution of deuterium excess as a function of $\delta^{18}O$ does not display any clear structure. By contrast, deuterium excess is weakly positively correlated with the accumulation rate during summer (r = 0.27, $p<0.05$). This finding is consistent with the GNIP data in the region that show no link between $\delta^{18}O$ and deuterium excess. The smoothed values of deuterium excess have prominent cycles with a period of about 25 years that are synchronous in both seasons (fig. 6). Deuterium excess is highly sensitive to surface humidity, which itself is very different and depends on the arrival of maritime air masses or dry continental air masses. This may add to the complexity of the deuterium excess signal (Pfahl and Wernli, 2008).

3.3 Comparison of ice core records with regional meteorological data

We compared the ice core data with the regional meteorological data and the large scale modes of variability. The result of the correlation analysis is summarized in Table 4. Multiannual variations of the parameters are shown in fig. 9 for the winter period and in fig. 10 for the summer period.
We found no significant correlation between the ice core $\delta^{18}O$ record and regional temperature, neither with the reanalysis data, nor with the observation data, when using the whole period. A significant correlation (r = 0.52, $p<0.05$) emerges for summer data, when calculated for the period since 1984. The slope for this period is 0.25 per mille per °C. We also repeated our linear correlation analysis using precipitation weighted temperature, and obtained the same results. We didn't find any statistically significant correlations when compared 3-, 5-, 7-years running means of these parameters. This result implies

that the isotopic composition at Elbrus is controlled by both local and regional factors such as changes in moisture sources. The possibilities for accurate reconstructions of past temperatures are therefore limited. For more accurate investigation of the $\delta^{18}O$ – temperature relation on-site experiments and subsequent modelling is required. Our results are comparable to those obtained in the Alps by Mariani et al. (2014): again, while the seasonal cycle of ice core $\delta^{18}O$ appears related to that of temperature, this is not the case for inter-annual variations, driven by other factors such as changes in moisture sources. Another research performed in the Alps by ~~(~~Bohleber et al.~~,~~ (2013) revealed significant correlation of modified local temperature and the ice core isotopic composition at decadal scale. The authors also report that there are some periods of correlation absence. The main finding is that for the periods of less than 25 years the difference between the modified according to the authors' method and original dataset temperature is crucial but for longer periods the two temperature datasets are close to each other. That conclusion implies that the isotopic composition reflects the local temperature in the high mountain regions to a limited extent. It seems to be impossible to calculate the modified temperature for the Caucasus region according to the methods described by ~~(~~Bohleber et al.~~,~~ (2013) because of the relatively short and sparse original datasets.

We also compared the annual mean temperatures and $\delta^{18}O$ values disregarding the difference in the isotopic composition trends in different seasons. The regression analysis showed significant negative correlation between the two parameters. The regression equation for 11-year running means in the 1914-1928 and 1994-2013 differs from the same for the 1929-1993 (see fig. 11 for the correlation plot and regression equations as well as for the sliding window correlation plot). The 10-years sliding window correlation shows the same result, i.e. sharp changes of the correlation between these parameters with predominant negative correlation. The shifts can be explained by a sharp change of the climatic system. The negative correlation between $\delta^{18}O$ and local temperature has already been observed in Antarctica (Vladimirova and Ekaykin, 2014). It can be explained by the change of the moisture source that can lead to increase of the difference between the source temperature and local temperature while local temperature slightly decreases.

Seasonal accumulation rate is linked to the precipitation rate on the stations situated south of the Caucasus in both seasons ($r = 0.45$), and even more closely related to precipitation from Klukhorski Pereval station ($r = 0.65$ for both seasons). We therefore establish a linear regression model for the period 1966-2013, and use this methodology to reconstruct past precipitation rates (1914-1965), when meteorological records are not reliable or not available. The reconstructed records are shown on fig. 9 and 10 for the winter and summer seasons respectively. We found no significant trend in the reconstructed precipitation values. Even so, these results can be useful for validation of regional climate models and water resource assesment.

Calculation of the seasonal cycle of precipitation isotopic composition using the LMDZiso model (Risi et al., 2010) do not correspond to the results obtained from the ice core in absolute values or in amplitude (Fig. S5). This can be explained by a complicated relief of the region that influences strongly the isotopic composition, but it is not taken into account in the model. Also in summer Elbrus is in a local convective precipitation system that is not included in the model.

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3.4 Comparison of ice core records with large scale modes of variability

We report a significant ($p<0.05$) negative correlation (r = - 0.33) between the ice core accumulation rate record and NAO in winter. Moreover, the year of extremely high accumulation in both seasons (2010) coincides with an extremely low NAO winter index. The role of NAO in regional climate had also been evidenced by Shahgedanova et al. (2005) for the mass-balance of the Djankuat glacier situated in 30 km south-east of Elbrus for the period of 1967-2001. Interestingly, the accumulation record is related to the variability of regional precipitation, but the latter is not significantly related to the NAO. This may suggest different influences of large-scale atmospheric circulation on precipitation at lower versus higher elevations.

The ice core winter $\delta^{18}O$ record shows a positive correlation with the NAO index (r = 0.42), while the NAO index is negatively correlated with regional temperature (r = - 0.42). It also contradicts the findings of Baldini et al (2008) who, based on the GNIP low elevation dataset, extrapolated a negative correlation between the $\delta^{18}O$ of precipitation and the NAO in this region. This finding also suggests different drivers of temperature and $\delta^{18}O$ at low and higher elevation. We propose the following explanation for this correlation. During the positive NAO phase, the predominant moisture source for the Caucasus precipitation is the Mediterranean. During the negative NAO phase the moisture sourse is the Atlantic. In the first case the precipitation $\delta^{18}O$ preserved in the ice core is higher because of higher initial sea water isotopic composition (Gat et al., 1996) and shorter distillation pathway. It is also the continental recycling of moisture (Eltahir and Bras, 1996) that influences the water isotopic composition. Due to this process the δ18O values became lower while *d* values increase (Aemisegger et al., 2014) which is observed in our ice core data. In the opposite situation the initial water isotopic composition is close to 0 ‰ (Frew et al., 2000) and the distillation pathway is longer which leads to lower values of precipitation $\delta^{18}O$.

In order to explore the relationships of the Elbrus ice core datasets with the AMO, we used 20-year smoothed data. We show a negative correlation between the AMO index and the summer ice core $\delta^{18}O$ signal (r = - 0.53) and a positive correlation between the AMO index and the winter accumulation record (r = 0.52). As the correlation analysis between the ice core data and AMO index was performed with smoothed records it is not reported in Table 4, in order to avoid misunderstanding.

We explored the links between the ice core parameters ($\delta^{18}O$, accumulation rate) with the NCP index and found no significant correlation neither in winter nor in summer despite the significant correlation between the NCP and local temperature and precipitation. A possible explanation may be that the NCP pattern only affects low elevation regional climate but not high elevation climate.

No significant correlation was identified between deuterium excess and indices of large scale modes of variability. So far, no regional or large-scale climate signal could be identified in Elbrus deuterium excess. Further investigations using backtrajectories and diagnoses of moisture source and evaporation characteristics will be needed to explore further the drivers of this second-order isotopic parameter.

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4 Conclusion

We found no persistent link between ice cores $\delta^{18}O$ and temperature, common feature emerging from non-polar ice cores (e.g. Mariani et al., 2014). This finding is not an artifact of high elevation versus low elevation difference because the variability of the regional temperature stack used for this comparison is in good agreement with the variability of the temperature at the drilling site as observed by the local AWS.

Our ice core records depict large decadal variations in $\delta^{18}O$ with high and variable values in the late 19th - early 20th centuries, lower and more stable values in the 1940s-1960s, followed by a step increase in the 1970s. No unusual recent change is detected in the isotopic composition or in the accumulation rate record, in contrast with the observed warming trend from regional meteorological data. The accumulation rate appears significantly related to the NAO index coherently with the earlier results for the Djankuat glacier (Shahgedanova et al. 2005).

Based on regional meteorological information and trajectory analyses, the main moisture source is situated not far from the drilling site in summer, and consists of evaporation from the Black Sea and continental evapotranspiration. Changes in regional temperature during summer may affect the initial vapour isotopic composition as well as the atmospheric distillation processes, including convective activity, in a complex way. This may explain the significant albeit non persistent correlation of summer $\delta^{18}O$ and temperature. Winter moisture sources appear more variable geographically, with potential contributions from the North Atlantic to the Mediterranean regions. Changes in moisture origin appear to dominate in regional temperature-driven distillation processes. As a result, the ice core isotopic composition appears mostly related to characteristics of large –scale atmosphere circulation such as the NAO index. The changes in moisture origin also influence deuterium excess parameter, which does not have any prominent seasonal variations.

Our data can be used in atmospheric models equipped with water stable isotopes for instance in order to assess their ability to resolve NAO – water isotope relationships (Langebroek et al., 2011, Casado et al., 2014). The accumulation rate at the drilling site is highly correlated with the precipitation rate and gives information about precipitation variability before the beginning of meteorological observations.

Acknowledgements

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References

Aemisegger F., Pfahl S., Sodemann H., Lehner I., Seneviratne S.I., Wernli H.: Deuterium excess as a proxy for continental moisture recycling and plant transpiration, Atmos. Chem. Phys, 14, 4029–4054, doi:10.5194/acp-14-4029-2014, 2014.

Baldini L.M., McDermott F., Foley A.M., Baldini J.U.L.: Spatial variability in the European winter precipitation δ18O-NAO relationship: Implications for reconstructing NAO-mode climate variability in the Holocene, Geophys. Res. Letters. 35, doi:10.1029/2007GL032027, L04709, 2008.

Bohleber P., Wagenbach D., Schoner W., Bohm R.: To what extent do water isotope record from low accumulation Alpine ice cores reproduce instrumental temperature series? Tellus B, 65, 20148, doi:10.3402/tellusb.v65i0.20148, 2013.

Brunetti M., Kutiel H.: The relevance of the North-Sea Caspian Pattern (NCP) in explaining temperature variability in Europe and the Mediterranean, Nat. Hazards Earth Syst. Sci., 11, 2881–2888, doi:10.5194/nhess-11-2881-2011, 2011.

Casado M, Ortega P., Masson-Delmotte V., Risi C., Swingedouw D., Daux V., Genty D., Maignan F., Solomina O., Vinter B., Viovy N., Yiou P.: Impact of precipitation intermittency on NAO-temperature records, Clim. Past, 9, 871-886, doi:10.5194/cp-9-871-2013, 2013.

Comas-Bru, L., McDermott, F. and Werner, M. (2016): The effect of the East Atlantic pattern on the precipitation δ18O-NAO relationship in Europe, Climate Dynamics, doi: 10.1007/s00382-015-2950-1

Dansgaard, W.:, Stable isotopes in precipitation, Tellus, 16(4), 436–468, 1964

Отформатировано: Шрифт: (по умолчанию) Times New Roman, 10 пт, Английский (США)

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.

Draxler, R.R., and Hess G.D.: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. Aust. Meteor. Mag., 47, 295-308, 1998.

Ekaykin A.A., Lipenkov V.Ya.: Formation of the ice core isotopic composition, Physics of ice core records II, ed. T.Hondoh, Low Temperature Science, 68, Hokkaido Univ. Press, Sapporo, 299-314, 2009.

Elizbarashvili E.Sh., Elizbarashvili, M.R., Tatishvili, M.E.. Elizbarashvili, Sh.E., Elizbarashvili, R.Sh.: Meskhiya Air temperature trends in Georgia under global warming conditions, Russ. Meteorol. Hydrol., 38, 234–238, 2013.

Eltahir E.A.B., Bras R.L.: Precipitation recycling, Reviews of Geophysics 34, 3, 367-378, doi: 8755-12 09/96/96 RG-01927, 1996

Отформатировано: Английский (США)

Отформатировано: Английский (США)

Forster C., Stohl A., Siebert P.: Parametrization of convective transport in a lagrangian particle dispersion model and its evaluation, Journ. of Applied Meteorology and Climatology, 46 (4), 403–422, doi:10.1175/JAM2470.1, 2007.

Frew, R., Dennis, P.F., Heywood K.J., Meredith M.P., and Boswell S.M.: The oxygen isotope composition of water masses in the northern North Atlantic, Deep Sea Research Part I: Oceanographic Research Papers, 47, 12, 2265-2286, doi:10.1016/S0967-0637(00)00023-6, 2000.

Gat, J.R., Shemesh, A., Tziperman, E., Hecht, A., Georgopoulos, D., and Basturk, O.: The stable isotope composition of waters of the eastern M<editerranean Sea, J. Geophysical Res., 101, 3, 6441-6451, doi: 10.1029/95JC02829, 1996.

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

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B.,Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D.: The NCEP/NCAR 40-Year Reanalysis Project, Bulletin of the American Meteorological Society, 77, 3, 437-472, doi: 10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Kozachek A.V., Ekaykin A.A., Mikhalenko V.N., Lipenkov V.Y., Kutuzov S.S.: Isotopic composition of ice cores obtained at the Elbrus Western Plateau, Ice and Snow, 55, 4, doi: 10.15356/2076-6734-2015-4-35-49, 35-49, 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.

Langebroek, P. M.; Werner, M.; Lohmann, G.: Climate information imprinted in oxygen-isotopic composition of precipitation in Europe, Earth and Planetary Science Letters, 311, 1, 144-154, 10.1016/j.epsl.2011.08.049, 2011.

Mariani I., Eichler A., Jenk M., Brönnimann S., Auchmann R., Leuenberger M.C., Schwikowski M.: Temperature and precipitation signal in two Alpine ice cores over the period 1961–2001, Clim. Past. 10, 1093–1108, doi:10.5194/cp-10-1093-2014, 2014.

Mikhalenko V., Sokratov S., Kutuzov S., Ginot P., Legrand M., Preunkert S., Lavrentiev I., Kozachek A., Ekaykin A., Faïn X., Lim S., Schotterer U., Lipenkov V., Toropov P.: Investigation of a deep ice core from the Elbrus western plateau, the Caucasus, Russia, The Cryosphere, 9, 2253-2270, doi:10.5194/tc-9-2253-2015, 2015.

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)

Mountain Research Initiative EDW Working Group: Elevation-dependent warming in mountain regions of the world, Nature Climate Change 5, 424–430, doi:10.1038/nclimate2563, 2015.

Panagiotopulos F., Shahgedanova M., Steffenson D.B.: A review of Northern Hemisphere winter time teleconnection patterns, J. Phys. IV France, 12, doi: 10.1051/jp4:20020450, 2002.

Persson, A., P. L. Langen, P. Ditlevsen, B. M. Vinther: The influence of precipitation weighting on interannual variability of stable water isotopes in Greenland, J. Geophys. Res., 116, D20120, doi:10.1029/2010JD015517, 2011.

Pfahl S. and Wernli H.: Air parcel trajectory analysis of stable isotopes in water vapor in the eastern Mediterranean, J. Geophys. Res., 113, D20104, doi:10.1029/2008JD009839, 2008.

Risi C., Bony S., Vimeux F., Jouzel J.: Water stable isotopes in the LMDZ4 general circulation model: Model evaluation for present-day and past climate and implications to climatic interpretation of tropical isotopic records, Journal of Geophysical Research, 115, D12118, doi:10.1029/2009JD013255, 2010.

Rolph, G.D., Real-time Environmental Applications and Display sYstem (READY) Website (http://ready.arl.noaa.gov). NOAA Air Resources Laboratory, Silver Spring, MD, 2016.

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., Stokes C., Gurney S., Popovnin V.: Interactions between mass balance, atmospheric circulation, and recent climate change on the Djankuat Glacier, Caucasus Mountains, Russia, Journ. of Geophys. Research, 110, D04108, doi:10.1029/2004JD005213, 2005.

Stein, A.F., Draxler, R.R, Rolph, G.D., Stunder, B.J.B., Cohen, M.D., and Ngan, F.: NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bull. Amer. Meteor. Soc., 96, 2059-2077, doi: 10.1175/BAMS-D-14-00110.1, 2015.

Stoffel M., Khodri M., Corona C., Guillet S., Poulain V., Bekki S., Guiot J., Luckman B.H., Oppenheimer C., Lebas N., Beniston M., and Masson-Delmotte V.: Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years, Nature Geoscience 8, 784–788, doi:10.1038/ngeo2526, 2015.

Stohl A., Thompson D.J.: A density correction for lagrangian particle dispersion models, Boundary Layer Meteorology, 90 (1), 155–167, doi:10.1023/A:1001741110696, 1999.

Tielidze L.G.: Glacier change over the last century, Caucasus Mountains, Georgia, observed from old topographical maps, Landsat and ASTER satellite imagery, The Cryosphere, 10, 713-725, doi:10.5194/tc-10-713-2016, 2016.

Toropov P.A., Mikhalenko V.N., Kutuzov S.S., Morozova P.A., Shestakova A.A.: Temperature and radiation regime of glaciers on slopes of the Mount Elbrus in the ablation period over last 65 years, Ice and Snow, 56(1), 5-19, doi:10.15356/2076-6734-2016-1-5-19, 2016 (In Russian with English summary).

Tsushima A., Matoba S., Shiraiwa T., Okamoto S., Sasaki H., Solie D.J., Yoshikawa K.: Reconstruction of recent climate change in Alaska from the Aurora Peak ice core, central Alaska, Clim. Past, 11, 217–226, doi:10.5194/cp-11-217-2015, 2015.

Vinther, B. M., S. J. Johnsen, K. K. Andersen, H. B. Clausen, A. W. Hansen: NAO signal recorded in the stable isotopes of Greenland ice cores, Geophys. Res. Lett., 30(7), 1387, doi:10.1029/2002GL016193, 2003

Vinther B.M., Jones P.D., Briffa K.B., Clausen H.B., Andersen K.K., Dahl-Jensen D., Johnsen S.J.:

Vladimirova D.O. and Ekaykin A.A.: Climatic variability in Davis Sea sector (East Antarctica) over the past 250 years based on the 105 km ice core geochemical data, Problemy Arktiki i Antarktiki, 1 (99), 102-113, 2014. (In Russian with English summary).

Отформатировано: Шрифт: (по умолчанию) Times New Roman, 10 пт, Английский (США)

Отформатировано: Шрифт: (по умолчанию) Times New Roman, 10 пт

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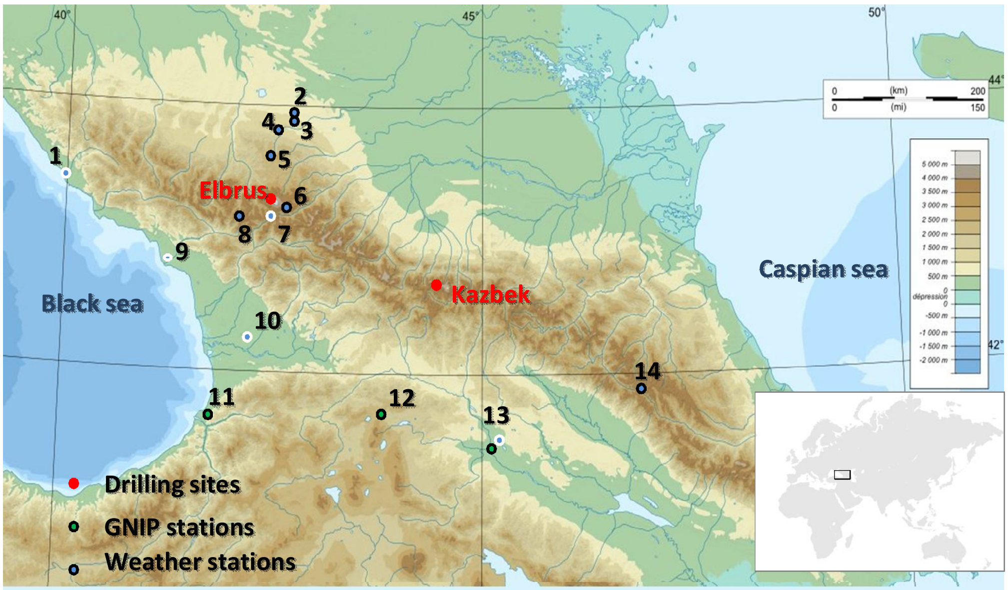
Отформатировано: Английский (США)

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

Wagenbach, D., Bohleber, P. and Preunkert, S.: Cold alpine ice bodies revisited: what may we learn from their impurity and isotope content? Geografiska Annaler: Series A, Physical Geography, 94, 245–263. doi:10.1111/j.1468-0459.2012.00461.x, 2012.

Figures



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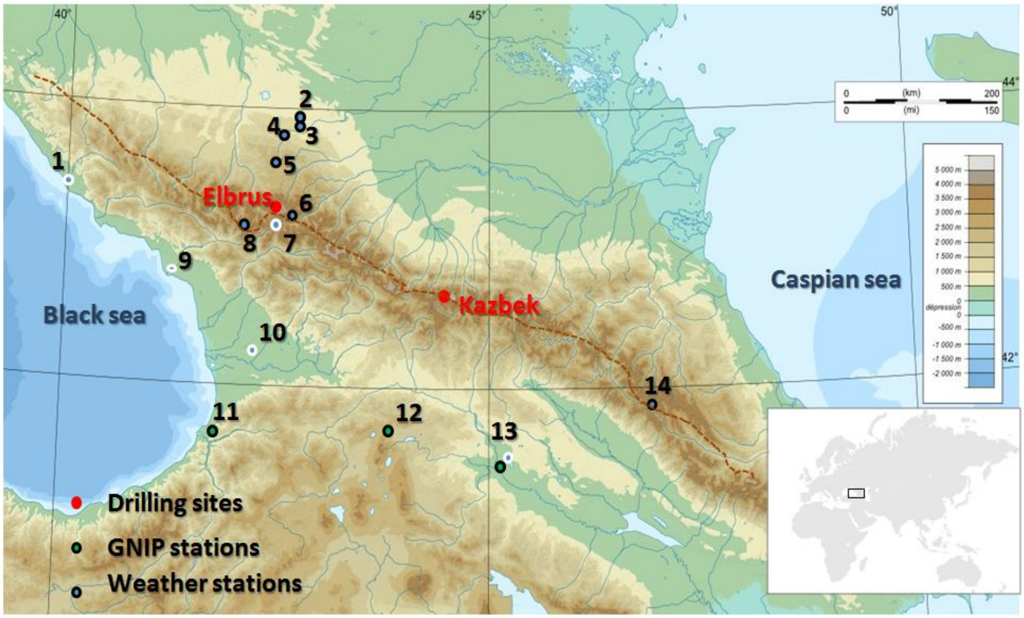

Fig. 1: Map showing the region around Elbrus (black rectangle in the world's map in the lower right corner), with shading indicating elevation (m above sea level). Drilling sites are indicated with red filled circles, GNIP stations as green filled circles, and meteorological stations as blue dots. Stations situated to the south of the Main Caucasus Ridge according to the precipitation cycle pattern are shown using a blue dot with white outside circle and the stations situated to the north are displayed with black outside circle (see text for the details). The brown dotted line shows the border between two types of precipitation seasonal cycles. The number of the various stations refers to Table 1 for their detailed description.

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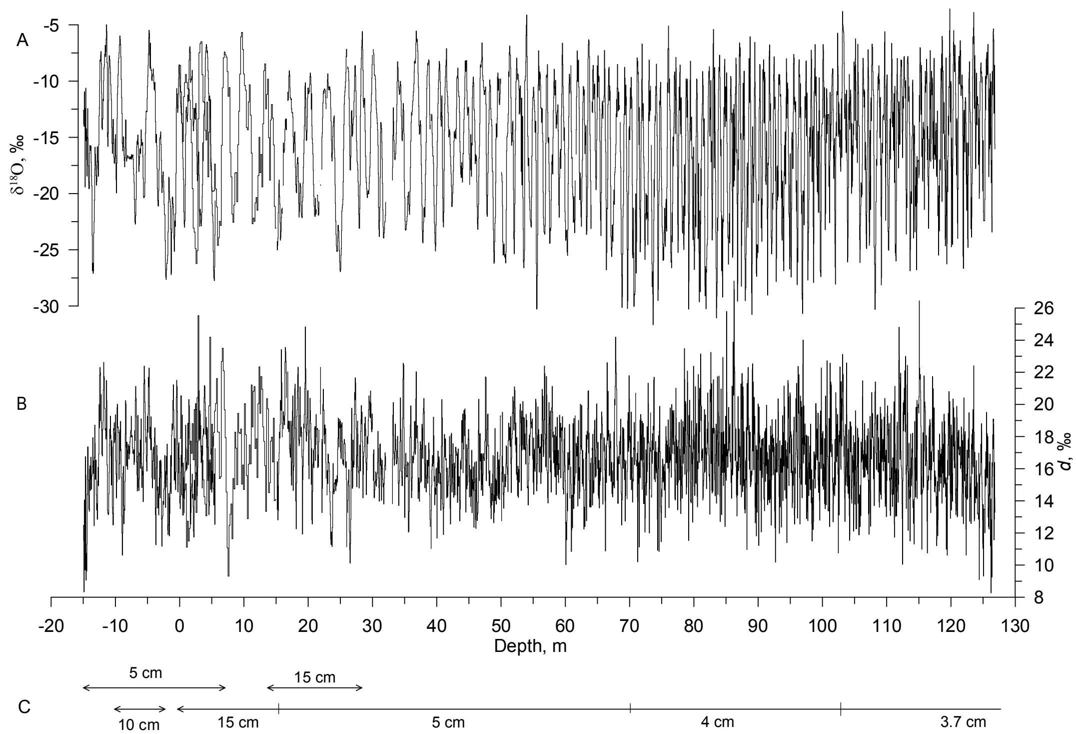
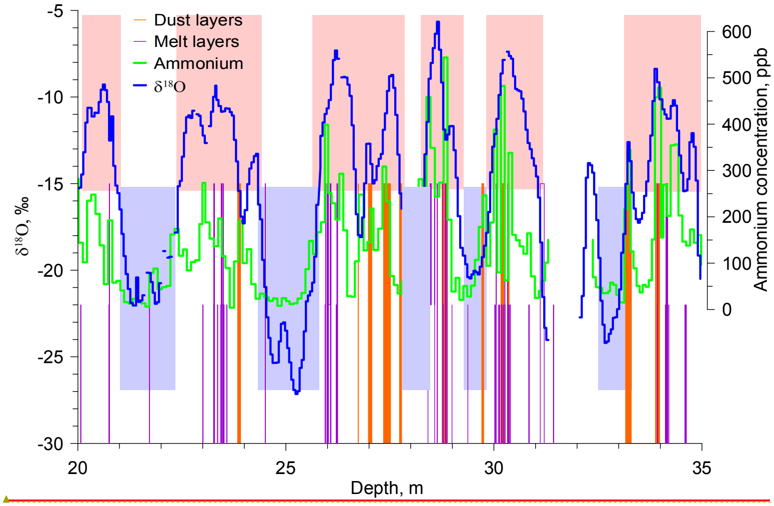


Fig. 2. Vertical profile of δ^{18}O (A), deuterium excess (B), and the number of the ice core as well as sampling resolution (C). 0 m depth corresponds to the surface of 2009.



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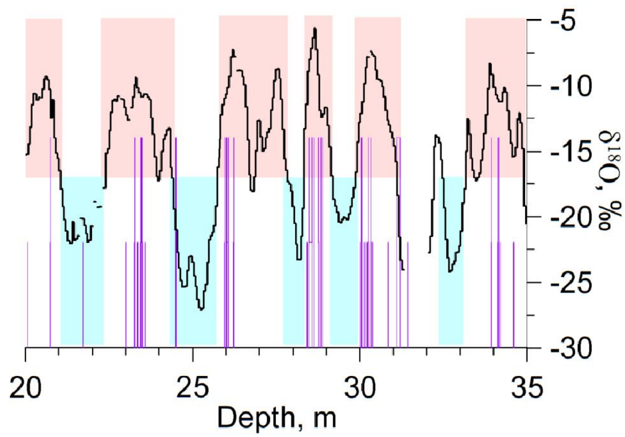


Fig. 3: Illustration of the scheme used to identify warm and cold half-years (respectively indicated by the light red and light blue shaded areas) based on the deviation of the mean $\delta^{18}O$ values from the long-term average value. The purple lines depict the melt

layers observed in the core, dust layers are shown in orange and ammonium concentration graph (Mikhalenko et al., 2015) is in green.

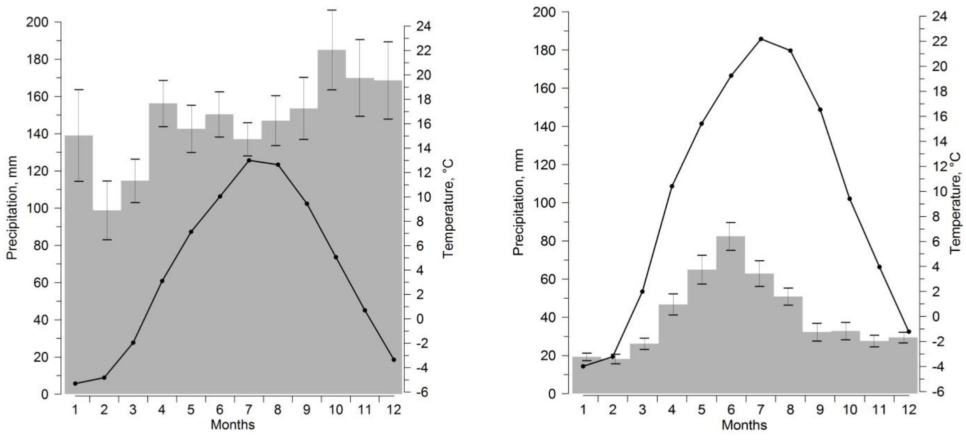


Fig. 4: Average seasonal cycle of temperature (black dots and line) and precipitation (grey bars) calculated over 1966-1990 period, a) for the Klukhorsky Pereval station (illustrating the lack of a distinct seasonal cycle in precipitation south of the Caucasus) and b) for the Mineralnye Vody station (illustrating the clear seasonal cycle in precipitation seen in stations north of the Caucasus). Error bars (SEM) are shown for the interannual standard deviation of the monthly precipitation rate while the same error bars for the temperature are dimensionless at the scale of the graph.

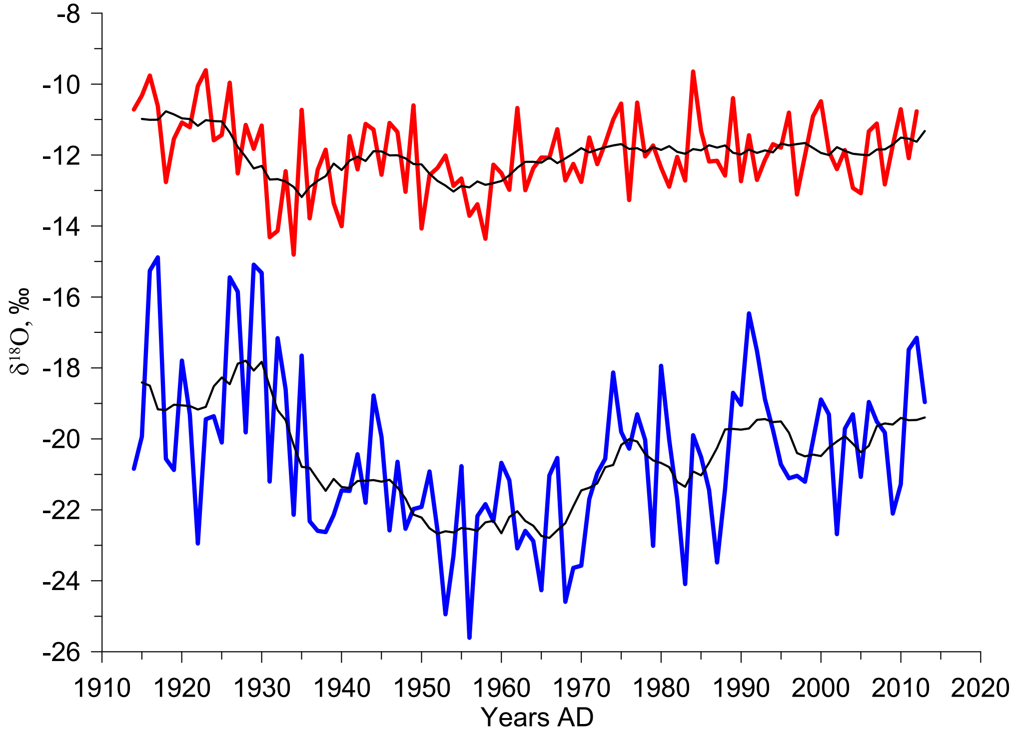


Fig. 5: Annual variations of $\delta^{18}O$ in summer (red line) and in winter (blue line). Thin black lines show 10-year running means of these parameters.

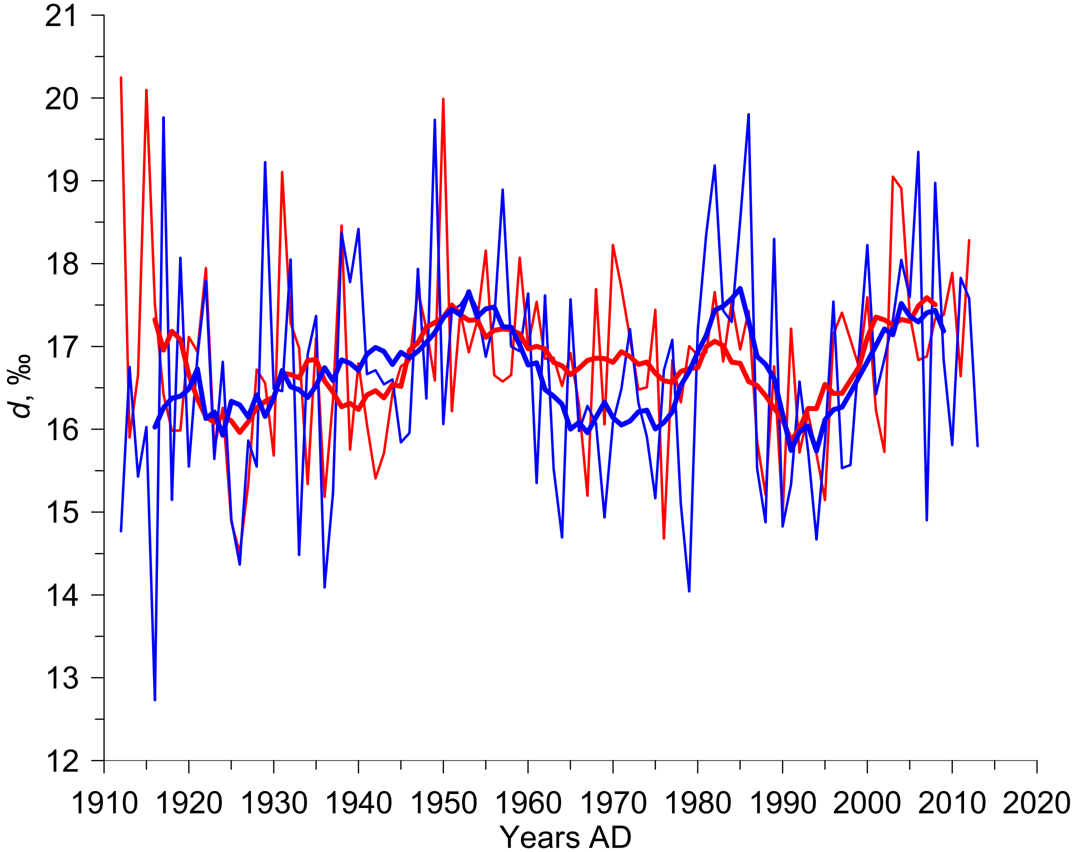
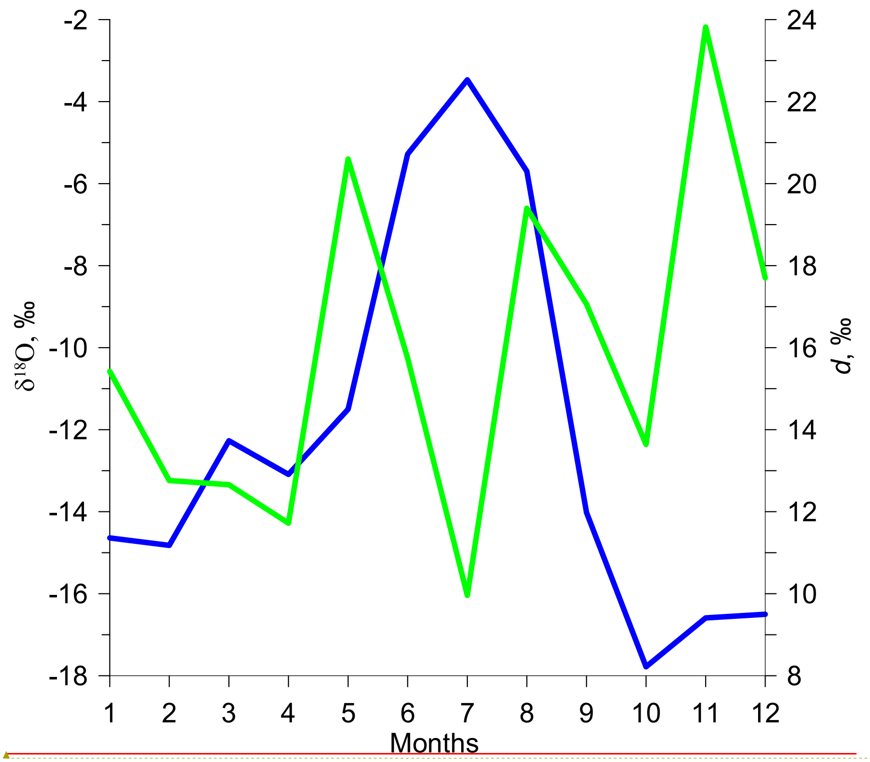


Fig. 6: Annual variations of deuterium excess in summer (red line) and in winter (blue line). Thick lines show the 10-year smoothed values and the thin ones display the raw values.

966 

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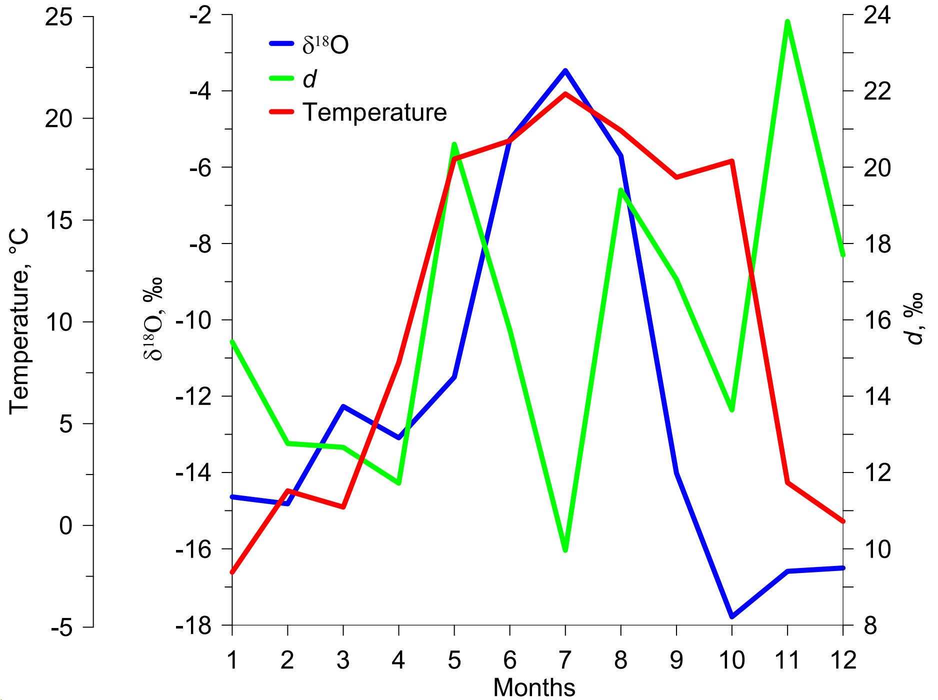

Fig. 7: Monthly $\delta^{18}O$ (blue line) ~~and~~, *d* (green line) and air temperature (red line) data at Bakuriani GNIP station in 2009 (see Table 1 for information on station and Fig. 1 for its location). Note that there is no clear seasonal cycle in deuterium excess, in contrast with $\delta^{18}O$ showing maximum values in summer and minimum values in winter.

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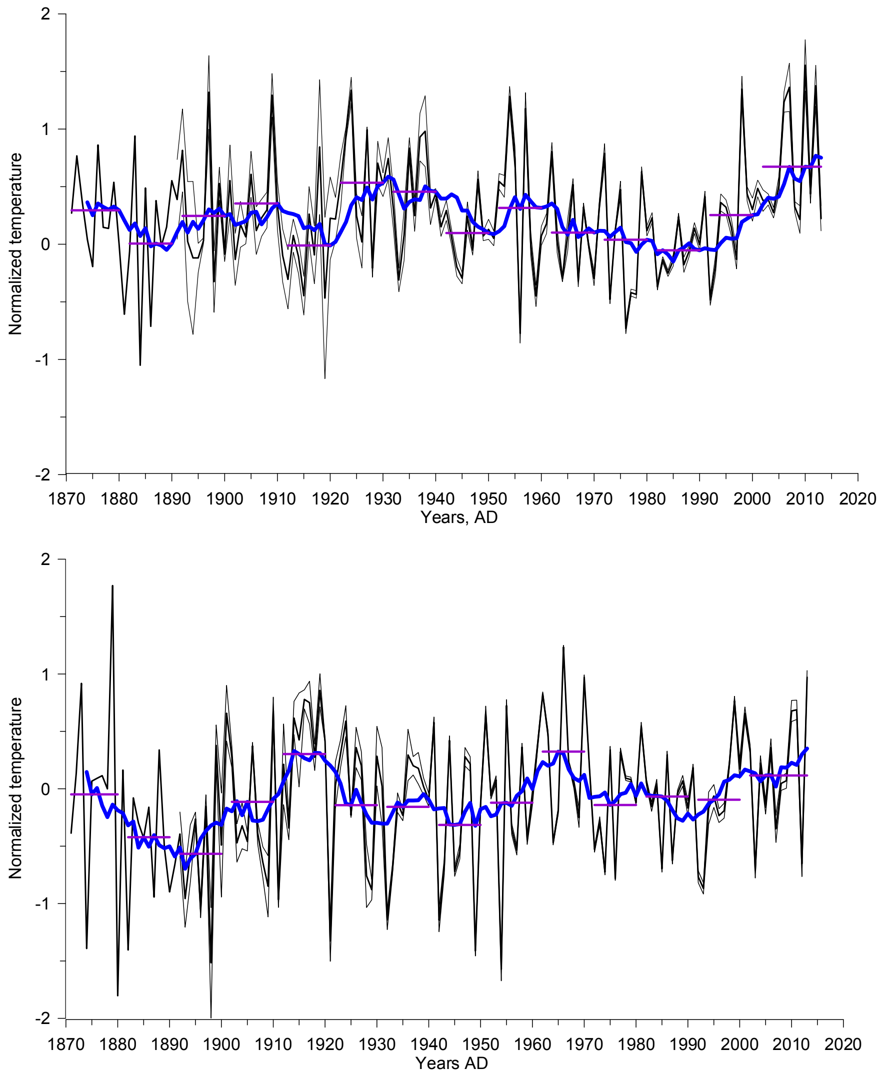

Fig. 8: Normalized regional temperature record based on meteorological data, with respect to the reference period 1966-1990, expressed as annual anomalies (°C). The thin lines illustrate the standard deviation across the individual records after accounting for the lapse rate from Fig. S3, the blue line shows 10 year running mean and the horizontal purple line demonstrates the decadal mean value, the upper panel for the warm season, and the lower panel for the cold season.

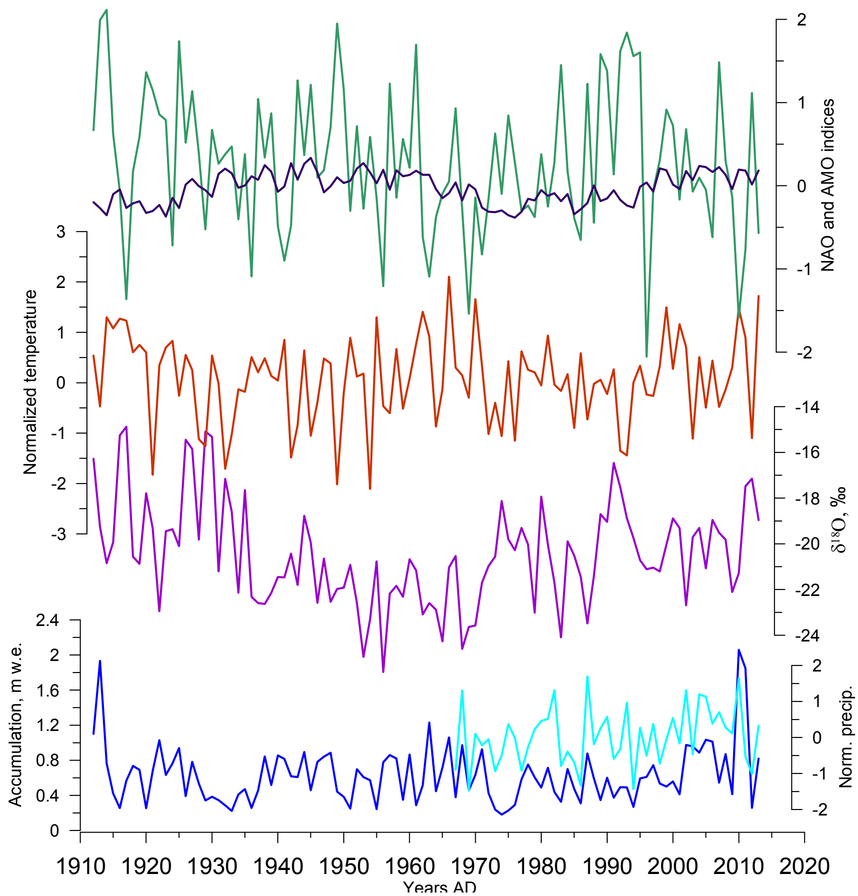

Fig. 9: Comparison of the ice core record with instrumental regional climate information, for the cold season: $\delta^{18}O$ composite (purple), regional meteorological composites of temperature (brown), precipitation to the south from the Caucasus (light blue) as well as the ice core accumulation estimate (dark blue) and NAO (green) and AMO (dark) indices.

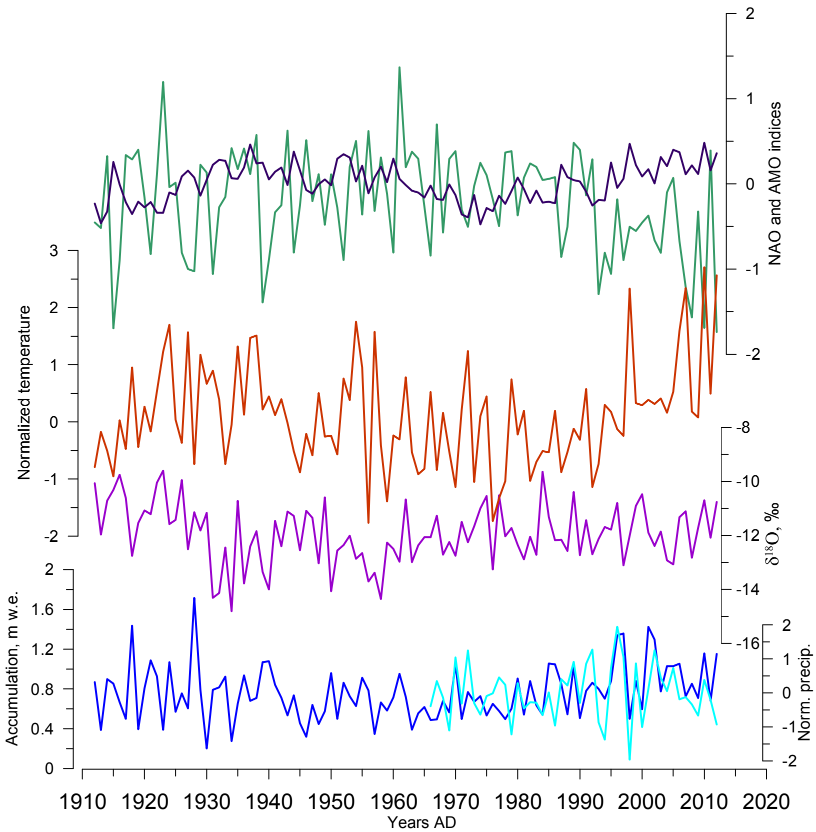

Fig. 10: Comparison of the ice core record with instrumental regional climate information, for the warm season: $\delta^{18}O$ composite (purple), regional meteorological composites of temperature (brown), precipitation to the south from the Caucasus (light blue) as well as the ice core accumulation estimate (dark blue) and NAO (green) and AMO (dark) indices.

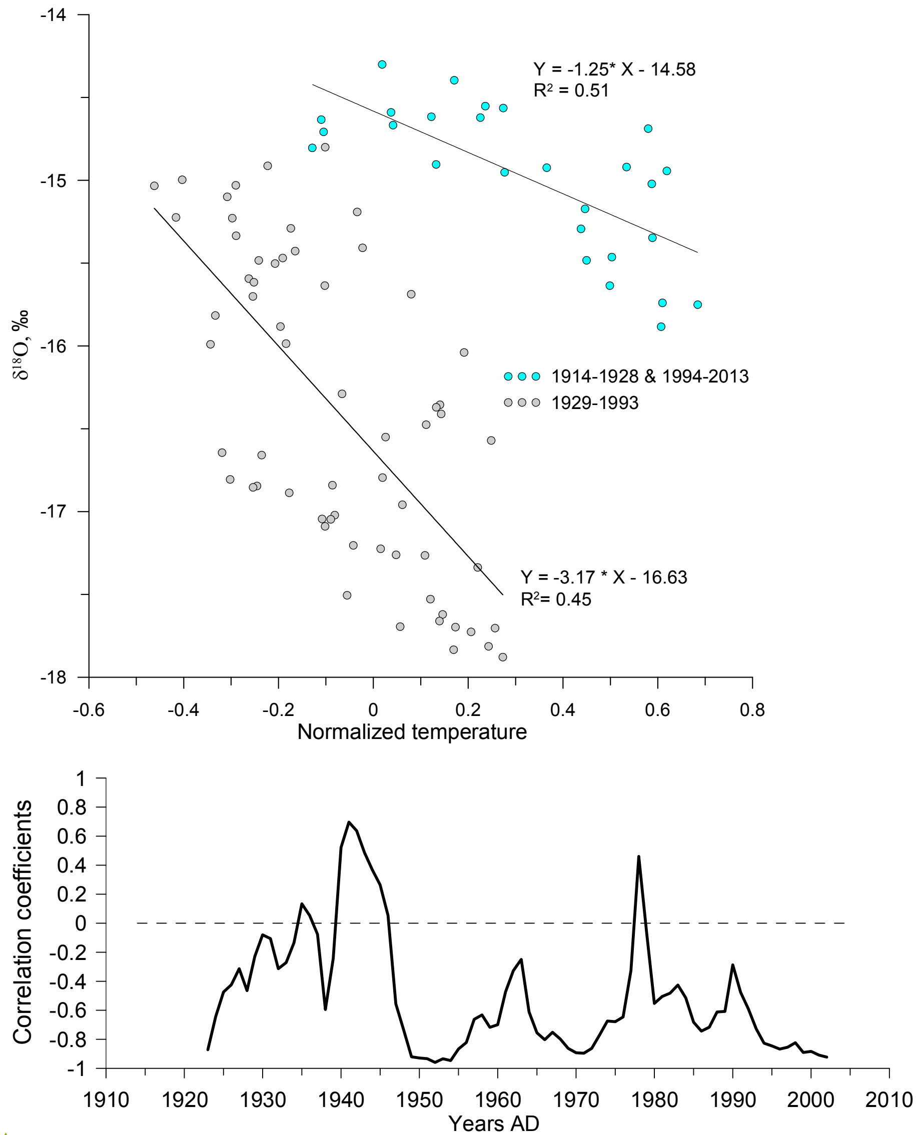

Fig. 11. Correlation plot and regression lines for the 11-year running means of the annual local temperature and annual δ^{18}O (upper panel) and 10-years sliding window correlation coefficients of the same parameters .

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Table 1: Description of meteorological and instrumental data used in the paper

Data type	Number on map (Fig. 1)	Location/Name	Altitude a.s.l.	Time span	Data source
Meteorological observations (temperature, precipitation rate) with daily resolution	1	Sochi	57 m	1871-present	www.meteo.ru
	2	Mineralnye Vody	315 m	1938-present	
	3	Kislovodsk	943 m	1940-present	
	4	Pyatigorsk	538 m	1891-1997	
	5	Shadzhatmaz	2070 m	1959-present	
	6	Terskol	2133 m	1951-2005	
	7	Klukhorskiy Pereval	2037 m	1959-present	
	8	Teberda	1550 m	1956-2005	
	9	Sukhumi	75 m	1904-1988	
	10	Samtredia	24 m	1936-1992	
	13	Tbilisi	448 m	1881-1992	
	14	Sulak	2927 m	1930-present	
	15	Mestia	1417 m	1930-1991	
GNIP data	11	Batumi	32 m	1980-1990	http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html
	12	Bakuriani	1700 m	2008-2009	
	13	Tbilisi	448 m	2008-2009	
Circulation indices	n/a	NAO	n/a	1821-present	Vinter et al., 2009 https:\\crudata.uea.ac.uk\~timo\datapages\naoi.htm
			n/a	1950-present	http:\\www.cpc.ncep.noaa.gov\products\precip\CWlink\
	n/a	NCP	n/a	1948-present	
	n/a	AO	n/a	1950-present	
	n/a	AMO	n/a	1856-present	
Reanalysis daily temperature	n/a	NCEP	500 mb level	1948-present	http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html Kalnay et al., 1996
Back trajectories	n/a	Flexpart	n/a	2002-2009	Forster et al., 2007, Stohl et al., 2009
	n/a	Hysplit	n/a	1948-present	Draxler, 1999, Stein et al., 2015, Rolph, 2016
	n/a	LMDZiso	n/a	n/a	Risi et al., 2010

Table 2: Correlation coefficients between meteorological data and indices of large-scale modes of variability (statistically significant coefficients at $p < 0.05$ are highlighted in bold). The period of calculation for each coefficient is shown in brackets.

	SUMMER			WINTER		
	Temperature	P south*	P north*	Temperature	P south*	P north*
NAO	**-0.47 (100)**	**0.23 (45)**	-0.03 (45)	**-0.41 (100)**	0.04 (45)	**0.26 (45)**
AO	-0.11 (63)	0.08 (45)	-0.14 (45)	**-0.40 (63)**	0.14 (45)	**0.37 (45)**
AMO	**0.24 (100)**	0.01 (45)	-0.02 (45)	0.07 (100)	**0.27 (45)**	**0.25 (45)**
NCP	**-0.50 (65)**	**0.34 (45)**	0.18 (45)	**-0.77 (65)**	**0.25 (45)**	**0.33 (45)**

*P south – precipitation rate at the weather stations to the South from the Caucasus, P north – precipitation rate at the weather stations to the North from the Caucasus.

Table 3: Mean characteristics of the Elbrus ice core records, calculated for the period from 1914 to 2013.

Winter	$\delta^{18}O$, ‰	δD, ‰	*d*, ‰	Accumulation rate (mm w.e./year)
Mean	-21.20	-152.42	17.16	0.61
Standard deviation	2.18	17.44	1.41	0.31
Summer				
Mean	-11.80	-77.32	17.06	0.76
Standard deviation	1.02	8.10	1.15	0.26

Table 4. Correlation coefficients between ice core data, meteorological data and indices of large-scale modes of variability (statistically significant coefficients at $p < 0.05$ are highlighted in bold). The period of calculation for each coefficient is shown in brackets.

Summer	δ[18]O	Accumulation	*d*	NAO	AO	NCP
T, °C	0.13 (100)	0.09 (100)	**0.21 (100)**	**–0.48 (100)**	–0.10 (63)	**–0.51 (65)**
P north	0.07 (45)	0.24 (45)	0.11 (45)	–0.03 (45)	–0.14 (45)	0.18 (45)
P south	–0.12 (45)	**0.44 (45)**	–0.04 (45)	0.23 (45)	0.08 (45)	**0.34 (45)**
δ[18]O		–0.17 (100)	–0.11 (100)	0.06 (100)	**0.23 (63)**	–0.04 (65)
Accumulation			**0.27 (100)**	**–0.25 (100)**	0.05 (63)	0.07 (65)
d				–0.17 (100)	0.00 (63)	**–0.18 (65)**
Winter	δ[18]O	Accumulation	*d*	NAO	AO	NCP
T, °C	–0.02 (100)	**0.31 (100)**	–0.08 (100)	**–0.42 (100)**	**–0.45 (63)**	**–0.79 (65)**
P north	**0.25 (45)**	0.13 (45)	–0.01 (45)	**0.26 (45)**	**0.37 (45)**	**0.23 (45)**
P south	–0.09 (45)	**0.44 (45)**	–0.06 (45)	0.04 (45)	0.14 (45)	**0.25 (45)**
δ[18]O		–0.05 (100)	–0.04 (100)	**0.42 (100)**	**0.34 (63)**	0.08 (65)
Accumulation			0.04 (100)	**–0.34 (100)**	**–0.35 (63)**	0.05 (65)
d				0.05 (100)	–0.09 (63)	0.04 (65)

*P south – precipitation rate at the weather stations to the South from the Caucasus, P north – precipitation rate at the weather stations to the North from the Caucasus.

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Отформатировано ... [49]
Отформатировано ... [50]

Стр. 51: [1] Отформатировано **Anna** **14.11.2016 16:48:00**

Шрифт: не полужирный

Стр. 51: [1] Отформатировано **Anna** **14.11.2016 16:48:00**

Шрифт: не полужирный

Стр. 51: [2] Отформатировано **Anna** **14.11.2016 16:53:00**

Английский (США)

Стр. 51: [3] Отформатировано **Anna** **14.11.2016 16:54:00**

Английский (США)

Стр. 51: [4] Отформатировано **Anna** **14.11.2016 16:54:00**

Английский (США)

Стр. 51: [5] Отформатировано **Anna** **14.11.2016 16:52:00**

Английский (США)

Стр. 51: [6] Отформатировано **Anna** **14.11.2016 16:53:00**

Английский (США)

Стр. 51: [7] Отформатировано **Anna** **14.11.2016 16:53:00**

Английский (США)

Стр. 51: [8] Отформатировано **Anna** **14.11.2016 16:53:00**

Английский (США)

Стр. 51: [9] Отформатировано **Anna** **14.11.2016 16:54:00**

Английский (США)

Стр. 51: [10] Отформатировано **Anna** **14.11.2016 16:48:00**

Шрифт: полужирный

Стр. 51: [10] Отформатировано **Anna** **14.11.2016 16:48:00**

Шрифт: полужирный

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Английский (США)

Стр. 51: [12] Отформатировано **Anna** **14.11.2016 16:53:00**

Английский (США)

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Английский (США)

Стр. 51: [14] Отформатировано **Anna** **14.11.2016 16:54:00**

Английский (США)

Стр. 51: [15] Отформатировано **Anna** **14.11.2016 16:54:00**

Английский (США)

Стр. 51: [16] Отформатировано **Anna** **14.11.2016 16:53:00**

Английский (США)

Стр. 51: [17] Отформатировано **Anna** **14.11.2016 16:54:00**

Английский (США)

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Английский (США)

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Английский (США)

Стр. 51: [21] Отформатировано **Anna** **14.11.2016 16:54:00**
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Стр. 51: [22] Отформатировано **Anna** **14.11.2016 16:55:00**
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Стр. 51: [26] Отформатировано **Anna** **14.11.2016 16:56:00**
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Стр. 51: [27] Отформатировано **Anna** **14.11.2016 16:56:00**
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Стр. 51: [28] Отформатировано **Anna** **14.11.2016 16:56:00**
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Стр. 51: [29] Отформатировано **Anna** **14.11.2016 16:55:00**
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Стр. 51: [30] Отформатировано **Anna** **14.11.2016 16:55:00**
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Стр. 51: [33] Отформатировано **Anna** **14.11.2016 16:56:00**
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Стр. 51: [35] Отформатировано **Anna** **14.11.2016 16:55:00**
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Стр. 51: [36] Отформатировано **Anna** **14.11.2016 16:55:00**
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Стр. 51: [37] Отформатировано **Anna** **14.11.2016 16:55:00**
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Стр. 51: [38] Отформатировано **Anna** **14.11.2016 16:56:00**
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Стр. 51: [39] Отформатировано **Anna** **14.11.2016 16:56:00**
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Стр. 51: [41] Отформатировано **Anna** **14.11.2016 16:55:00**
Английский (США)
Стр. 51: [42] Отформатировано **Anna** **14.11.2016 16:55:00**
Английский (США)

Стр. 51: [43] Отформатировано	Anna	14.11.2016 16:56:00

Английский (США)

Стр. 51: [44] Отформатировано	Anna	14.11.2016 16:56:00

Английский (США)

Стр. 51: [45] Отформатировано	Anna	14.11.2016 16:57:00

Английский (США)

Стр. 51: [46] Отформатировано	Anna	14.11.2016 16:55:00

Английский (США)

Стр. 51: [47] Отформатировано	Anna	14.11.2016 16:56:00

Английский (США)

Стр. 51: [48] Отформатировано	Anna	14.11.2016 16:56:00

Английский (США)

Стр. 51: [49] Отформатировано	Anna	14.11.2016 16:57:00

Английский (США)

Стр. 51: [50] Отформатировано	Anna	14.11.2016 16:56:00

Английский (США)

Стр. 51: [51] Отформатировано	Anna	14.11.2016 16:56:00

Английский (США)

Стр. 51: [52] Отформатировано	Anna	14.11.2016 16:57:00

Английский (США)