We would like to thank the reviewers for the thorough reviews and detailed comments. Here we provide answers to the questions raised in the reviews.

Comments of the reviewers are in blue, our answers are in green, and corrections in the paper text are in black.

Reviewer 1.

This is a review of the 2nd revision of this study by Kozachek et al., and I was also reviewer of the original version and the 1st version. I appreciate the authors efforts into investigation the seasonal divisions of the ice core data and the manuscript has generally improved a lot, although I still struggle a bit to understand how exactly the seasons are defined in the new version. However, it is clear that the variability changes a lot depending on the definition of the seasons and that the new definitions have greater decadal variability. If the author address the (minor) points in the comments below I think the manuscript could be accepted for publication.

Detailed comments:

L22 “allowed” changed to “allow”

Changed

There is a distinct seasonal cycle of the isotopic composition which allow dating by annual layer counting

L23 Remove extra punctuation mark after “shallow cores”

Removed

with additional data from the shallow cores.

L78-79 The potential for reconstructing the NAO using Greenland ice cores was suggested by Vinther et al. (2003) rather than proven. They show that the relation between the NAO and the main variability of the Greenland d18O from ice cores is not stable.

Correected

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 suggested

L158 “18” should be superscript in d18O. Check for other instances. For example in L172, L332, L333 and L416

Corrected

L171-172 I don't understand what you mean here: We changed the borders when needed in order to avoid ascribing minimum of d18O to the warm season and maximum to the cold season". In figure 4 of Vinther et al. (2010) warm and cold seasons is defined similarly as in your Figure 3? Vinther et al performed a correlation analysis to define the extent of the seasons. How did you do this? How much accumulation was assigned to each season?

There is a slight difference between fig. 4 of Vinther et al. (2010) and our fig. 3. We basically used the same approach as there is an obvious seasonal cycle of δ18O which is coherent with the seasonal cycle of temperature in the region. We therefore assume that the maximum value of δ18O in the annual cycle corresponds to July and the minimum value corresponds to January and put the boundary so that these extreme values are in the middle of a season. However, there were several situations when this approach could potentially lead to assign minimum values to summer and maximum to winter. In order to avoid this problem we used the middle point between minimum and maximum as a border between seasons in such cases.
The amount of accumulation assigned to each season varies depending on the accumulation rate in-between minimum and maximum values of the annual cycle.

We basically used the same approach as there is an obvious seasonal cycle of δ18O which is coherent with the seasonal cycle of temperature in the region. We therefore assume that the maximum value of δ18O in the annual cycle corresponds to July and the minimum value corresponds to January and put the boundary so that these extreme values are in the middle of a season. However, there were several situations (six for the whole ice core record) when this approach could potentially lead to assign minimum values to summer and maximum to winter. In order to avoid this problem we used the middle point between minimum and maximum as a border between seasons in such cases.

L173 "We stacked…" you stacked the ice core data? And you assign the maximum and minimum to the center of the warm and cold seasons, respectively? This sentence is not clear.

It was a typo. We reformulated the paragraph and this sentence was removed.

L177-178 What is the motivation for this definition of warm and cold seasons?

The motivation was based on the coherence between seasonal cycle of δ18O and air temperature. The details are given above

L183 "We didn't…" the use of contractions is in general too informal for academic writing. Check for other instances. For example in L372

Corrected

L228 Concider using the PC-based NAO index, although it doesn't make much of a difference during winter.

We did this and got almost the same result. We used PC-based NAO from National Center for Atmospheric Research Staff (Eds). Last modified 03 Mar 2017. "The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based)." Retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based. The graph are shown here in the fig. A1 for the warm season, and A2 for the cold season.

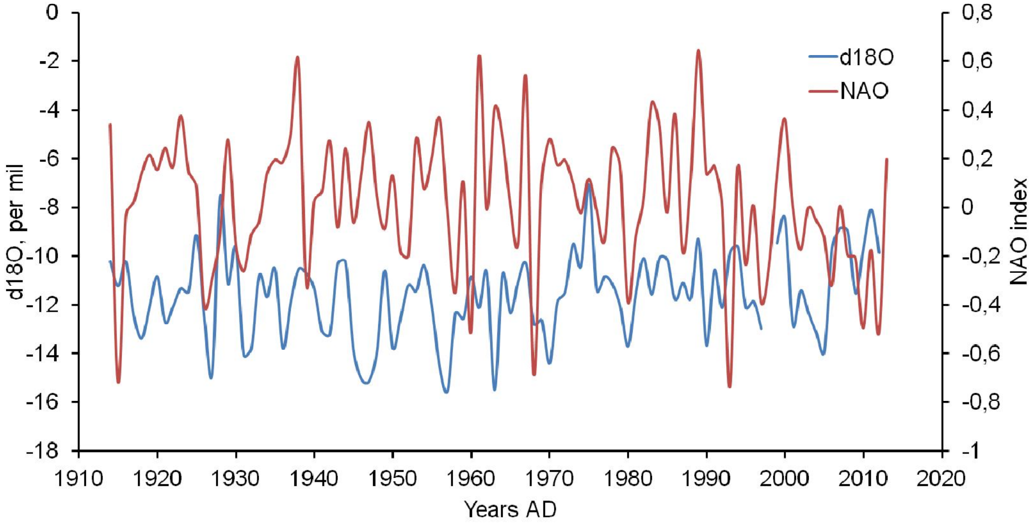


Fig. A1. Comparison of the δ18O and PC-based NAO index in the warm season

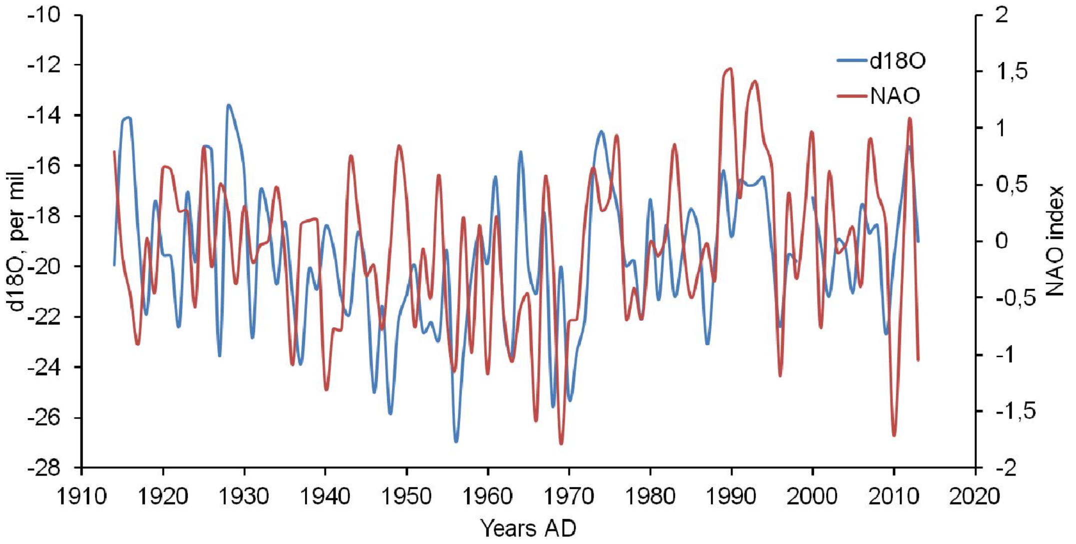


Fig. A2. The same as A1 but for the cold season.

L264-265 The definition of summer and winter is generally done using temperature, or one might talk of dry and wet seasons of summer and winter doesn't exist. Think of southern versus northern hemisphere. Use months to define the seasons in relation to temperature.

Agree. We use terms "warm season" and "cold season" for the ice core data. In the other cases we use months to define the seasons.

The lapse rate is lowest in December-February (2.3°C per 1000 m) and highest (5.2 °C per 1000 m) in June-August (Fig. S3).

L420 Remove punctuation mark.

Removed

Reviewer 2.

General

A 100 year record of water stable isotopes and accumulation derived from the combination of multiple alpine shallow cores and a deep ice core collected at Mt. Elbrus in the Caucasus is presented. The high annual net accumulation rate at the site allows for high temporal resolution and a seasonally resolved data set. Meteorological data, reanalysis temperatures, GNIP isotope data and isotope modeling results as well as atmospheric circulation indices are used to investigate the regional climate and to investigate the parameters recorded by the ice core. The study concludes that for the ice core site the isotopic composition in the warm season is related to local temperature for certain time periods whereas in the cold season the atmospheric circulation is the main driver of modulation. The accumulation data is used to derive a reconstructed precipitation record for the Caucasus highlands for the time period prior to reliable observations.

The successful drilling and subsequent analysis of the presented ice core is already an impressive achievement on its own. The drilling location is characterized by limited surface melt and the ice cores and analysis performed are of high quality. The presented records with clear seasonal variations are certainly useful to gain further insight into the past climate and atmospheric conditions in the studied region which lacks of high-elevation meteorological data. In the current version of the manuscript, most of the issues raised previously in the review process were addressed and implemented. In particular, the approach to split the data into seasonal values is now much more convincing. Still, some issues remain which need more careful investigation and discussion. Addressed later on in more detail, this concerns in particular a) the lack of discussion regarding the dating uncertainty and its effect on the performed correlation analysis, b) the different conclusions drawn for the relation between T and precipitation and their respective ice core proxies which might be caused simply by the different length of the available time series of meteorological data and c) the choice in this version to use the altitude adjusted T (lapse rate corrected station data) for the correlation analysis which might have resulted due to a misunderstanding of a previous review request. Further, some of the figures presented in this version contain serious mistakes which also may or may not have occurred when performing the statistical analysis. This potentially may be a very serious issue and in any case is certainly very unfortunate to happen at this stage of review. Considering the above points, the interpretation and final conclusions drawn by the authors cannot be convincing. Also, the language still needs further improvement, which however is a minor issue.

Taking into consideration all the excellent work and big efforts already undertaken to receive the presented data, it would be a pity to reject this study for publication despite the still existing flaws. I therefore suggest once again major revisions but at the same time would like to urge the authors to invest additional effort and time to carefully reconsider their analysis and interpretation, also being open for potentially different final conclusions even when requiring rewriting substantial sections of the manuscript.

More detailed major comments:

Line numbering refers to the current revised version (version 4 I think).

2.1.4 Dating:

Lines 161-162: What is the estimated dating uncertainty at the bottom of the presented record?

We discuss the dating uncertainty below

The depth given here as 126 m is confusing because in fact 1914-2013 is contained in the 15 m covered by the shallow cores plus the 126 m covered by the deep core, thus around 140 m in total.

Line 164: Also here, 1914-2013 is not contained in 126 m. Please reformulate accordingly, e.g. "…which corresponds to the total of 140 m presented in this study (the 15 m covered by the shallow cores plus the 126 m covered by the deep ice core.".
Accordingly, please reconsider formulation also elsewhere in the manuscript.

Reformulated

Hereafter, we focus our analysis on one hundred years, from 1914 till 2013, which corresponds to the total of 140 m of ice thickness studied here (the 15 m covered by the shallow cores plus the 126 m covered by the deep ice core

Line 164-165: The formulation regarding the dating uncertainty ("…relatively small...") is extremely vague. Please indicate a number for the estimated dating uncertainty.

The number has been indicated. The dating uncertainties are discussed in more details below.

This period has been chosen because of relatively small dating uncertainty (±2 years)

Line 166: Reformulate to "In the bottom part of the core the cycles in the isotopic composition are less prominent and dating becomes less reliable leading to a significant increase in uncertainty."

Reformulated

In the bottom part of the core the cycles in the isotopic composition are less prominent and dating becomes less reliable leading to a significant increase in uncertainty.

The threshold of exactly 126 m seems arbitrary. I assume the uncertainty already increased above compared to the top let's say 50 m or so. So the estimated dating uncertainty should definitely be indicated as a number somewhere (also see later comments).

We took the threshold of 100 years for the discussion. Yes, the depth is arbitrary; we could have discussed 102 or 98 years with the same uncertainty. However, a round figure of 100 years seems more beautiful for the discussion.

Line 173: I do not understand what you mean by "stacked"? It is used later on in line 328 where it refers to the overlap of the various cores. This does not seem to be the same thing since here this refers to the entire record of which most is covered by the deep core only. Please explain and clarify accordingly in the manuscript.

In line 173 it was a typo. We meant sticked. We reformulated this paragraph following the comments of the reviewer 1.

Line 182 and Figure 3: To me it is not evident at all that "two seasons (one warm and one cold) are partially missing". If so, this would be a year with an exceptional low accumulation. So this certainly is one year of dating uncertainty.

We agree this gap can cause age scale uncertainty. The missing 75 cm of the core are not the sum of two seasons. This sum is higher (it is about 1 m actually) which leads to the layer thickness of 0.5 meter per season. This value is close to the average. In the opposite situation, if we consider that the whole gap corresponds to one winter, then we get a winter with extremely high accumulation rate. However, for the estimation of the dating uncertainties we used the absolute age markers. These markers are tritium peak in 1963 and sulfate peak in 1912 (this year is not discussed in this paper still we know its depth) which corresponds to Katmai eruption. The uncertainty was calculated as the difference of age estimation using different methods at these dates. The maximum difference was 2 years.

Also Line 183: It is unclear what you mean by "we did not use these values for the correlation analysis"? If you have a gap, i.e. not data/value of course you cannot use it. Do you mean that for this missing year xy (if it really is one year considering the then very low accumulation…) you also did not include a value for the meteorological data? This seems trivial and I just hope you did not shift the age scale of the two records against each other when performing the analysis… Please re-check carefully.

Of course we didn't shift the age scales. We show on the figures the value obtained from the 2004 ice core where the sampling resolution was 50 cm and these values were not used for the correlation analysis because their low reliability.

Figure 3: Again, regarding the dating uncertainty to me it seems questionable if the minima in both d18O and Ammonium is really occurring in summer (double peak) or if this does not rather indicated another winter minima (with a rather high winter d18O). I think this is rather challenging to judge and cannot be decided without some uncertainty. The point is that this should probably be assigned with another year of dating uncertainty. Together with the gap, this would make ± 2 years of uncertainty just for this section shown in Fig. 3. So the total uncertainty for the year 1914 (including the dating of > 90 additional annual layers) is very likely much higher than ±2 years.

The comparison of different dating methods on age control points shows that the overall error of our timescale at these two depth levels does not exceed ±2 years which means that independent dating uncertainties discussed by the reviewer should compensate each other at this points

For the estimation of the dating uncertainties we used the absolute age markers. These markers are the tritium peak in 1963 and the sulfate peak in 1912 which corresponds to the Katmai eruption (Mikhalenko et al., 2015). The comparison of different dating methods on age control points shows that the overall error of our timescale at these two depth levels does not exceed ±2 years which means that independent dating uncertainties should compensate each other at this points

Line 329 and Fig. 2S: The inter-core disagreement is indeed small. However, there is at least half a year of disagreement between the very bottom of the 2013 shallow core and the 2009 deep core (around 5 m depth in Fig. S2). This indicates that even in the top seven years (2007-2013) with 2 available absolute time markers (the drilling date of the 2012 and 2009 cores) there exists uncertainty in the dating. For the 93 years before with no absolute time markers available, the dating uncertainty will certainly be quite substantial and will definitely affect the correlation analysis particularly on an annual or seasonal scale. So when discussing the correlations found in Section 3.3. this should be addressed more carefully (a first step has been made by including 3, 5 and 7 yr running averages to the analysis).

We disagree with the point that "…the 93 years before with no absolute time markers available" as there are two markers corresponding to 1912 and 1963 that are described in (Mikhalenko et al., 2015). The question of the correlation analysis is addressed below.

Line 187 / Figures 5, 6 and also 8, 9 and 10:
I do not see a gap there for the missing year (or season) you discuss for Figure 3?
Please correct.

We used data from 2004 ice core. However this value is less reliable than the values for the neighboring years because of 50-cm sampling resolution in this part of the core. We excluded it from the correlation analysis but show it on pictures for the uniformity.

3.1 Regional climate:
Lines 260-263 and line 270:
According to the comment made in the previous revision it would be helpful to show the precipitation data for all the stations discussed (lines 260-263). As written in line 270 the authors intended to follow this suggestion but it seems they unfortunately have forgotten to actually include all the data in Fig. S4. Please add.

We used stations Klukhorskiy Pereval as a representative of the Southern stations and Mineralnye Vody as a representative of the Northern stations. We include several other stations to the fig. S4. For the data from another stations in the region the reviewer is referred to Shahgedanova et al. (2014), Shahgedanova et al. (2007), Tielidze (2016) and references therein.

Line 269: It is unclear how the temperature for the drill site was calculated based on the determined lapse rate? Was the seasonal cycle in the lapse rate considered? Please clarify in the text.

Yes, the seasonal cycle of the lapse rate was taken into account. We added this point to the text.

Based on the lapse rate we calculated temperature at the drilling site taking into account its seasonal variability shown on fig. S3.

Also, the authors followed the suggestions made in the previous review regarding the loss of information (namely the d18O/T relation) when only showing normalized T data. Unfortunately it seems a misunderstanding occurred. The reviewer's idea was this lapse rate adjusted temperature ("drill site T") to be used to determine the d18O/T relationship (i.e. in a way the calibration of d18O as a proxy for temperature). Whereas the correction for the lapse rate is a necessary step to do so, it is not required for the correlation analysis. This is where the misunderstanding happened. The authors now also used this adjusted T data for the correlation analysis (and accordingly also in the figures 8, 9 and 10). This was not suggested! In fact it does not make sense for the following reasons: Because the determined lapse rate certainly comes with an uncertainty (also a change in the rate over time cannot be excluded), an additional source of uncertainty will be introduced to the data set. This will bias the correlation analysis.
To include such a bias is unnecessary because the d18O recorded in the ice core also reflects processes taking place on a larger regional scale such as evaporation temperature in the moisture source region, re-evaporation processes etc. and therefore a regional T (i.e. the station average) is likely most representative for the potential T proxy recorded in the ice core (i.e. d18O). This is a different matter for the precipitation data for which the closest/high altitude stations are most relevant and the authors decision to only use those is a reasonable choice (precipitation and as well as accumulation may vary significantly within regional scale because of orography/altitude effects etc.).
In summary, for the correlation analysis the authors should absolutely stick to the averaged T including all stations as in the previous version (i.e. divided into N and S). It thereby does not matter if they are normalized or simply averaged as for the correlation the results will be the same. For the figures, I suggest to not show the normalized data.

Now we use the normalized values for the correlation again. The normalization was used in order to avoid introducing of the errors. The stations are situated at the different altitude levels. Consequently, despite the same tendencies in the temperature changes they are characterized with the different absolute values of temperature. For example, if one year of observations is missing at the coldest station, the simple average will be higher. If we use the normalized values for construction of the regional temperature record we do not introduce these errors.

3.2 Ice core records:
Line 332-334: In the authors response you wrote: "We calculated continental gradient and lapse rate for δ18O using the data from the GNIP stations in the region that are situated at the lower elevations and in our opinion one should be very cautious when using this data for the high elevations ice cores study. The lapse rate is -0.25 ‰/100 m and continental gradient is -0.85 ‰ /100 km. The mean value of δ18O for Kazbek ice core should be 1.25‰ more positive because of elevation difference and 1.7‰ more negative due to continentality factor."
I think the fact that these calculated effects actually match up with what is observed in the two ice cores is a very nice and interesting result. Please include this more detailed description and results given in the above answer to the manuscript.

Added

This is a result of a mutual compensation of δ18O increase due to lower elevation position (Kazbek drilling site is 500 m lower) and of δ18O decrease because of continentality effect (Kazbek is 200 km further from the sea). We calculated continental gradient and lapse rate for δ18O using the data from the GNIP stations in the region that are situated at the lower elevations. The lapse rate is -0.25 ‰/100 m and continental gradient is -0.85 ‰ /100 km. The mean value of δ18O for Kazbek ice core should be 1.25‰ more positive because of elevation difference and 1.7‰ more negative due to continentality factor.

3.3 Comparison of ice core records with regional meteorological data:
Line 363-385 and Fig. 9 and 10: In those figures the meteorological temperature data is shifted on the age scale by around 42 years! Shown is 1870-1970 instead of 1910-2013, see the combined figure created form the manuscript figs 8 & 9 and 8 & 10 included on the next page. The same mistake may have occurred when performing the statistical analysis (correlations). Please correct and check carefully!

We used the correct dataset for the correlation. Unfortunately the error occurred for the graph. Following several reviewer's comments we changed fig. 8, 9, and 10.

Line 386-390: This is not very convincing. The problem is that you draw different conclusions for T-d18O and Precipitation-Accumulation relation which might only be caused by the difference in length of the available meteorological time series. In other words, a reasonable correlation was also found for warm season T with d18O for the younger part of the record. Still, the correlation is lost in the older section. How can you exclude the exact same thing is true for the precipitation data?

Unfortunately this problem cannot be resolved with the available data. However, it is easy to imagine, for instance, that change of the moisture source lead to change of the precipitation isotopic composition at the same air temperature. Thus the correlation between T and d18O is unstable in time. It is much less probable that the correlation between accumulation rate and precipitation rate varies in time.

Also, layer thickness is not equal net accumulation! If precipitation is reconstructed from ice core derived accumulation data, one needs to account for layer thinning (Cuffey and Paterson, 2010). See for example in Mariani et al., 2014 ("The reconstructed net accumulation can be regarded as precipitation proxy, considering few caveats. (i) In order to account for thinning effects, such reconstructions require an accurate description of the glacier ice flow by means of physical models.").
Therefore, please address following the literature (e.g. Schwerzmann et al., 2006; Herren et al., 2013 or probably easiest Equations 1 both in Henderson et al, 2006 and Mariani et al., 2014 which is based on the Nye model).

We used the Dansgaard-Johnsen model for the correction of the layer thickness or the layer thinning. It is pointed in the text (line 190 of version 4). We also added this to the discussion of the accumulation section.

The seasonal accumulation rate is seasonal layer thickness corrected for densification using the density profile from Mikhalenko et al. (2015) and for the layer thinning due to glacier flow using the Nye model (Nye, 1963; Dansgaard and Johnsen, 1969). It is linked to the precipitation rate…

Line 376-378 and lines 432-433: The conclusions and results of Mariani et al., 2014 are still not stated correctly.
In their response to the previous review the authors stated: We agree, that in (Mariani et al., 2014) the authors found strong link between temperature and δ18O on seasonal cycle scale. While on annual scale the signal is biased by other factors. Though they report correlation between δ18O and precipitation weighted temperature, this result is not useful for palaeoclimatology. Citation: “For such a glacier site, a paleotemperature reconstruction is not feasible.”
When re-reading the study in question, the authors will realize that 2 separate ice cores are discussed therein: “We assume that at the Grenzgletscher the non-uniform snow deposition throughout the year is more pronounced than at Fiescherhorn (see Section 3.2.1), as it is generally the case in the Southern Alps compared to the Northern Alps (Frei and Schär, 1998; Eichler et al., 2004; Sodemann and Zubler, 2009).”
Obviously, those 2 ice cores are located in meteorologically significantly different regions. So whereas your above statement about the annual scale and the need for precipitation weighting is true for Grenzgletscher it is different for Fiescherhorn (no p weighting was necessary and performed for this core).
Because for the ice core in your study where you point out the relatively equal distribution of precipitation between the seasons, the conclusions/results you should cite are the ones related to Fiescherhorn. Accordingly the results/conclusion from Mariani et al. which you should consider are:
- 3.1.2 Annual scale: “The annual Fiescherhorn δ18O correlates significantly with the Jungfraujoch annual temperature (r=0.44, p<0.01, period 1961-2001). The resulting slope is (0.50±0.16)‰/°C which is consistent with the result based on the seasonal values.”
- Conclusions: “For a glacier site with homogeneously preserved accumulation throughout the year the mean temperature signal is partly preserved on annual scale.” The difference of your finding should be stated accordingly (or as it might change considering the previous comment it might turn out to still be the agreement). So please reformulate.

Reformulated

Our results are comparable to those obtained in the Alps by Mariani et al. (2014) for the Fiescherhorn glacier where the authors found significant though weak correlation between temperature and δ18O. However for the Elbrus ice core this correlation was found in the warm season only.

Concerns regarding final results and conclusion.
Out of curiosity after compiling the two figures shown further above, I created the two additional Figures A and B shown below. In this case, I adjusted the scales against each other the way they should

be (the aforementioned 42 year shift). Also, following the comment made earlier (see 3.1 Regional climate – Line 269), I here used the earlier version of Fig. 8 (more precisely the normalized T data for the cold and warm period respectively). Assuming reasonable uncertainty in the dating (see comments regarding the dating above) I allowed the age scale of the T data to stretch until reaching a best fit (determined visually due to lack of the actual data which is admittedly a very crude method). For better visibility the d18O records from Fig. 9 and 10, respectively were copied, the background removed and these curves were directly overlaid with the according normalized T from the earlier version Fig. 8 (either warm or cold season T data). For a shift of 8 years, which does not seem unreasonable considering the potential dating uncertainty (i.e. an offset in dating by 8 years out of 100), a strikingly good agreement between T and d18O can visually be seen, particularly for the cold season for which some very characteristic features in the T record can also be found in the d18O record, e.g. between around 1908 and 1935 or 1990 to 2013 with ages referring to the T age scale (upper scale) (Figure A). Also the overall trend is in close agreement except maybe between a short period around 1965 -1970 (Figure A). For the warm season also some characteristic features in both T and d18O exist for the period around 1908-around 1930 and from around 2000-2013 (Figure B), although not as closely related as for the cold season. Also the trend for the warm season does not seem to agree as well as for the cold season. For the location and setting of the ice core site, a reasonable explanation why d18O might be more closely related to T during the cold season than during the warm season could be that in the cold season re-evaporation processes are reduced and transport from the source region is more direct (see manuscript supplement Fig. S1).

In any case, these findings completely disagree with the results and conclusions of the reviewed manuscript although it is based on the exact same data figures:

See for example line 28-30: “In the warm season (May - October) the isotopic composition depends on the local temperature, but the correlation is not persistent in time, while in cold season (November – April), the atmospheric circulation is the predominant driver of the ice core isotopic composition. “

Also line 367-368: “A significant correlation ($r = 0.44$, $p<0.05$) emerges for warm season data, when calculated for the period since 1984.”, “line 372-373: We didn’t find any statistically significant correlations when compared 3-, 5-, 7-years running means of these parameters.”

or line 432: “We found no persistent link between ice cores δ18O and temperature on interannual scale…”.

Even for the visually good agreement between T and d18O (see Figure A top panel), I would not expect a very high correlation because as stated somewhere earlier, even a 1 year offset can potentially destroy any correlation. However, on a multi-annual scale (3, 5 or 7 year running means) I would expect the correlation to be high. I thus strongly suggest to carefully revisiting your dating and subsequent data analysis, evaluation and interpretation of your results. Previous publication of the dating can certainly not be a justification for not reconsidering. The potential finding that d18O does indeed reflect T and thus could be used as a T proxy would make this ice core archive certainly much more valuable.

We thank the reviewer for the huge effort put into looking on the age scale of our record. However we stay strong by our dating. There are several reasons for this position. We use the chronology elaborated for this ice core and described in (Mikhalenko et al., 2015). This chronology based on the count of annual cycles in isotopic composition and ammonium concentration. Also there are two absolute age markers: tritium peak in 1963 and sulfate peak in 1912 (this year is not discussed in this paper still we know its depth) which corresponds to Katmai eruption. This time scale is also confirmed by the ice flow modeling. We do not have any reason for the change of the dating.

However, following the advice of the reviewer we have made changes in the text that allow more flexibility in interpreting the obtained data, as the reviewer requests.

Obviously, the above inferences strongly depend on the uncertainties of the timescale used. If one concedes that the error of the timescale could be significantly greater than ±2 year, quite different conclusions may be reached by adjusting the scale of the $\delta^{18}O$ and T records against each other. For instance, by contracting the $\delta^{18}O$ record by 8 years with respect to the initial timescale in Figs 9 and 10, one would find much better correlation between $\delta^{18}O$ and temperature, thus reaching the conclusion that the local temperature is the main driver of the $\delta^{18}O$ variability. However, based on various experimental evidences, as discussed in the dating section, we argue that the timescale developed for the Elbrus ice core is accurate within ±2 years.

Therefore, the most realistic conclusion of those that can be drawn from the data obtained is that the temperature is weakly correlated with the $\delta^{18}O$, and that this correlation is unstable in time.

As mentioned in the paper there is no correlation between running means of d18O and temperature. We include the figures showing the running means of δ18O and temperature here (fig. A3 and A4). There are some common features in the recent period in the warm season that is discussed in the paper. For the other periods no correlation found. As was pointed by the reviewer in the previous review, the correlation based on running means is insignificant because of lower number of degrees of freedom, we do not include these figures to the paper.

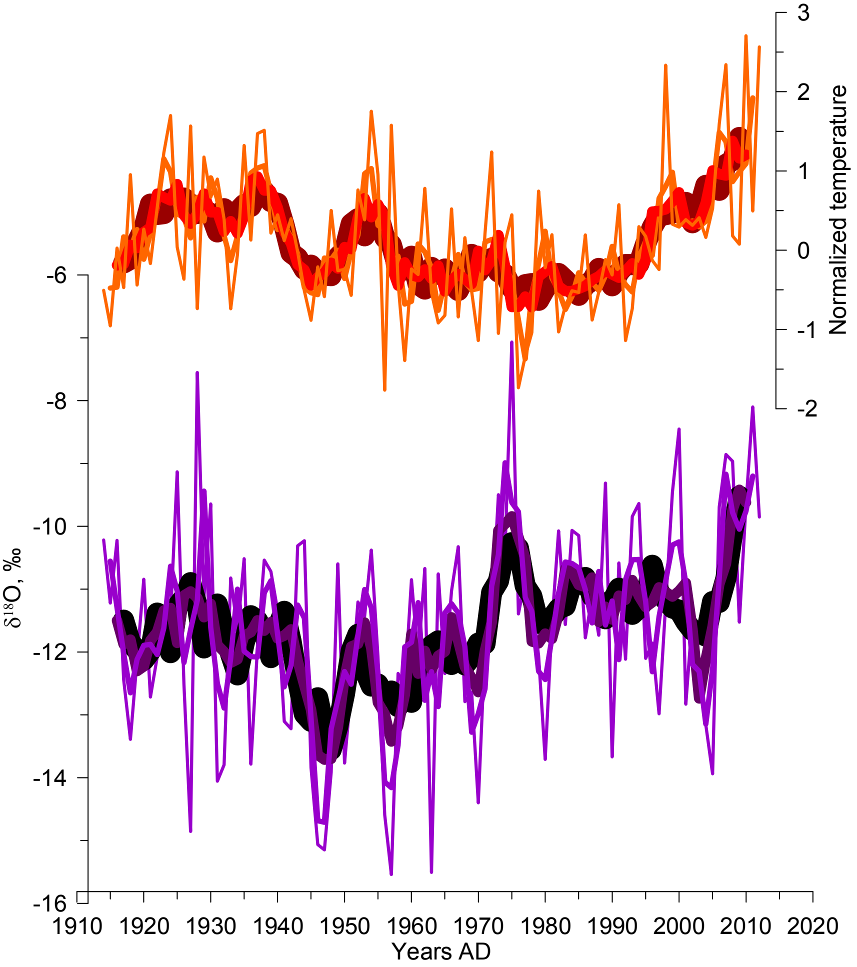
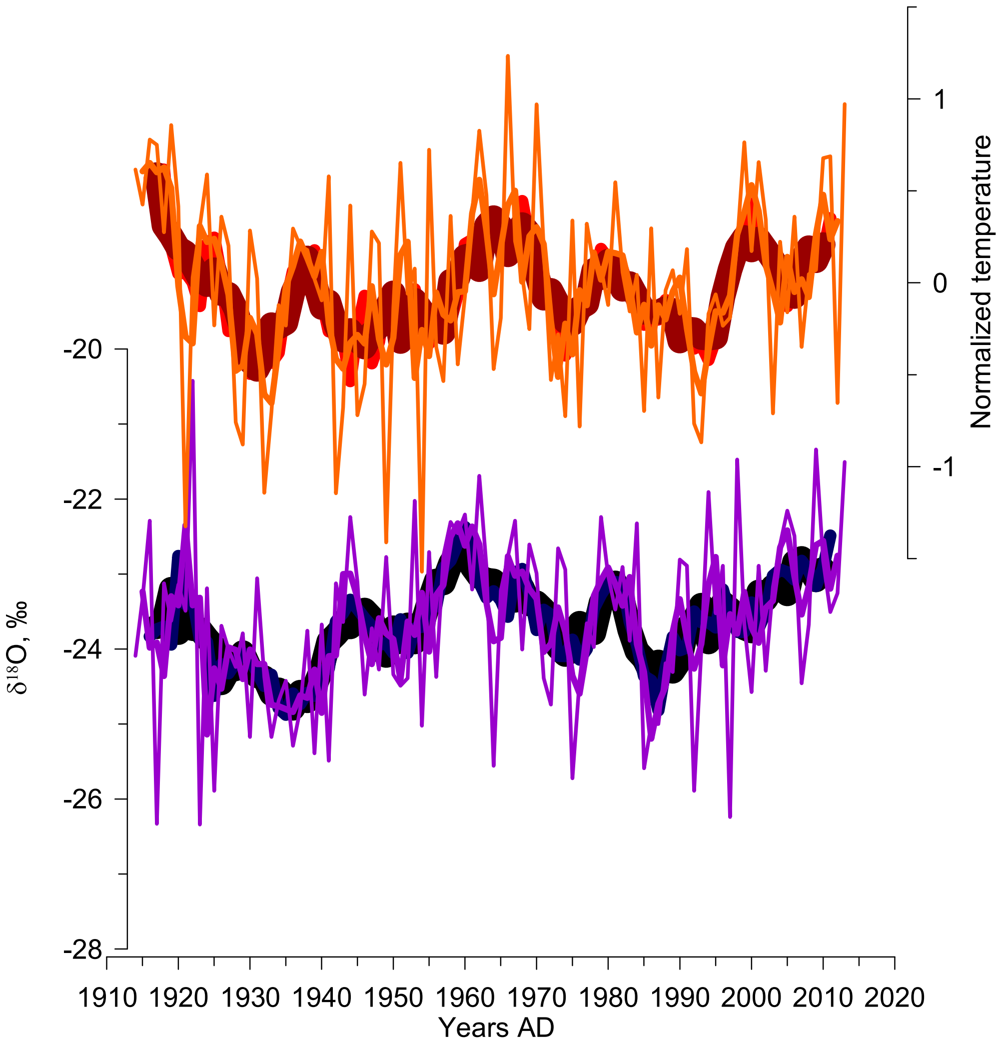


Fig. A3. The running means (3-, 5-, 7-years) of isotopic composition and regional temperature in the warm season. Thin line represents the raw data. The thickest and darkest lines represent 7-years running means



A4. The same as A3 but for the cold season.

Minor comments:

Table 3 and 4:

Some significant correlations are not in bold.

Corrected

Language (due to lack of time just one example for one of the newly written sections):
Line 170: …we used ***a*** slightly…
Line 172: …ascribing ***minima*** in….and ***maxima***…
Line 174: ……using ***the*** criteria…described ***by***…
Line 177: …using the ***seasonal signal in the isotopic composition***…
Line 177-178: ***For the*** meteorological data we ***selected the period*** from November to April for the cold season and ***the*** period…
Line 179: There ***are*** some gaps…

The language was checked by the native speaker

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 with additional data from the shallow cores~~.~~. The distinct seasonal cycle of the isotopic composition allows dating by annual layers counting.~~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 20 m from the shallow cores~~.~~. The whole record covers 100 years, 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 warm season (May~~-~~-October) the isotopic composition depends on~~ the~~ local temperatures, but the correlation is not persistent in time, while in the cold season (November—April),~~ the~~ atmospheric circulation is the predominant driver of the ice core's isotopic composition. The snow accumulation rate correlates well with the precipitation rate in the region all year round, ~~this ~~which 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) 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 only started ~~only ~~in 1966. I~~An i~~mproved 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, a 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, the isotopic composition of the ice cores was governed both by ~~the ~~local meteorological conditions and by ~~the ~~regional and global factors. These studies discussed the complexity of interpreting ice core records from high-altitude glaciers due to the potential bias from post-depositional processes and frequent changes in the origin of moisture sources. 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). 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~~ do 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 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. The ~~C~~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~~reconstruction of the past NAO changes was ~~proved~~ suggested (Vinther et al., 2003). The authors also revealed the importance of the study 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).

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), 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 δ^{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 δ^{18}O, temperature, and the NAO. The influence of the NAO index on European climate and precipitation δ^{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~~and 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~~ puroposes of comparison only. ~~Its~~ A detailed description of it 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~~ for the isotopic measurements have been partially discussed in (Mikhalenko et al., 2015). Water stable isotope ratios (δ^{18}O and δD) were measured at the Climate and Environmental Research Laboratory (CERL) ~~of~~ at the Arctic and Antarctic ~~r~~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 δ^{18}O and 0.30‰ for δD. The depth profile of δ^{18}O (Mikhalenko et al., 2015; Kozachek et al., 2015) and of the deuterium excess (d= δD – 8*δ^{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 δ^{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 for dating 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 δ18O with the average seasonal amplitude of 20 ‰. For annual mean values we calculated averages of δ18O from one minimum of this parameter to another one as well as from one maximum to another. As we found no significant differences between the records obtained with two ways of year allocation we used minimum to minimum dating as a more common ~~one~~method. 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 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. For the estimation of the dating uncertainties we used the absolute age markers. These markers are the tritium peak in 1963 and the sulfate peak in 1912 which corresponds to the Katmai eruption (Mikhalenko et al., 2015). The comparison of different dating methods on age control points shows that the overall error of our timescale at these two depth levels does not exceed ±2 years which means that independent dating uncertainties should compensate each other at this points

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Hereafter, we focus our analysis on one ~~century~~hundred years, from 1914 till 2013, which corresponds to the total of 140 m of the ice thickness studied here (the 15 m covered by the shallow cores plus the 126 m covered by the deep ice core~~corresponds to the upper 126 m of the core~~. This period has been chosen because of the relatively small dating uncertainty (±2 years) and the availability of other records such as local meteorological observations. In the bottom part of the core the cycles in the isotopic composition are less prominent and dating becomes less reliable leading to a significant increase in uncertainty~~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 meteorological data we used average values from January to December of each year for the comparison with annual means of ice cores parameter.

For warm and cold seasons allocation we used a method adapted slightly ~~slightly adapted method~~ from (Vinther et al., 2010). The original method requires ascribing of an equal accumulation rate for the warm and cold season of each year. Basically weused the same approach as there is an obvious seasonal cycle of δ^{18}O which is coherent with the seasonal cycle of temperature in the region. We therefore assume that the maximum value of δ^{18}O in the annual cycle corresponds to July and the minimum value corresponds to January and put the border so that these extreme values are in the middle of a season. However, there were several situations (six for the whole ice core record) when this approach could potentially lead to assign minimum values to summer and maximum to winter. In order to avoid this problem we used the middle point between minimum and maximum as a border between seasons in such cases. ~~We changed the borders between the seasons when needed in order to avoid ascribing minimum of δ18O to the warm season and maximum to the cold season. We stacked to keeping the extreme values in the middle of the season as this is in coherence with meteorological data.~~ We also used ammonium concentration as an independent marker, using criteria described on (Mikhalenko et al., 2015). 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 succinic acid concentration data that also have seasonal variations (Mikhalenko et al., 2015).

Figure 3 illustrates the identification of seasons using the isotopic composition seasonal cycle. In the meteorological data we used period from November to April for the cold season and ~~period from~~ May to October for the warm season.

There some gaps in the isotopic composition data that came from ~~the~~ technical problems during the drilling operations and the ~~analysis process~~process of analysis. The drilling problems are described in (Mikhalenko et al., 2015). The biggest gap appears at the depth of 31.3 and 32.1 m. ~~There was a~~A piece of the core was lost during the drilling operations. This part is covered by the bottom part of the 2004 core where the sampling resolution was 50 cm. It is evident that two seasons (one warm and one cold) are partially missing. We did~~n'~~ not use these values for the correlation analysis because of the large uncertainty of the seasonal values calculations in this case. In case of ~~one sample~~a missing sample we considered its isotopic value to be the average between the two neighboring 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 annual and seasonal values of δ^{18}O and *d* obtained as a result of the dating are shown in fig. 5 and 6 respectively.

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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~~Nye model (Nye, 1963; 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).

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2.1.5 Diffusion of stable isotopes

We calculated the potential influence 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 δ^{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 δ^{18}O maxima and increasing of minima with depth. Moreover we would find a positive correlation between layer thickness and a seasonal amplitude of δ^{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 i~~o~~n 1984 and the minimum in 1925. We therefore consider that the diffusion does not sufficiently influence ~~sufficiently~~ 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 δ^{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 δ^{18}O and *d* cycles. Thus, for obtaining climatic information from the bottom part of the core, a very high sampling resolution is required.

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~~of the 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. Circulation indices

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Circulation of the atmosphere sufficiently influences ~~sufficiently~~ isotopic composition of the ice cores (Casado et al., 2013 and references therein). Atmospheric circulation is quantitatively characterized by circulation indices. In this research we used three indices: NAO, AO, and NCP that are widely used to characterize European climate (Jones et al., 2003, Thompson and Wallace, 2001, Brunetti et al., 2011 and references therein). Time span and references for the indices are presented in table 1.

NAO (North-Atlantic Oscillation) characterizes the type of circulation in Europe, strength of Azores maximum and Icelandic minimum. ~~P~~The positive values of the NAO index correspond to the lower than usual value of the atmospheric pressure in Iceland and the higher than~~t~~ usual value of atmospheric pressure at Azores. The ~~N~~negative index corresponds to the less prominent centre~~er~~s of action in the Nor~~r~~thern Hemisphere. Usually this index is calculated as a difference of atmospheric pressure measured at Reykjavik and Lisbon, Ponta Delgada or Gibraltar. Here we used data from (Vinther et al., 2003 and https:\\crudata.uea.ac.uk\~timo\datapages\naoi.htm) that were calculated using data from Gibraltar station. The ~~N~~negative NAO leads to an increase ~~of~~ in the precipitation rate in Southern Europe, while a positive NAO leads to an increase in the~~of~~ precipitation rate in Northern Europe (Hurrel, 1995, Jones et al., 2003, Vinther et al., 2003).

The Arctic Oscillation index (AO) ~~also~~ is also a characteristic of the Northern Hemisphere circulation. It is used to analyze climatic variability with periods longer that 10 years. It is calculated as EOF of 500 hPa surface. Negative value~~d~~s correspond to high pressure at the Pole and the cooling of Europe, while positive values correspond to low pressure at the Pole and the drying of the Mediterranean (Thompson and Wallace, 2001). We used AO data from NOAA (http:\\www.cpc.ncep.noaa.gov\products\precip\CWlink\).

The NCP (North-Sea Caspian Pattern) index is less widely used, though it was proved that it is convenient to use it in Mediterranean climate studies (Kutiel et al., 1997; Brunetti et al., 2011). The index is calculated as a normalized difference of geopotential heights between the Caspian and Northern seas. Positive values correspond to stronger meridional circulation in Europe and lower summer temperatures, while ~~N~~negative values reflect the strengthening of zonal circulation and higher summer temperatures in Europe (Brunetti et al., 2011). We used NCP data from NOAA (http:\\www.cpc.ncep.noaa.gov\products\precip\CWlink\).

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 the locations of 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~~ However, 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. More examples of the Caucasus weather stations climatologies are given in (Mikhalenko et al., 2015). 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~~an 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~~throughout the region surrounding the Caucasus, with the warmest conditions observed in summer and the 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~~,~~. ~~w~~We used the data from all ~~of~~ the stations for the calculation. The lapse rate is lowest in ~~winter~~ December-February (2.3°C per 1000 m) and highest (5.2 °C per 1000 m) in ~~summer~~ June-August (Fig. S3).

Based on the lapse rate, we calculated the temperature at the drilling site taking into account its seasonal variability ~~(see Fig.8a for the annual mean temperature variations. and 8b and 8c for seasonal records~~shown on the fig. S3~~)~~. This record was used for the estimation of the δ^{18}O-temperature relashionship. For the comparison with the ice core data we used the dataset of the normalized temperature data. Normalized temperature time series were calculated for each station for each season or for the whole year, and results were then averaged (fig. 8). For precipitation data, available in this region since 1966, we show all the data (fig. S4), while in the calculations we used data from Klukhorskiy Pereval station as an example of stations without a seasonal cycle, and from Mineralnye Vody station as an example of those with a prominent cycle. More examples of annual variations of temperature and precipitation at the Caucasus meteorological stations can be found in (Shahgedanova et al., 2014) and (Tielidze, 2016). 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 the difference in absolute values on ~~the~~ a 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 corresponds 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.

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We then investigated long-term trends in the meteorological records. Mean annual temperatures show a significant increase during the last two decades. We also observe higher than average values of mean decadal temperature in 1930-1940. And the beginning of the observations in the region, i.e. the period from 1881 till 1900, was as cold as the 1990s. It is evident that the last 20 years in the warm season were the warmest for the whole observation period (fig. 8), while in the cold season the recent warming is not unprecedented. For example, cold seasons in the 1960s – 1970s were even warmer (fig. 8). Multi-decadal patterns of temperature variations also differ in the late 19th c~~C~~entury, where negative anomalies are identified in cold season temperature (Fig. 8) but not in warm season temperature (Fig 8). On the other hand in cold season temperatures we can observe lower temperatures at the end of the 19th century that can be due to the impact of the volcanic eruptions (Stoffel et al., 2015). We also noted the high temperature values in the 1910s - 1920s that ~~is~~ are not completely understood. We did not find any trends in the precipitation rate for ~~neither~~any of the groups of stations (fig. S4).

A significant anti-correlation is observed between temperature and the NAO index, both in the cold and warm seasons (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 the cold season, as also reported by Brunetti et al. (2011). 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 both seasons (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 δ^{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 an interannual scale. We therefore restrict discussion of GNIP data to seasonal variations. The δ^{18}O and δD in precipitation have a distinct seasonal cycle with maximum values observed in the warm season (JJA) and minimum values observed in the cold season (DJF). As an example we show the seasonal cycle of δ^{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 δ^{18}O is about 17 ‰. The slope between δ^{18}O and temperature is 0.32 ‰/°C. The *d* variations show no seasonal cycle varying randomly between 10 ‰ and 25 ‰. We found no significant correlation between δ^{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 the number of extremely cold months decreased faster in the Eastern than in the Western region. In addition, the 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 a recent increase ~~of~~ in the annual mean temperatures at different elevations in the Georgian Caucasus. The region experienced glacier area loss over the

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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 cannot be explained by increase of temperature during the ablation period because of an increase ~~of~~ in precipitation during the accumulation period. They concluded that the main driver of glacier retreat is the ~~if~~ increase of the solar radiation balance for 4% for the 2001-2010 period which corresponds to the 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 result of a mutual compensation of $\delta^{18}O$ increase due to lower elevation position (Kazbek drilling site is 500 m lower) and of $\delta^{18}O$ decrease because of continentality effect (Kazbek is 200 km further from the sea). We calculated continental gradient and lapse rate for $\delta^{18}O$ using the data from the GNIP stations in the region that are situated at the lower elevations. The lapse rate is -0.25 ‰/100 m and continental gradient is -0.85 ‰ /100 km. The mean value of $\delta^{18}O$ for Kazbek ice core should be 1.25‰ more positive because of elevation difference and 1.7‰ more negative due to continentality factor.

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The inter-annual variability in isotopic composition is about twice larger in the cold season than in the warm season 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 the cold versus the warm season.

The δD and $\delta^{18}O$ values are highly correlated ($r = 0.99$) on a 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 a 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 cold / warm season $\delta^{18}O$, nor in the cold /-warm season accumulation rate or deuterium excess. We observe large variations in $\delta^{18}O$ with high and variable values in the 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 as well as in annual means 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 seasons are observed in 1912-1920. While a recent warming trend is observed in the regional meteorological data (in warm season), 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 the high snow accumulation rate. The highest δ^{18}O values for a single year correspond to the warm 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 δ^{18}O does not display any clear structure. By contrast, deuterium excess is weakly positively correlated with the accumulation rate during the warm season ($r = 0.31$, $p<0.05$). This finding is consistent with the GNIP data in the region that show no link between δ^{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 cold season and in fig. 10 for the warm season.

We found no significant correlation between the ice core δ^{18}O record and regional temperature, neither with the reanalysis data, nor with the observation data, when using the whole period. A significant correlation ($r = 0.44$, $p<0.05$) emerges for warm season data, when calculated for the period since 1984. The slope for this period is 0.6 per mille per °C. We also repeated our linear correlation analysis using precipitation weighted temperature, and obtained the same results. The precipitation weighted temperature was calculated using daily meteorological data. We used data from two stations: Klukhorskiy Pereval (as a representative of the southern stations) and Mineralnye Vody (as a representative of the northern stations).

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Obviously, the above inferences strongly depend on the uncertainties of the timescale used. If one concedes that the error of the timescale could be significantly greater than ±2 year, quite different conclusions may be reached by adjusting the scale of the δ18O and T records against each other. For instance, by contracting the δ18O record by 8 years with respect to the initial timescale in Figs 9 and 10, one would find much better correlation between δ18O and temperature, thus reaching the conclusion that the local temperature is the main driver of the δ18O variability. However, based on various experimental evidences, as discussed in the dating section, we argue that the timescale developed for the Elbrus ice core is accurate within ±2 years. Therefore, the most realistic conclusion of those that can be drawn from the data obtained is that the temperature is weakly correlated with the δ18O, and that this correlation is unstable in time.

We also did~~n't~~ not 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 δ^{18}O – temperature relation on-site experiments and subsequent modeling is required.

Our results are comparable to those obtained in the Alps by Mariani et al. (2014) for the Fiescherhorn glacier where the authors found significant though weak correlation between temperature and δ^{18}O. However for the Elbrus ice core this correlation was found in the warm season only.

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~~Our results are comparable to those obtained in the Alps by Mariani et al. (2014): again, while the seasonal cycle of ice core~~ ~~δ^{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 dataset 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.

The ~~S~~seasonal accumulation rate is seasonal layer thickness corrected for densification using the density profile from Mikhalenko et al. (2015) and for the layer thinning due to glacier flow using the Nye model (Nye, 1963; Dansgaard and Johnsen, 1969). It is linked to the precipitation rate on the stations situated south of the Caucasus in both seasons (r = 0.49), and even more closely related to precipitation from Klukhorski Pereval station (r = 0.63 for both seasons). We therefore establish a linear regression model for the period 1966-2013, and use this methodology to reconstruct past precipitation rates for the Klukhorskiy Pereval station (1914-1965), when meteorological records are not reliable or un~~not~~ available. The reconstructed records are shown on fig. 9 and 10 for the cold and warm seasons respectively. We found no significant trend in the reconstructed precipitation values. Even so, these results ~~can~~ may be useful for validation of regional climate models and water resource assessment.

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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 strongly 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.

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

We did~~n’t~~ not find any statistically significant correlations between ice cores data and large scale modes of variability when using the mean annual values. We present the results of calculations in the table 4. We report a weak though significant ($p<0.05$) negative correlation ($r = - 0.18$) between the ice core accumulation rate record and NAO in the cold season. 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 cold season $\delta^{18}O$ record shows a positive correlation with the NAO index ($r = 0.41$), 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 source is the Atlantic. In the first case the precipitation $\delta^{18}O$ preserved in the ice core is higher because of the higher initial sea water isotopic composition (Gat et al., 1996) and the shorter distillation pathway. ~~It is also t~~The continental recycling of moisture (Eltahir and Bras, 1996) ~~that~~ also influences the water isotopic composition. Due to this process the $\delta^{18}O$ values became lower while the *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 $\delta^{18}O$.

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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, ~~n~~or 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.

4 Conclusion

We found no persistent link between ice cores $\delta^{18}O$ and temperature on an interannual scale, a 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

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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 the warm season, and consists of evaporation from the Black Sea and continental evapotranspiration. Changes in regional temperature during warm season 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. Cold season 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~~the isotopic composition of the ice cores ~~-~~appears mostly related to characteristics of large~~-~~-scale atmosphere circulation such as the NAO index. The changes in moisture origin also influence the 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 significantly correlated with the precipitation rate and gives information about precipitation variability before the beginning of meteorological observations.

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Figures

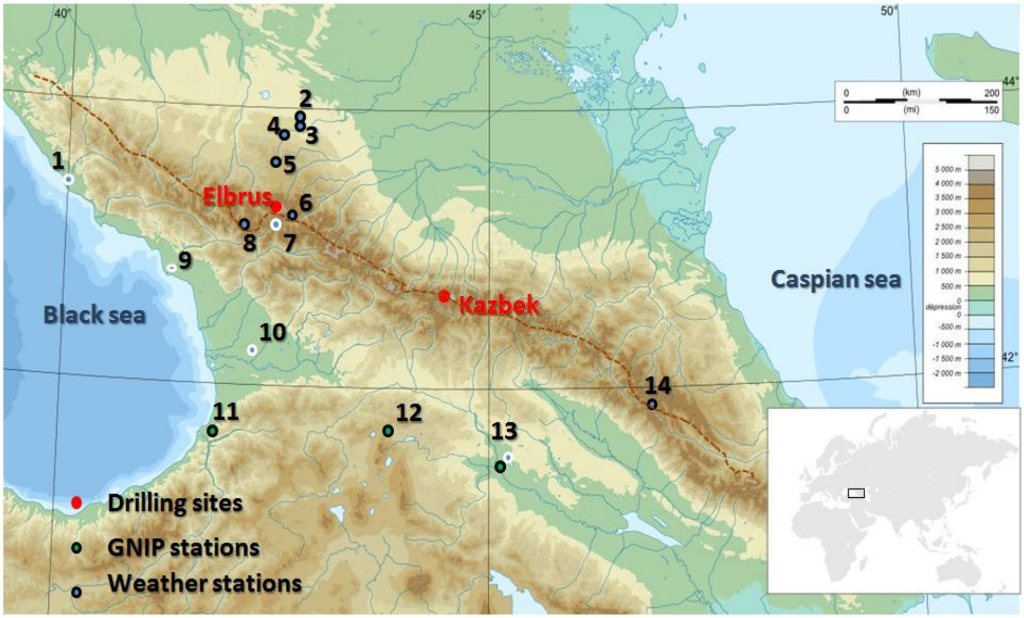


Fig. 1: Map showing the region around Elbrus (black rectangle in the world's map in the lower right corner), with shading indicating elevation (m above sea level). Drilling sites are indicated with red filled circles, GNIP stations as green filled circles, and meteorological stations as blue dots. Stations 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.

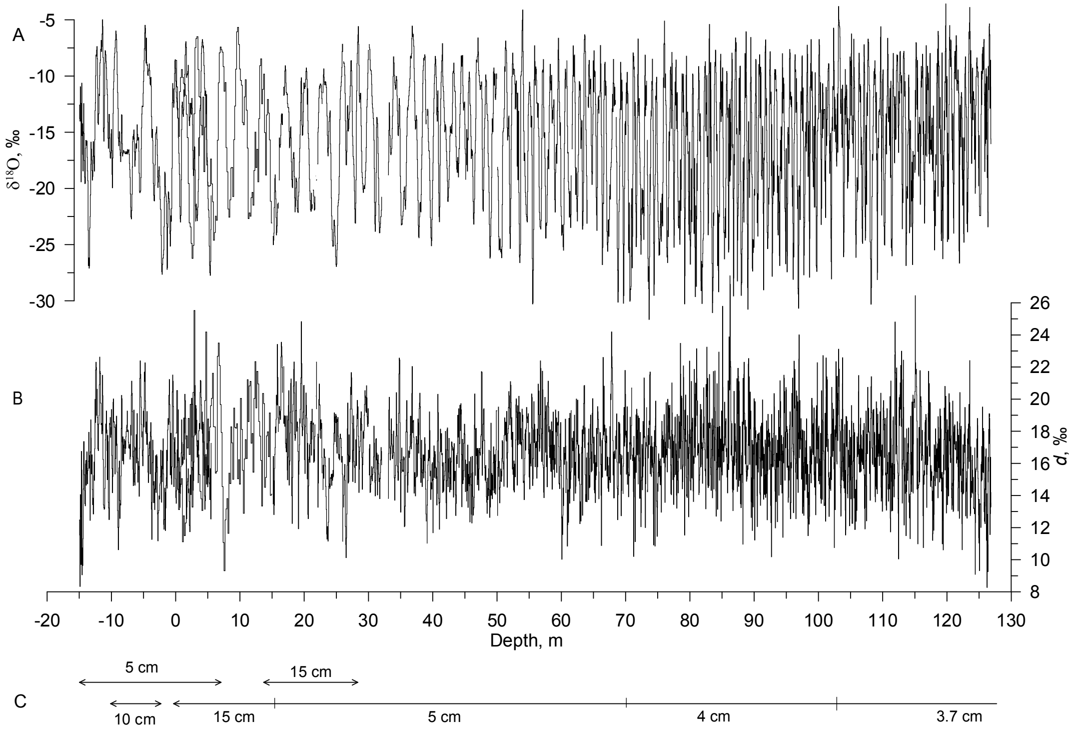


Fig. 2. Vertical profile of δ^{18}O (A), deuterium excess (B), and the number of the ice core as well as sampling resolution (C). 0 m depth corresponds to the surface of 2009.

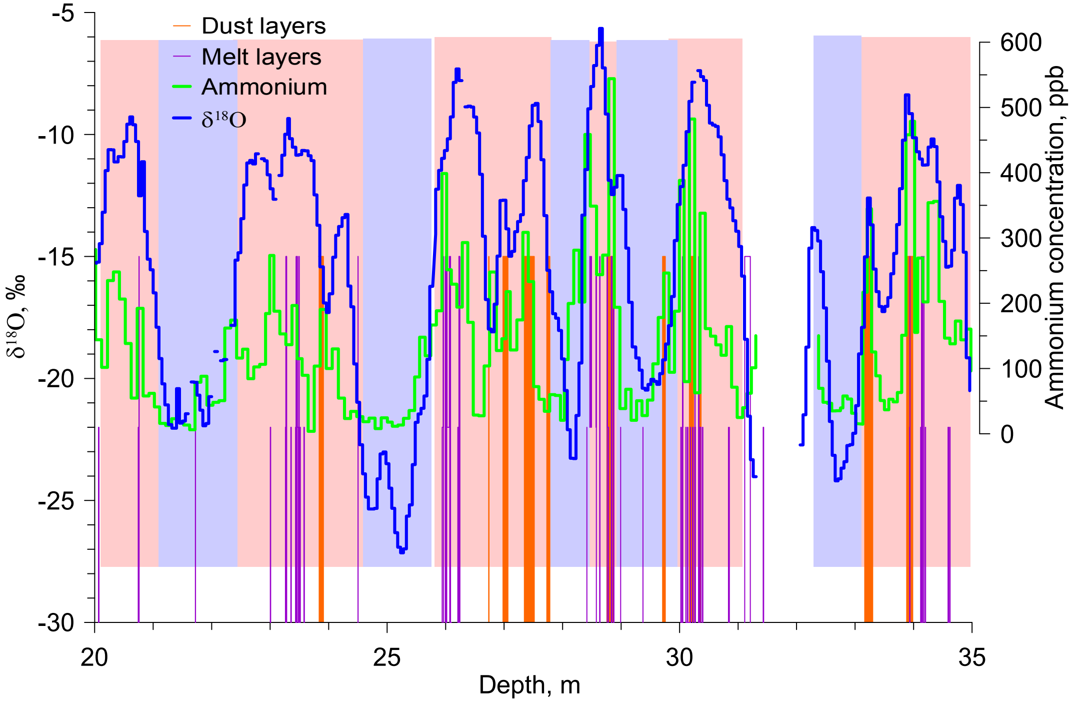


Fig. 3: Illustration of the scheme used to identify warm and cold half-years (respectively indicated by the light red and light blue shaded areas) based on the deviation of the mean δ^{18}O values from the long-term average value. The purple lines depict the melt layers observed in the core, dust layers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

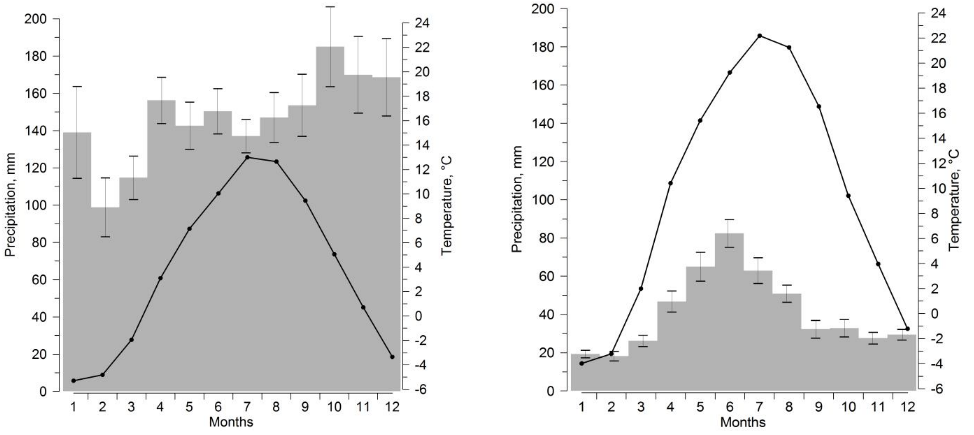


Fig. 4: Average seasonal cycle of temperature (black dots and line) and precipitation (grey bars) calculated over 1966-1990 period, a) for the Klukhorsky Pereval station (illustrating the lack of a distinct seasonal cycle in precipitation south of the Caucasus) and b) for the Mineralnye Vody station (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.

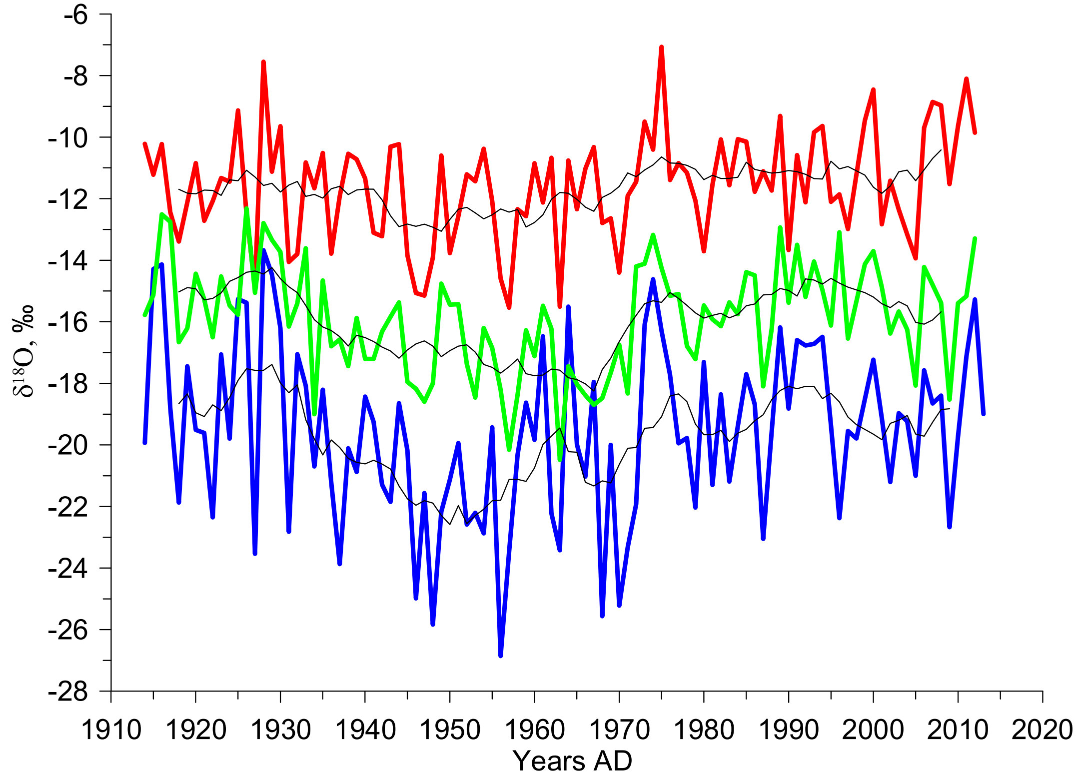


Fig. 5: Annual variations of $\delta^{18}O$ in warm season (red line), in cold season (blue line), and annual means (green line). Thin black lines show 10-year running means of these parameters.

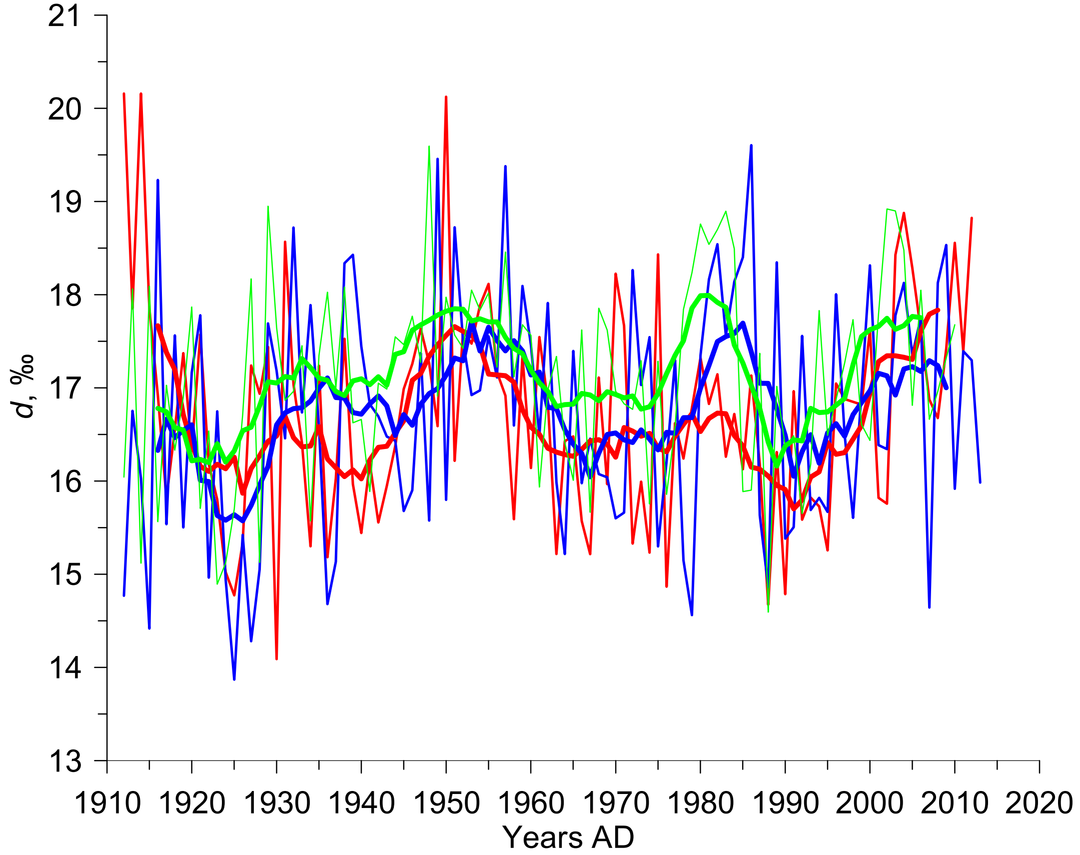


Fig. 6: Annual variations of deuterium excess in warm season (red line), in cold season (blue line), and mean annual values (green line). Thick lines show the 10-year smoothed values and the thin ones display the raw values.

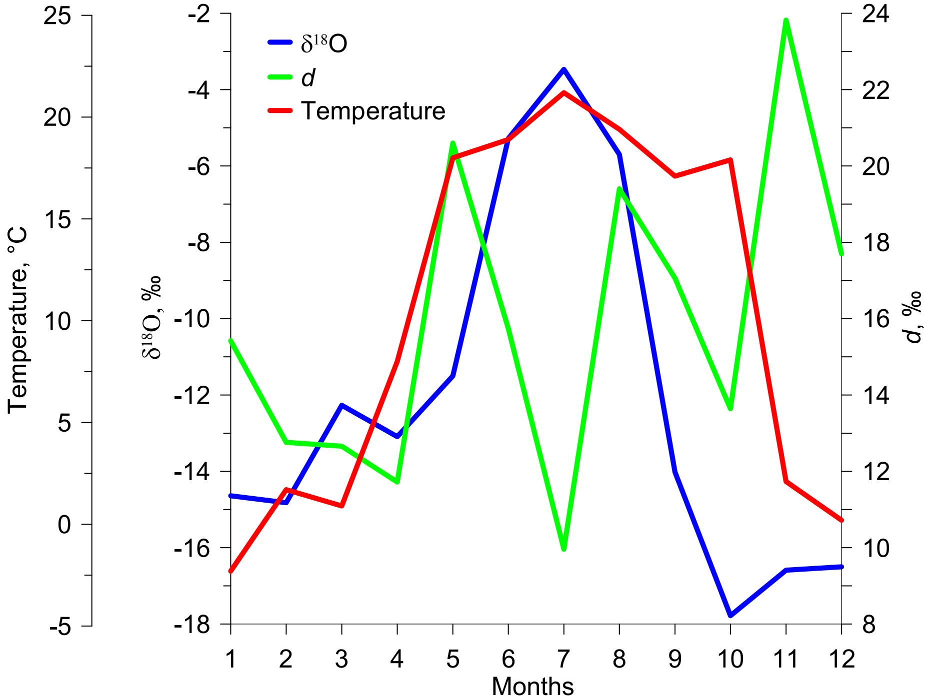
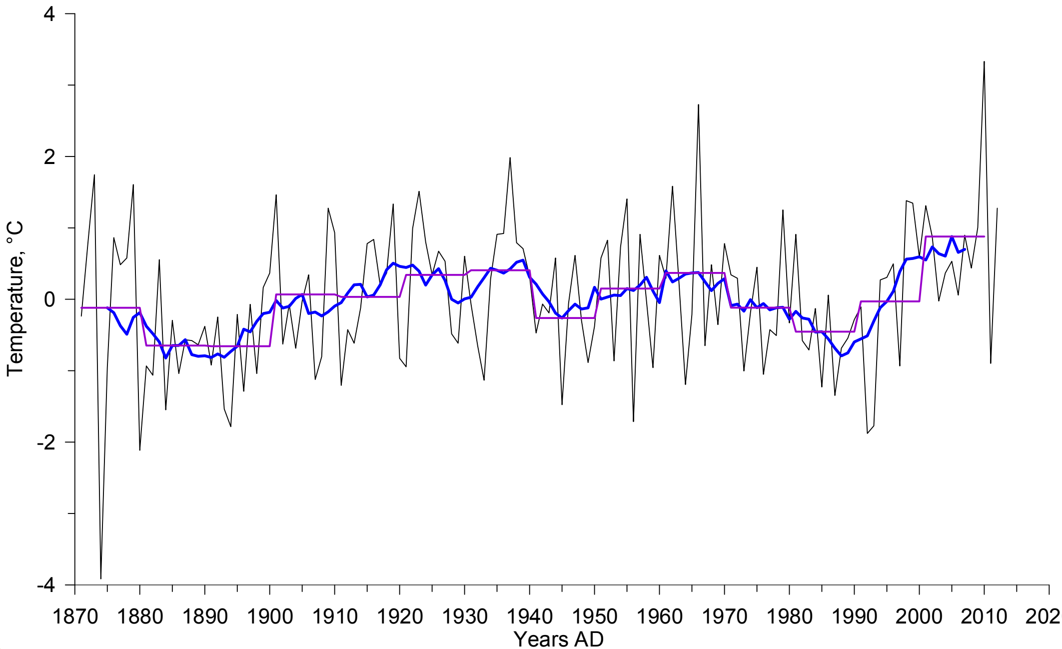
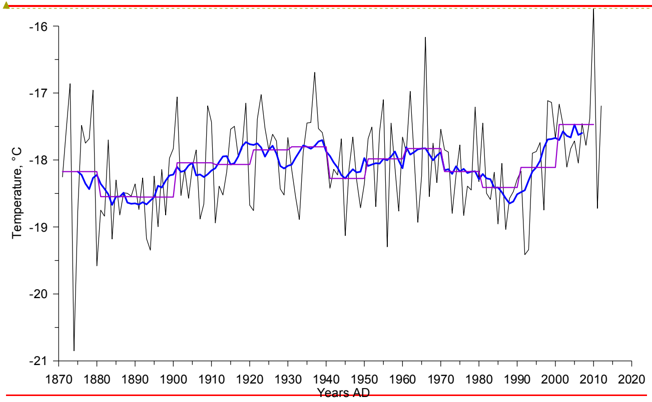
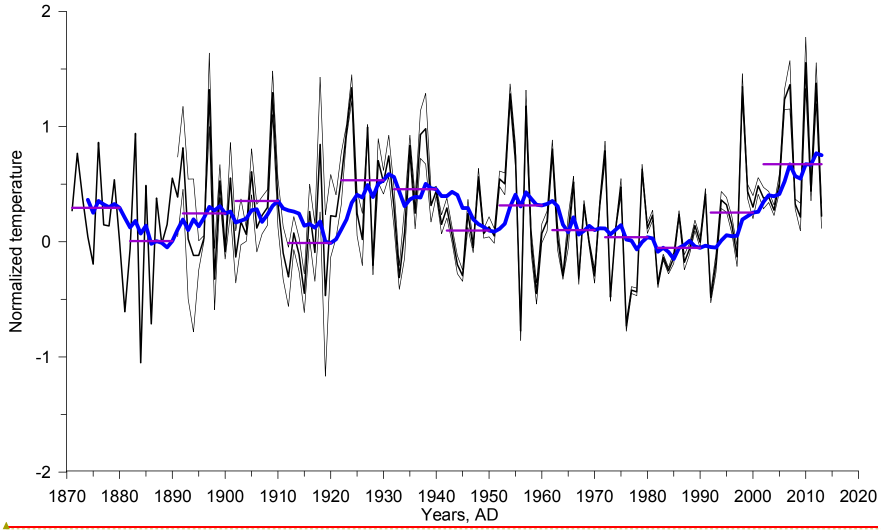


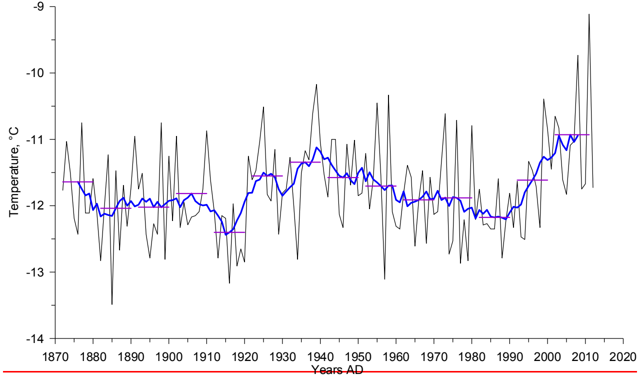
Fig. 7: Monthly $\delta^{18}O$ (blue line), *d* (green line) and air temperature (red line) data at Bakuriani GNIP station in 2009 (see Table 1 for information on station and Fig. 1 for its location). Note that there is no clear seasonal cycle in deuterium excess, in contrast with $\delta^{18}O$ showing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



Отформатировано: Шрифт: 9 пт, полужирный







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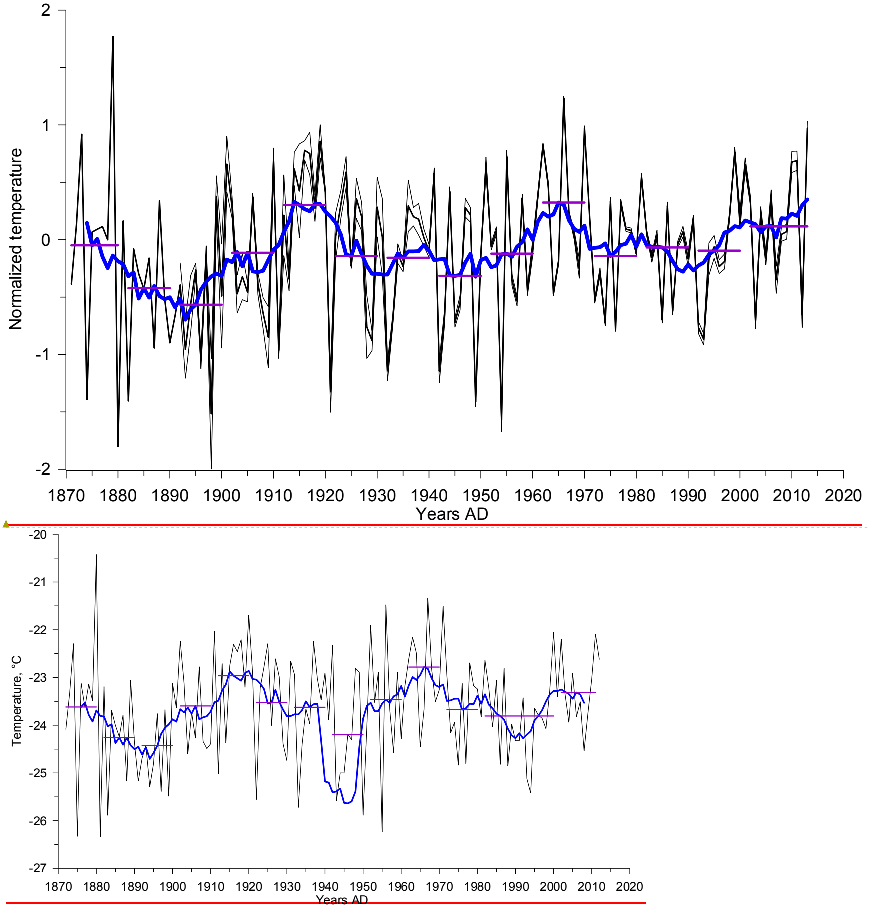
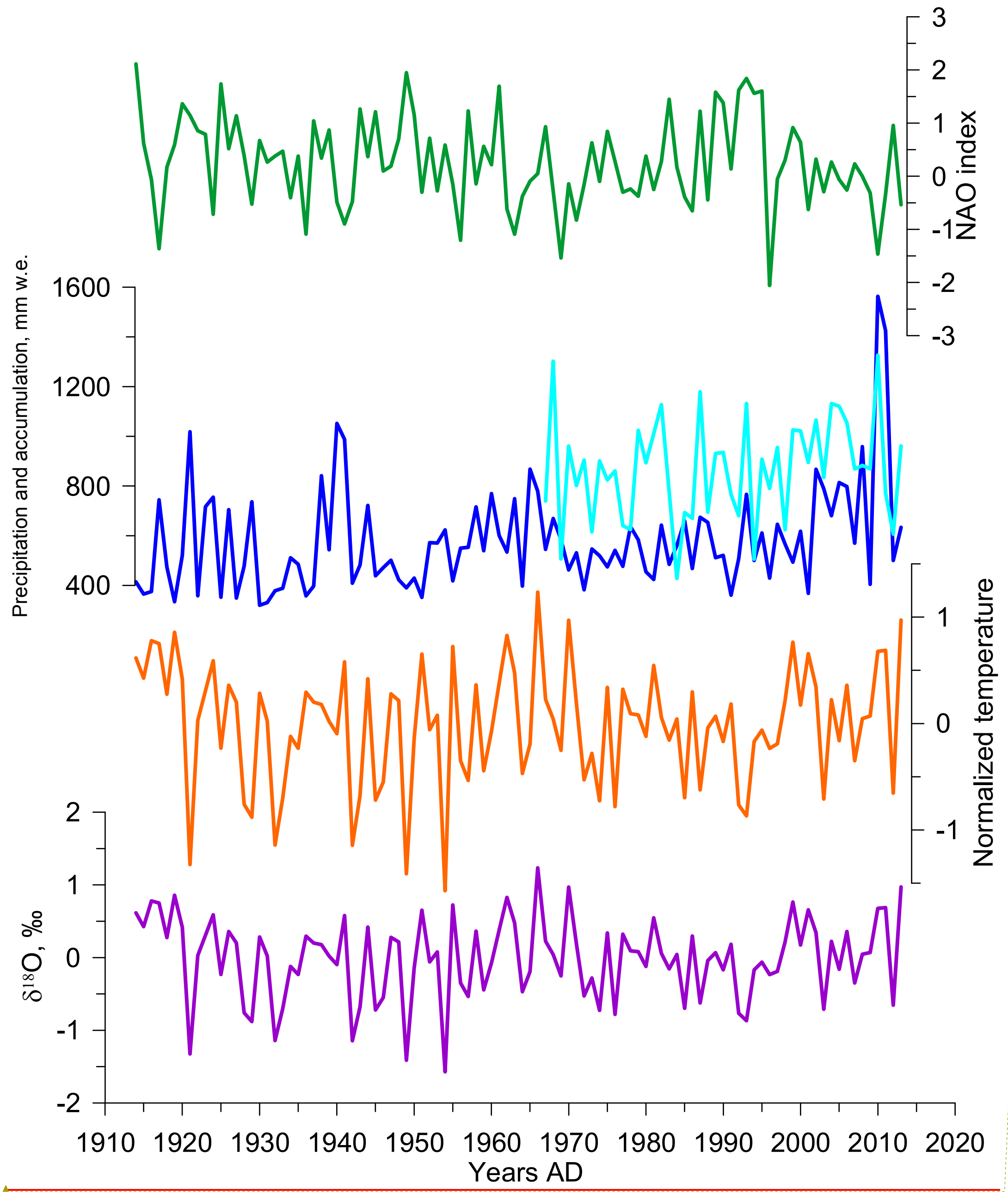


Отформатировано: Шрифт: 9 пт, полужирный

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 annual means, middle panel for the warm season, and the lower panel for the cold season.



Отформатировано: Шрифт: 9 пт, полужирный

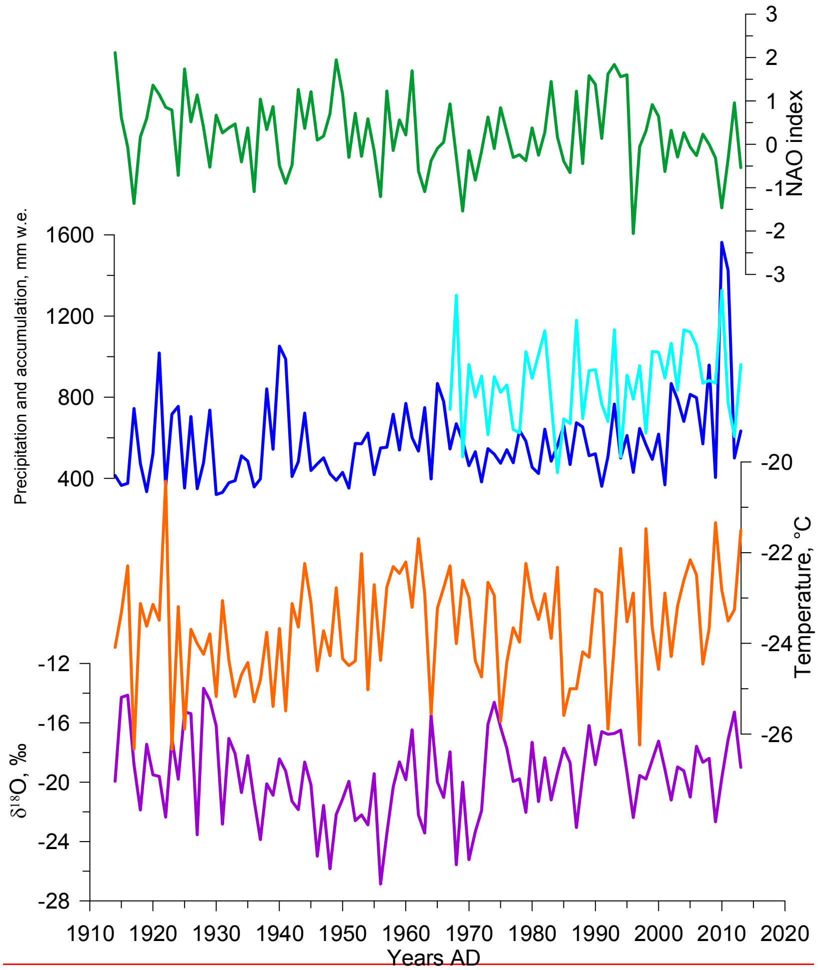
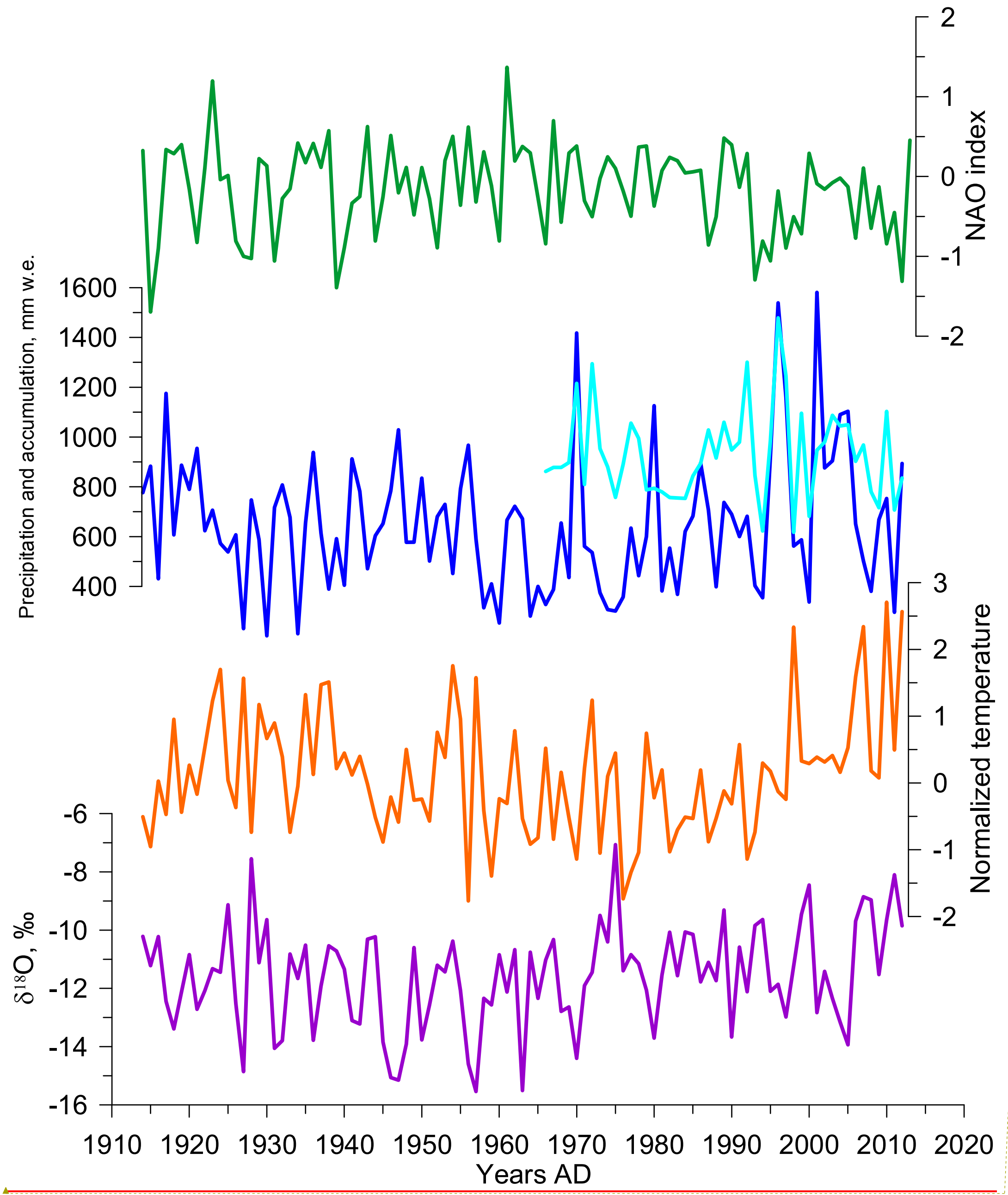


Fig. 9: Comparison of the ice core record with instrumental regional climate information, for the cold season: δ^{18}O composite (purple), temperature at the drilling site calculated from the lapse rate (brown), precipitation at the Klukhorskiy Pereval station (light blue) as well as the ice core accumulation estimate (dark blue) and NAO index(green).



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Отформатировано: Шрифт: 9 пт, полужирный

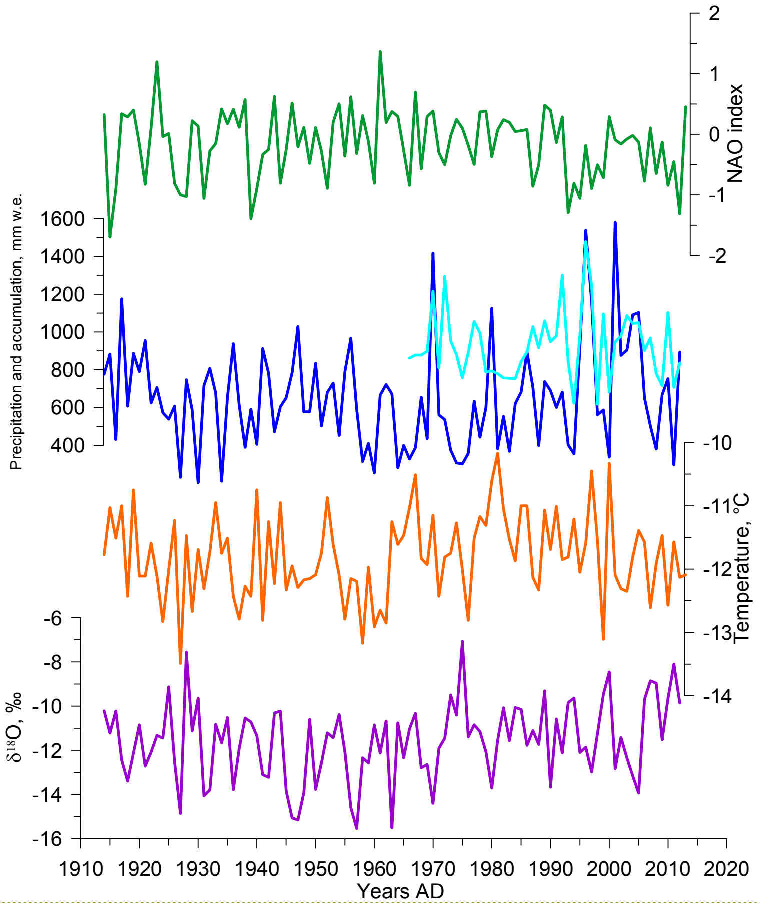

Fig. 10: Same as fig. 9 but for the warm season.

Отформатировано: Шрифт: 0 пт, Цвет шрифта: Черный, Масштаб знаков: 0%

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	
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 and number of data points (n) for each coefficient are shown in brackets.

Annual mean	Temperature	P south*	P north*
NAO	**-0.24** (1914-2013, n=100)	-0.24 (1966-2013, n=48)	-0.03 (1966-2013, n=48)
AO	**-0.34** (1950-2013, n=64)	-0.06 (1966-2013, n=48)	0.02 (1966-2013, n=48)
NCP	**-0.55** (1948-2013, n=66)	0.26 (1966-2013, n=48)	0.26 (1966-2013, n=48)
Warm season			
NAO	**-0.47** (1914-2013, n=100)	0.23 (1966-2013, n=48)	0.03 (1966-2013, n=48)
AO	-0.11 (1950-2013, n=64)	0.08 (1966-2013, n=48)	0.14 (1966-2013, n=48)
NCP	**-0.50** (1948-2013, n=66)	**0.34** (1966-2013, n=48)	**0.34** (1966-2013, n=48)
Cold season			
NAO	**-0.41** (1914-2013, n=100)	0.04 (1966-2013, n=48)	0.26 (1966-2013, n=48)
AO	**-0.40** (1950-2013, n=64)	0.14 (1966-2013, n=48)	**0.37** (1966-2013, n=48)
NCP	**-0.77** (1948-2013, n=66)	0.25 (1966-2013, n=48)	**0.33** (1966-2013, n=48)

*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.

Annual means	$\delta^{18}O$, ‰	δD, ‰	*d*, ‰	Accumulation rate (m w.e./year)
Mean	-15.90	-110.10	17.11	1,29
Standard deviation	1.76	14.03	1.02	0.44
Cold season				
Mean	-19.61	--140.11	16.59	0.71
Standard deviation	2.81	22.54	2.11	0.36
Warm season				
Mean	-11.58	-75.97	16.69	0.65
Standard deviation	1.75	13.98	1.14	0.27

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 and number of data points (n) for each coefficient is shown in brackets.

Annual means	$\delta^{18}O$	Accumulation	*d*	NAO	AO	NCP
T. °C	-0.01 (1914-2013, n=100)	**0.16** (1914-2013, n=100)	0.00 (1914-2013, n=100)	**-0.24** (1914-2013, n=100)	**-0.34** (1950-2013, n=64)	**-0.55** (1948-2013, n=66)
P north*	**-0.30** (1966-2013, n=48)	**0.36** (1966-2013, n=48)	0.17 (1966-2013, n=48)	-0.03 (1966-2013, n=48)	-0.03 (1966-2013, n=48)	0.27 (1966-2013, n=48)
P south*	0.06 (1966-2013, n=48)	**0.52** (1966-2013, n=48)	0.07 (1966-2013, n=48)	-0.24 (1966-2013, n=48)	-0.06 (1966-2013, n=48)	0.18 (1966-2013, n=48)
$\delta^{18}O$		**-0.20** (1914-2013, n=100)	-0.06 (1914-2013, n=100)	0.07 (1914-2013, n=100)	**0.41** (1950-2013, n=64)	0.11 (1948-2013, n=66)
Accumulation			**0.21** ~~06~~ (1914-2013, n=100)	**-0.29** (1914-2013, n=100)	**-0.29** (1950-2013, n=64)	-0.03 (1948-2013, n=66)
d				-0.08 (1914-2013, n=100)	**-0.26** (1950-2013, n=64)	-0.14 (1948-2013, n=66)
Warm season	$\delta^{18}O$	Accumulation	*d*	NAO	AO	NCP
T. °C	0.13 (1914-2013, n=100)	-0.04 (1914-2013, n=100)	**0.20** (1914-2013, n=100)	-0.02 (1914-2013, n=100)	-0.10 (1950-2013, n=64)	**-0.51** (1948-2013, n=66)
P north*	0.01 (1966-2013, n=48)	0.16 (1966-2013, n=48)	0.09 (1966-2013, n=48)	0.13 (1966-2013, n=48)	-0.14 (1966-2013, n=48)	0.18 (1966-2013, n=48)
P south*	-0.27 (1966-2013, n=48)	**0.49** (1966-2013, n=48)	-0.02 (1966-2013, n=48)	-0.01 (1966-2013, n=48)	0.07 (1966-2013, n=48)	**0.34** (1966-2013, n=48)
$\delta^{18}O$		**-0.42** (1914-2013, n=100)	-0.05 (1914-2013, n=100)	-0.08 (1914-2013, n=100)	0.16 (1950-2013, n=64)	0.00 (1948-2013, n=66)
Accumulation			**0.31** ~~06~~ (1914-2013, n=100)	0.00 (1914-2013, n=100)	0.09 (1950-2013, n=64)	0.00 (1948-2013, n=66)
d				0.00 (1914-2013, n=100)	-0.01 (1950-2013, n=64)	-0.14 (1948-2013, n=66)
Cold season	$\delta^{18}O$	Accumulation	*d*	NAO	AO	NCP
T. °C	-0.09 (1914-2013, n=100)	0.11 (1914-2013, n=100)	-0.15 (1914-2013, n=100)	**-0.30** (1914-2013, n=100)	**-0.45** (1950-2013, n=64)	**-0.79** (1948-2013, n=66)
P north*	0.20 (1966-2013, n=48)	0.21 (1966-2013, n=48)	-0.12 (1966-2013, n=48)	**0.51** (1966-2013, n=48)	**0.37** (1966-2013, n=48)	0.23 (1966-2013, n=48)
P south*	**-0.30** (1966-2013, n=48)	**0.37** (1966-2013, n=48)	-0.13 (1966-2013, n=48)	0.26 (1966-2013, n=48)	0.14 (1966-2013, n=48)	0.25 (1966-2013, n=48)
$\delta^{18}O$		0.05 (1914-2013, n=100)	0.02 (1914-2013, n=100)	**0.41** (1914-2013, n=100)	**0.41** (1950-2013, n=64)	0.19 (1948-2013, n=66)
Accumulation			0.07 (1914-2013, n=100)	-0.18 (1914-2013, n=100)	-0.15 (1950-2013, n=64)	0.18 (1948-2013, n=66)
d				-0.06 (1914-2013, n=100)	-0.01 (1950-2013, n=64)	0.11 (1948-2013, n=66)

*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.

Отформатировано: Шрифт: полужирный

Отформатировано: Цвет шрифта: Текст 1

Отформатировано: Шрифт: полужирный

Отформатировано: Шрифт: полужирный

Отформатировано: Цвет шрифта: Текст 1

Отформатировано: Цвет шрифта: Текст 1

Отформатировано: Шрифт: полужирный

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