Answers to Referees' comments on manuscript "Non-climatic signal in ice core records: Lessons from Antarctic mega-dunes" by A. Ekaykin et al.

Referee 1 – M. Frezzotti

General comment:

In the manuscript the Authors do not distinguish megadune from others wind-glazed morphologies and transversal dune (see Frezzotti et al., 2002a, Scambos et al., 2012, Das et al., 2013). The wind-glazed morphologies are located over steep bedrock topography beneath relatively steep surface topography (>4 m/km). Megadune, as also the authors pointed out, is conventionally used to describe the specific dune field observed only in the central East Antarctica, mainly in the southern part of East Antarctic ice divide. Megadune forms a system of parallel rideges with the wavelength of 2-5 km and amplitude of 2-8 m. Megadune are different from that described by Pettre in Adelie Land, Anschutz and Eisen in DML etc or in WAIS etc. Wind crust in megadune area is not controlled by steep bedrock topography as pointed out previous paper (Frezzotti et al., 2002a), but it appear to be formed by an oscillation in the katabatic air flow leading to a wave-like variation in net accumulation (Frezzotti et al., 2002b). The wind-waves are formed at the change of slope along wind direction, in response to the buoyancy force, in strongly stable environments with light winds, and might be related to a natural resonance. Authors should distinguish the different morphologies (megadune, wide glazed area, transversal dune etc.) and relative snow accumulation process, chemical and isotopic properties in the introduction paragraph and elsewhere.

Answer: we agree with the referee, that we mixed all the dune forms, which might be confusing for a reader. Actually, we argue that the relationships between surface slope, snow accumulation rate and surface snow isotopic content, revealed in this manuscript, should be common for any type of dunes. However, since we only studied mega-dunes, we should more accurately distinguish between mega-dunes and other dune types. Thus we have made numerous corrections in the Introduction and in the Results section (see the corrections in the supplement file).

Specific comments:

Pettre et al., 1986; Anschuutz et al., 2006 and 2007; Eisen et al., 2005; Fujita et al.,2002; Gow and Rowland, 1965; Whillans, 1975; Dolgushin, 1958; Vladimirova and Ekaykin, 2014; Black and Budd, 1964; Goodwin, 1990; Black and Budd, 1964; Ekaykin et al. (2002), Frezzotti et al. (2007), Fujita et al. (2011), Hamilton (2004), Kaspari et al. (2004), Richardson et al. (1997), Rotschky et al. (2004); Dixon et al., 2013; Neumann et al., 2005; van der Veen et al., 1999 have studied wind crust or transversal dune area, no megadune.

We agree with this comment. Corresponding changes have been made in the text (see the supplement file).

Pag 6911 Line 20, the dune does not redistribute the snow, is the wind. Dune is an eolian morphology, no an eolian process.

We agree with this comment and suggest the following changes in the text:

The first observations of relationship between the ice sheet surface topography (surface slope) and snow accumulation rate have shown that **in all types of the dunes the snow is subjected to a very strong aeolian redistribution** with the increased accumulation in the concaves and reduced accumulation on the convexities

Pag 6917 line 10-15. Frezzotti et al., 2002b have evaluated the SMB in megadune area on the base on the GPR layer at 12 m, which is the SMB average since Tambora (around 185 yr). Could the authors provide similar evaluation from GPR and compare with two years stake measurements?

Thank you for a very good idea! We made such an evaluation and added the following paragraph in the text:

Snow accumulation variability observed at the stakes during only 2 years of observations may not adequately represent the long-term average due to very large random component. We used the GPR data (Fig. 3g) and data on firn density from the 20-m core in order to evaluate spatial variability of the multi-year average of the snow accumulation rate. The first internal reflection horizon (estimated age is about 130 years, see below) is located at the depth that varies from 3 to 11 m. Thus, mean 130-year snow accumulation rate varies between 1 and 35 mm w.e. over one full dune wavelength, with an average of 21 mm w.e. Thus, the multi-year spatial variability of snow accumulation rate is considerably smaller than that obtained from 2-year stake measurements, but still larger than that reported by (Frezzotti et al., 2002b).

Pag 6917 line 27 Anschutz et al., 2006 is not in megadune area, the SMB, slope and wavelength is an order of magnitude different from Vostok megadune.

We agree with that, so we eliminated this reference.

Pag 6918 line 1-27 and Fig 3, on the base of stake measurements: 1.5 m of integrated sample represents between 10 to 100 yrs of snow accumulation. The δD isotopic composition is less negative in low accumulation area, and does not appear enriched in heavy isotope, whereas δO17 appear depleted in the leeward part close to MD00.

We agree with that, except for “isotopic composition is less negative” means “enriched in heavy isotopes”. This comment does not suggest any question or correction, so we have not made any changes in the text.

We also agree that the sampling layer, 1.5 m, comprises different number of annual layers in different parts of the dune (from 18 to 65 years), which by itself may lead to different isotopic composition of these samples. However, from Figure 5a it is obvious that this factor may account for max 5-10 ‰, which is much less then observed 20-30 per mil over the dune.

Paragraph 3.2 The peculiarity of megadune process is the upstream migration (Frezzotti et al., 2002b). Megadune internal structures suggest that they are prograding windward with time and the ice is flowing downhill, so their surface position are teorethical “sagnant” whereas the buried megadune flowing downhill at ice sheet velocity (2 m/yr). The two velocities (upstream migration and ice velocity) have opposite direction and different module. Arcone et al., 2005 referes to other structures.

Even if Arcone et al., 2005 refers to other structures, the principle of the formation of apparent dune velocity (as seen in GPR images) as combination of dune drift relative to the ice, and movement of the ice itself, is valid for the mega-dunes, too. I agree that in most cases dune drift relative to ice (upwind) and ice movement itself (downslope) counteract one another. But in case of Vostok mega-dunes we have a rare situation when vectors of ice and of dunes are perpendicular one to another. This is due to the fact that here we have a regional anomaly of ice flow (ice flow is not orthogonal to the altitude contour lines) due to the presence of Lake Vostok. Thus in Figure 3g we see pure drift of the dunes.

Pag 6922 line 20-23, Benoist et al., 1982 have drilled at old Dome C site, that is not at Dome position and it is about 55 km NE of real Dome C site. Dome site is characterized by absence of local variation of topography with absence of wind crust and very low spatial snow accumulation (see Frezzotti et al., 2002a, Urbini et al., 2008; Fuijta et al., 2011; Das et al., 2013). Frezzotti et al., 2005 and Proposito et al., 2002 show the spatial variability in snow accumulation at 5 km distance using GPR and ice core along Terra Nova Bay Dome C traverse, and stressed the implication for paleoclimatic reconstruction.

I am absolutely agree with this comment, and this is why in manuscript we wrote “Even the **vicinities of** the main domes cannot be considered as “dune-safe””, so we are not talking about the dome summits. However, in order to make this part of the text more clear, we suggest the following corrections:

Even the vicinities of the main domes cannot be considered as “dune-safe”. Indeed, the study of the snow isotopic composition profile in two neighboring cores drilled **about 55 km to the north-east from the summit of** Dome C showed a very low signal-to-noise ratio likely related to the local ice sheet topography (Benoist et al., 1982).

Pag 6924 line 10-15. The glazed surface area at change of slope along wind direction presents in very short distance very high spatial variability in snow accumulation, more than megadune. For post depositional process studies these site are more useful because the distortion of megadune is characterised by the periodicity and complicate the interpretation of process due to the ovelapping of periodicity process.

I may agree with the Referee that the glazed areas are more useful to study post-depositional processes, though I do not have personal experience of working in the glazed areas, so I cannot refer to them in the manuscript in this context. From this comment I understand that the Referee in principle agree that the mega-dunes **are** useful to study the PD processes, although less than the glazed areas. If so, I suggest to leave this part of the manuscript’s text without changes. Moreover, the periodical structure of the mega-dunes is not a drawback in many cases. For example, one can think of a field experiments to study the post-depositional changes in snow isotope content, so that one experimental site is located in the low-accumulation part of the dune, and another site – in the high-accumulation part. Then, if this experiment lasts much shorter than 1 full period of the dune drift, than the results of such experiment will not be disturbed.

Referee 2 – T. Scambos

General comments:

There is some ambiguity in the analysis and the conclusions regarding the relationship of these megadunes to other true megadune areas. There is also some confusion or 'blurring' of what constitute true megadunes and other windrelated snow features. The paper will be a solid contribution, but I think there will need to be some significant revision to the Introduction, Results, and Discussion section. It is a bit unclear exactly what the paper is concluding at this point. One strong recommendation is to look more closely at the Vostok –area isotopic data and compare it with the megadune region they have studied. It may also be valuable to do a closer comparison with the structural characteristics reported in Frezzotti et al. studies (slopes, spacing of dunes, accumulation variations).

We agree that in the previous version of the manuscript we mixed different types of the dunes, as was also noted by Referee 1. In new version we have made a numerous corrections in Introduction and Results sections in order to distinguish between mega-dunes and other dune types – see the supplementary file. However, we think that our Vostok mega-dunes are "true" mega-dunes, as they fit the mega-dune definition: system of parallel ridges found in central (East) Antarctica in the areas characterized by relatively small slopes of ice surface.

In order to make our message more clear for a reader, we add the following text to the Conclusion:

As a result of our study we come to the following conclusions:

1) For the first time we demonstrated that snow isotopic composition has significant spatial variability in the mega-dune area in covariance with the snow accumulation rate and surface slope, although the mechanism that forms this variability is yet to be clarified. We also demonstrated how these spatial waves are transformed into the oscillations of snow isotopic composition in a firn/ice core vertical profile.

2) Based on published data we may conclude that significant (periodic or non-periodic) spatial variability is widespread in Antarctica, even outside the mega-dune areas. The drift of different types of dunes across the show/ice sheet surface causes non-climatic temporal variability of snow accumulation rate and isotopic composition, as observed in snow or ice cores, thus considerably reducing the signal-to-noise ratio on the timescales from decades to millennia.

3) The only robust way to obtain a reliable climatic signal is to investigate several ice cores and to construct a stack record of studied parameters.

We thank the Referee for the great idea to compare the snow isotopic data in the mega-dune area with the data from Vostok's vicinities. Unfortunately, we do not have at Vostok similar dataset (probes of the upper 1.5 m of snow sampled every 100 m), but still the data we have clearly demonstrate the difference between two regions. We added the following text to Section 3.1:

The spatial variability of the snow isotopic composition in the mega-dune area is significantly larger than in the area outside the mega-dunes. For example, the standard deviation of the δD values in the samples representing upper 1.5 m of snow and taken along a 40-km profile in the southern part of Lake Vostok, where the glacier is characterized by flat surface, is ±4 ‰ (Ekaykin et al., 2012) against ±6 ‰ in the mega-dune area. Another difference is that outside the mega-dunes the variability of snow isotopic composition is random, with no clear periodicity. At the same time, the average values of δD are similar in both cases, around -440 ‰.

In our manuscript we present all the data we have that describe the structural characteristics of the mega-dunes (slopes, spacing, accumulation variations) and compare them to the data reported in the previous studies (mainly in the works of M. Frezzotti). However, in new version of the manuscript we strengthen the discussion of the spatial variability of the accumulation rate (Section 3.1):

Snow accumulation variability observed at the stakes during only 2 years of observations may not adequately represent the long-term average due to very large random component. We used the GPR data (Fig. 3g) and data on firn density from the 20-m core in order to evaluate spatial variability of the multi-year average of the snow accumulation rate. The first internal reflection horizon (estimated age is about 130 years, see below) is located at the depth that varies from 3 to 11 m. Thus, mean 130-year snow accumulation rate varies between 1 and 35 mm w.e. over one full dune wavelength, with an average of 21 mm w.e. Thus, the multi-year spatial variability of snow accumulation rate is considerably smaller than that obtained from 2-year stake measurements, but still larger than that reported by (Frezzotti et al., 2002b).

Introduction – to many 'the' - and, in most studies the features are referred to as 'megadunes', without a hyphen. It is not clear to me that all the older studies are referring to true megadunes; Megadunes are (properly) repeated snow accumulation features (or accumulation / ablation pairs) that are not tied to a bedrock-driven high: something created by an oscillation in the atmosphere. It is true that at the upstream end of megadunes, there is usually a bedrock-driven break in slope, but the train of dunes following the slope break are atmospherically driven. Many studies have confused the strong accumulation variations around bedrock-driven ice sheet undulations, or areas where glaze is often seen on the lower ice sheet, as 'megadunes', and they are not the same. I think this term should be reserved for the features similar to those observed by Frezzotti, Fahnestock and Scambos, Arcone (some of his profiles, not all of them); and your area near Vostok. There is much to sort out regarding wind redistribution of snow in Antarctica and Greenland. Megadunes are part of it, but the term is sometimes applied too broadly. It would be good to distinguish these from the menagerie of wind-related forms. I'm a bit unclear as to excactly what you mean (later on in the paper) by 'meso-dunes' – do you mean longitudinal dunes? Or complex multi-formational sastrugi features? It would be good to spend a paragraph sorting these things out. I agree that true ‘megadunes’ occupy about 500,000 km2 of the East Antarctic interior, but not that they encompass all these studies.

As mentioned above, we substantially modified Introduction and Results sections in order to distinguish between mega-dunes and other dune types.

As for meso-dunes, we use this term to describe the snow relief forms bigger than micro-relief, but smaller than mega-dunes. We added some text to Discussion to make it clearer:

Meso-dunes are relatively small forms (with typical wavelengths from 200 to 300 m) of snow relief observed in the vicinities of Vostok Station. It was shown that the meso-dunes cause a spatial variability of snow properties: on the bumps the snow accumulation is lower, and its isotopic composition is higher, while in the hollows between the dunes more snow accumulates with lower concentration of heavy isotopologues (Ekaykin et al., 2002). Since these dunes seem to be not stagnant, it is likely that the drift of the meso-dunes causes the non-climatic temporal oscillations of snow isotopic composition and accumulation rate with a period of few decades due to mechanisms similar to those described in this paper for the mega-dunes.

Specific comments:

P6912-L12 – suggest you remove citation of Zwally et al., 2015. You are citing works that agree with you, and one that did not properly account for accumulation (Zwally). Citing incorrect studies (Zwally) is confusing to the reader.

The citation has been removed.

Data and methods – keep track of superscripts, in some cases the 17O is not superscripted properly. (Perhaps there is a new convention about ‘17O-excess’ that I am not aware of? To me, it should be superscripted.)

I agree with this comment. In all cases 17O-excess was replaced by ^{17}O-excess.

P6916, l10: : : :Figure 2, we show the GPR registration recorded: : : (replace ‘showed’)

Done

on line 20, p6916, yes, both smaller wavelength horizontally, and smaller in amplitude – this may be a factor in the degree to which the glaze / ablation effect is present, perhaps it explains the minor differences seen in mean accumulation and surface structures here. What is the amplitude of the waves relative to the regional slope? And the slope variations from the windward and leeward faces?

Indeed, in both length and amplitude our dunes are relatively small, and ratio amplitude/length is rather small, too: - 0.0006 (compared to 0.0006-0.001 for other dunes, given 2-5 m of amplitude and 2-8 km of length, see the review in Introduction). The regional slope is 0.0016, as pointed out in the beginning of Section 3, and local slope in our dunes changes from -0.005 at the windward side of the dune to 0.01 at the leeward side of the dune, as can be seen in Figure 3f.

It is likely that rather humble sizes and proportions of our dunes are responsible for the fact that the surface micro-relief differences between low-accumulation and high-accumulation zones of the dune are very small (if any). On the other hand, it does not explain why the corresponding difference in accumulation rate is relatively **big**! (see Discussion in Section 3.1). Smaller size of dunes should imply smaller wind speed at the leeward side of the dune – hence smaller ability to carry snow. Probably this is compensated by shorter distance to which snow has to be carried?

To explain all these things modeling of air flow over the dune is needed. This is beyond the scope of our paper since here we just need to show that our dunes behave like the other known dunes in the sense that they cause re-distribution of the snow. As soon as we prove that, we have the reason to discuss the influence of the dune on other snow properties (isotopic composition).

Still, to highlight possible relationships between different properties of the dune, we suggest the following changes in the text:

During the field work **seasons** we also did not observe big difference between snow surface character in leeward and windward slopes of the dunes (Fig. 4). The erosion zone does not demonstrate the dominance of the glaze surface, and no big sastrugi are observed in the accumulation zone, as reported by (Frezzotti et al., 2002b) for the Victoria Land mega-dune field. **The small difference in snow morphology between low- and high-accumulation zones of the dune may be related to the relatively small dune size, although it does not explain rather big spatial variability of snow accumulation.**

P6917, L20 ": : :during the field work seasons: : :' (need to change 'field-works', not commonly used).

Done

P6919, L1-3, restate the slopes as 0.000X, etc., per mil is not used for slope

In this case we refer to the slopes (or regression coefficients) between changes in isotopic composition, this is why we use ‰/‰. This is a dimensionless unit, indeed, but if we do not use ‰/‰, the reader may be confused: for the 17O-excess/dD slope we use per meg/‰, so it's better to use ‰/‰ for the dxs/dD slope, to be consistent. Also, this is often used in literature (see Landais et al., 2012, cited in the paper), so we prefer to keep this tradition.

P6920, L7-8 ": : :.a dune drifts by one full wavelength in about 410 years

Done

P6921, L21 "..the core has a δD isotopic composition of -420%

Done

The other major issue I have is that there is a strong isotopic variation but the authors do not infer much ablation : : : or even any net mass movement by vapor ? At one point the idea of summer versus winter accumulation is introduced, but disproved — and so, how do the large variations form if not by ablation? Yet I agree that it is perplexing that the total accumulation rate is so similar to the mean Vostok stake array value of 23 mm / year w.e.

Well, first point is: what "strong" isotopic variation means? Personally, I expected much stronger spatial variability of snow isotopic composition in the mega-dunes. The 20-25 ‰ of the amplitude (for dD) is the same order of magnitude as seen in the Vostok 300-year climatic record (as mentioned somewhere in the text and shown in Figure 5a) – for me it's a quite modest variability. Second, we do not need ablation to change the isotopic composition of the snow: (strong) sublimation, or just exchange with atmospheric water vapor, is enough. These processes are conventionally called "post-depositional", I cited in the manuscript few papers that describe them. In the low-accumulation zones of the dunes the snow is exposed to atmosphere for a longer time, so the post-depositional processes have more time to play, so the remaining snow is enriched in heavy isotopes – and the opposite in the high-accumulation zone. Last, the mean snow accumulation rate in the Vostok mega-dunes is the same as over the flat surface of Lake Vostok around the Vostok Station. The mean present-day isotopic composition of snow in the mega-dunes is the same as around Vostok, too. So, the whole picture is logical and consistent: on average the intensity of the post-depositional processes is the same in the mega-dunes and outside mega-dunes (given the same climatic conditions), but in the low-accumulation zone of MD these processes are stronger, which causes a **slight** enrichment in heavy isotopes, and in the high-accumulation zone they are weaker, which causes a slight depletion in heavy isotopes.

One thing to add to the paper (to Table 1 and then to the discussion) is a few values for the mean isotopic composition of the Vostok snow itself – enough well-analyzed samples for the reader to see the variability near the Base but away from the megadunes. How do these average values for snow on the flat lake surface compare with the megadune range of values? Does this provide some insight into formation processes or post-depositional modification of snow?

I agree with this suggestion, although I think that Table 1 is not a suitable place for this information, as Table 1 only gives glaciological information from 21 points along the mega-dune profile. As mentioned above, I added the following text to the Section 3.1:

The spatial variability of the snow isotopic composition in the mega-dune area is significantly larger than in the area outside the mega-dunes. For example, the standard deviation of the δD values in the samples representing upper 1.5 m of snow and taken along a 40-km profile in the southern part of Lake Vostok, where the glacier is characterized by flat surface, is ±4 ‰ (Ekaykin et al., 2012) against ±6 ‰ in the mega-dune area. Another difference is that outside the mega-dunes the variability of snow isotopic composition is random, with no clear periodicity. At the same time, the average values of δD are similar in both cases, around -440 ‰.

Some discussion, not formally related to my review here: I think there may be a range of megadune characteristics. Your study area appears to me to be incipient megadune formation, with measurable accumulation through the entire wave (according to the radar layering). Frezzotti's work showed a somewhat more developed pattern, much closer to zero accumulation in the leeward faces, but still traceable. In our study of large-wavelenth -3 to 5km, ~8 m amplitude dunes downhill from Vostok by ~300 km, we saw complete erasure of layering in the areas where glaze surfaces formed on the leeward sides, strong layering and high accumulation on the windward faces, and strong isotopic cycles in a vertical core.

From my(our) field work and the existing literature, my best assessment of how megadunes and associated glaze areas form is firmly linked to local variations in wind speed and the effective humidity of the near-surface air layer. In decending, drying conditions, it is not easy for snow grains to stick together; in ascending or flat airflow, the near surface layer quickly saturates with water by sublimation of entrained snow. Thus snow is not 'trapped' by the surface easily on the leeward slopes, and is either blown to the windward slope or consumed by evaporation. See Scambos, Frezzotti, et al., 2012; also Das et al, 2013 and 2015.

Thank you for this comment. As you can see in Figure 1 of the manuscript, our study area is located just in the middle of the Vostok mega-dune field: if we would move just 10 km further to the east, the mega-dunes would fade away. Probably, the dunes we study are as developed as they could be in these conditions; probably, the regional conditions are on the margin of the range of conditions suitable for mega-dunes.

It would be interesting to make similar investigations, as we made here, at the zone of mega-dune inception just 15 km to the east of Vostok station. This could likely help to understand how these dunes form.

It would be also nice to install automatic weather stations (including gradient observations) in the mega-dune field to test what you wrote in the end of your comment, but we do not have logistic facilities for such works.

Non-climatic signal in ice core records: Lessons from Antarctic mega-dunes

Alexey Ekaykin[1,2], Lutz Eberlein[3], Vladimir Lipenkov[1], Sergey Popov[4], Mirko Scheinert[3], Ludwig Schröder[3], Alexey Turkeev[1]

1 – Climate and Environmental Research Laboratory, Arctic and Antarctic Research Institute, 38 Beringa st., 199397, St. Petersburg, Russia

2 – St. Petersburg State University, 33-35, 10th line VO, 199178 St. Petersburg, Russia

3 – Technische Universität Dresden, Institut für Planetare Geodäsie, 01062 Dresden, Germany

4 – Polar Marine Geological Research Expedition, 24 Pobedy st., 198412 Lomonosov, Russia.

Corresponding author: ekaykin@aari.ru

Abstract

We present the results of glaciological investigations in the mega-dune area located 30 km to the east from Vostok Station (central East Antarctica) implemented during the 58th, 59th and 60th Russian Antarctic Expedition (January 2013 - January 2015). Snow accumulation rate and isotope content (δD, $\delta^{18}O$ and $\delta^{17}O$) were measured along the 2-km profile across the mega-dune ridge accompanied by precise GPS altitude measurements and GPR survey. It is shown that the spatial variability of snow accumulation and isotope content covaries with the surface slope. The accumulation rate regularly changes by one order of magnitude within the distance < 1 km, with the reduced accumulation at the leeward slope of the dune and increased accumulation in the hollow between the dunes. At the same time, the accumulation rate averaged over the length of a dune wave (22 mm w.e.) corresponds well with the value obtained at Vostok Station, which suggests no additional wind-driven snow sublimation in the mega-dunes compared to the surrounding plateau. The snow isotopic composition is in negative correlation with the snow accumulation. Analyzing dxs/δD and ^{17}O-excess/δD slopes, we conclude that the spatial variability of the snow isotopic composition in the mega-dune area could be explained by post-depositional snow modifications. Using the GPR data, we estimated the apparent dune drift velocity (4.6 ± 1.1 m yr^{-1}). The full cycle of the dune drift is thus about 410 years. Since the spatial anomalies of snow accumulation and isotopic composition are supposed to drift with the dune, an ice core drilled in the mega-dune area would exhibit the non-climatic 410-yr cycle of these two parameters. We simulated a vertical profile of snow isotopic composition with such a non-climatic variability, using the data on the dune size and velocity. This artificial profile is then compared with the real vertical profile of snow isotopic composition obtained from a core drilled in the mega-dune area. We note that the two profiles are very similar. The obtained results are discussed in terms of interpretation of data obtained from ice cores drilled beyond the mega-dune areas.

Отформатировано: надстрочные

1 Introduction

~~Mega-~~Large snow and ice dunes are one of the most intriguing and spectacular phenomena in Antarctica. The first reports on the existence of the huge waves on the surface of the Antarctic ice sheet was made soon after the beginning of the extensive exploration of the Antarctic interior during the IGY (Dolgushin, 1958), although the term “mega-dunes” was not yet used at that time.

Since then such surface undulations have been observed in different parts of the Antarctic continent – in Adelie Land (Pettre et al., 1986), Dronning Maud Land (Anschutz et al., 2006;Eisen et al., 2005), Enderby Land (Fujita et al., 2002), Marie Byrd Land (Whillans, 1975;Gow and Rowland, 1965), Victoria Land (Frezzotti et al., 2002b;Frezzotti et al., 2002a), Queen Mary Coast (Vladimirova and Ekaykin, 2014;Dolgushin, 1958), Wilkes Land (Black and Budd, 1964;Goodwin, 1990) – or, simply speaking, almost everywhere.

In 1988 Swithinbank suggested to call such waves term “mega-dunes” (Swithinbank, 1988) based on their similarity to the desert sand mega-dunes. At present this term is conventionally used to describe the specific dunes observed in central East Antarctica (Albert et al., 2004;Alberti and Biscaro, 2010;Fahnestock et al., 2000;Arcone et al., 2012b;Frezzotti et al., 2002b), which form the system of parallel ridges with the wavelength of 2-5 km, the amplitude 2-8 m, and the length of the ridges of up to 100 km. One should distinguish between mega-dunes and other forms of periodic, or “transversal” dunes that mainly form in the coastal zone of East Antarctic Ice Sheet and differ from mega-dunes in their morphology and, likely, origin.

The first observations of relationship between the ice sheet surface topography (surface slope) and snow accumulation rate have shown that in all types of the dunes the snow is subjected to a very strongly aeolian redistribute redistribution the snow with the increased accumulation in the concaves and reduced accumulation on the convexities (Black and Budd, 1964). This relationship has been later confirmed in a number of studies, e.g. (Frezzotti et al., 2007;Fujita et al., 2011;Hamilton, 2004;Kaspari et al., 2004;Richardson et al., 1997;Rotschky et al., 2004;Anschutz et al., 2007;Ekaykin et al., 2002;Dadic et al., 2013). These studies have also shown that the dunes are not stagnant, but rather drift across the ice sheet surface, which does not allow the snow to simply fill in the hollows between the dunes thus maintaining their dynamical equilibrium. The estimates of the dunes' horizontal drift velocity ranges from 4 to 25 m yr^{-1} (Whillans, 1975;Frezzotti et al., 2002b;Van der Veen et al., 1999;Black and Budd, 1964).

The first dedicated ground survey of mega-dunes was made by (Frezzotti et al., 2002b). It was shown, in particular, that snow is removed from the leeward slopes of the dunes where specific erosional type of snow, “glaze surface”, is formed. In contrast, snow accumulation is increased on the windward slopes that are characterized by the depositional types of the snow microrelief.

Since the 1980s the mega-dunes are observed with the use of the satellite methods (Swithinbank, 1988;Fahnestock et al., 2000;Alberti and Biscaro, 2010;Scambos et al., 2012), which has revealed that these snow features are widely presented in Antarctica occupying in total about 500,000 km^2.

The Antarctic glaciology has gained a lot from implementing the ground penetrating radar (GPR) technique (Eisen et al., 2008). The GPR survey has also been made in mega-dune areas (Anschutz et al., 2006;Frezzotti et al., 2002a;Arcone et al., 2012a;Eisen et al., 2005;Arcone et al., 2012b). In particular, this allowed to discover the mega-dune-like structures in the central Antarctica outside the "classical" mega-dune areas. Similar to mega-dunes, they are characterized by persistent zones of snow erosion (glaze surfaces) and increased accumulation. The disturbed stratigraphy that marks the buried glaze surfaces is found at the depths more than 2000 m, which suggests that these structures have been persistent for tens of thousands of years (Arcone et al., 2012a, b).

Отформатировано: зачеркнутый

Примечание [a1]: The paragraph was eliminated, because it does not address the mega-dunes

The precipitated snow is not simply re-distributed in the mega-dune area. Indeed, it is widely recognized that the wind-driven sublimation is an important part of the surface snow mass-balance (Bintanja and Reijmer, 2001;Lenaerts et al., 2010;Thiery et al., 2012) removing from 20 to 75% of precipitation (Frezzotti et al., 2007;Frezzotti et al., 2004). In the mega-dunes this figure may increase to 85 % (Frezzotti et al., 2004).Thus, the wide extent of the mega-dune fields and glaze surfaces (that occupy in total more than 10% of the continent area), where snow drift processes are intensified, must be taken into account for correct estimate of the Antarctic surface mass balance (Scambos et al., 2012;Das et al., 2013;~~Zwally et al., 2015~~).

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Physical properties of snow in the mega-dune areas have been studied by (Albert et al., 2004;Courville et al., 2007;Severinghaus et al., 2010;Gregory et al., 2014). In particular, the snow erosion zones of mega-dunes are represented by coarse-grained snow (depth hoar) characterized by increased air permeability. The processes taking place in snow under near-zero accumulation help to understand the data on isotopic composition of gas trapped in the ice core air bubbles (Severinghaus et al., 2010). It is suggested that low-accumulation highly permeable snow zones, similar to that currently existing in the mega-dune areas, had large extent in Antarctica in the glacial times (Dreyfus et al., 2010).

Chemical properties of the mega-dune snow were considered in very few studies (Dixon et al., 2013). It is noted that the surface slope may, at least in the coastal areas, affect the snow chemistry (Mahalinganathan et al., 2012).

The strong post-depositional metamorphosis of snow in the mega-dunes has to modify its stable water isotope properties (Courville et al., 2007;Frezzotti et al., 2002b;Neumann et al., 2005). It is also known that irregular snow redistribution by wind due to complex surface topography does affect the isotopic content of the deposited snow, which cause a poor correlation of isotopic profiles obtained in two points separated by only a short distance (Ekaykin et al., 2014;Benoist et al., 1982;Karlof et al., 2006). However, no systematic study of snow isotopic composition in the mega-dunes has been conducted up to now.

In the summer seasons of 58th, 59th and 60th Russian Antarctic Expeditions (RAE), 2013-2015, we carried out complex glaciological investigations in the mega-dune area located about 30 km to the East from Russian Vostok Station (Fig. 1). In this paper we analyze the spatial distribution of the snow isotope content in the mega-dunes.

2 Data and methods

2.1 Glaciological and stable water isotope data

In January 2013 the Vostok mega-dune area was visited for the first time. The accumulation-stake profile was established perpendicular to the mega-dune crest. The total number of stakes was 21 (named MD00 to MD20), the distance between adjacent stakes was about 100 m, and the total length of the profile was 1983 m (Fig. 1). The samples of the upper 1.5 m of snow were also taken near each stake to be analyzed for the concentration of the stable water isotopes (δD, $\delta^{18}O$ and $\delta^{17}O$).

In January 2014 and January 2015 the stakes were revisited, and the repeated measurements of their heights and surface snow density allowed to obtain the amount of snow accumulated during 2 years (January 2013 - January 2015). The snow samples were taken again for chemical and isotopic analyses.

In January 2015 we also drilled a 20-m borehole in point MD00 (Fig. 1). In the obtained firn core we measured snow density and took samples for stable water isotope analysis with a resolution of 10 cm.

The concentration of heavy water isotopes (δD and $\delta^{18}O$) in 42 snow surface samples taken in 58th and 59th RAE, as well as in 183 samples from MD00 core, was measured at Climate and Environmental Research Laboratory (CERL) using a Picarro L2120-*i* analyzer. Our working standard (VOS), measured after every 5 samples, was made of the light Vostok snow and calibrated against the IAEA standards VSMOW-2, GISP and SLAP-2. The reproducibility of results defined by re-measurements of randomly chosen samples was 0.04 ‰ for $\delta^{18}O$ and 0.2 ‰ for δD, which is 2 orders of magnitude less than the natural variability of the snow isotopic composition (see below) and thus satisfactory for the purposes of the study.

In October 2015 we also measured ^{17}O-excess values in the samples collected during the 59th RAE using a Picarro L2140-*i* analyzer. For this, each sample was measured 15 times in the high-precision mode and we took an average of the last 10 measurements. Every 3 samples we measured the VOS standard previously calibrated against VSMOW-2, GISP and SLAP-2 (taking into account that they have ^{17}O-excess values of, correspondingly, 0, 22 and 0 per meg (Schoenemann et al., 2013)). The ^{17}O-excess value of VOS was found to be 0 per meg, similar to SLAP. The reproducibility of the ^{17}O-excess values of individual samples was 8 per meg.

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All the data discussed in this paper is presented in Table 1.

2.2 GNSS positioning

The absolute altitude and location was determined with high accuracy along the profile using the geodetic GPS technique.

Therefore the Bernese GPS Software 5.1 (Dach et al., 2007) was used to process the two kinematic GNSS profiles (K58B and K58C) as a combined differential solution from GPS and GLONASS observations. As reference stations for this network solution we used two local receivers at Vostok station in a distance of ~~less than 50km~~ 30km and additional two reference stations at the coast with baseline lengths of about 1350 km (near the Russian research stations Progress and a station of the global IGS-network near the Australian Station Casey). After reducing the antenna positions to the snow surface we estimated the accuracy by calculating the height differences at track crossovers. Crossovers inside one track imply an internal RMS of the differences of 2.9 cm (at 160 crossover points) for track K58B and 2.4 cm (at 9 crossover points) for track K58C. With a RMS of 7.7cm at 5159 crossovers between the two tracks we can estimate the absolute precision of a single kinematic surface height according to the variance propagation to about 5.4 cm.

2.3 GPR data

During the austral summer field season of the 58th Russian Antarctic Expedition (January 2013) the GPR profiling was performed to study the snow-firn layer structure of the mega-dune area. The 200 MHz GSSI SIR10B GPR with "5106 200 MHz" antenna was applied.

The GPR equipment was installed on 2 sledges towed by a ski-doo. The route of the GPR profiling was the same with the geodetic observations. In total, about 80 km of the GPR profiles were obtained (Fig.

1), though in this paper we only use the 2-km section obtained along the glaciological profile (points MD00-MD20 in Fig. 1).

The main problem in the processing and interpretation of the GPR data is the dielectric properties of the media where the electromagnetic waves ~~are propagating~~ propagate. We used the model published in (Popov and Eberlein, 2014) to transform the radio-echo time-section (Fig. 2) into the depth section. To calculate the vertical electromagnetic wave speed we used the firn density data measured in MD00 core.

In Fig. 2 we show~~ed~~ the GPR registration recorded along the glaciological profile (MD00-MD20).

3 Results

The mega-dune formation is related to a sharp increase of the ice sheet slope in the prevailing wind direction (SPWD) (Frezzotti et al., 2002b). The Vostok mega-dunes are not an exception, as they form leeward from the eastern shore of the Lake Vostok, where the SPWD changes from near zero or even negative values (interestingly, in the closest vicinities of Vostok Station the wind is blowing uphill) to about 1.6 m km^{-1}. The latter figure generally agrees with the Frezzotti and others' (2002) conclusion that the mega-dunes only develop where the SPWD is from 1 to 1.5 m km^{-1}.

The wavelength of the Vostok mega-dunes are about 1.9 km, and the amplitude (the elevation change between the dune crest and the nearest windward hollow) is about 1.2 m, i.e., they are relatively small compared to those reported in the above mentioned studies.

Below we present the results of the glaciological investigations in the Vostok mega-dune area (Fig. 3).

3.1 Accumulation rate and isotopic content of snow in mega-dunes

Due to the subsequent measurements of the heights of the stakes established across the mega-dunes, we were able to define the snow accumulation between January 2013 and January 2015 (Fig. 3e). One may clearly see the regular spatial variability of the snow build-up. In accordance with the previous studies (see the review in Introduction), the snow is removed from locations with the increased surface slope (leeward side of the dunes) and deposited where the slope is decreased or inversed (hollow between dunes and windward side of the dunes). In a distance of few hundred meters the accumulation changes by an order of magnitude, from -0.5 to 16 cm of snow (or from -0.2 to 58 mm w.e. according to the surface snow density, Fig. 3d). This range is larger than that reported by (Frezzotti et al., 2002b) (from 7 to 35 mm). The mean annual accumulation over ~~the 1~~ one dune wavelength is 22 mm, which is very similar to the accumulation at the Vostok stake network (23 mm). If the precipitation rate at Vostok station and in the mega-dune area was the same, then our result does not support the observation that over the mega-dune areas the accumulation is reduced due to the wind-driven sublimation (Frezzotti et al., 2004).

Snow accumulation variability observed at the stakes during only 2 years of observations may not adequately represent the long-term average due to very large random component. We used the GPR data (Fig. 3g) and data on firn density from the 20-m core in order to evaluate spatial variability of the multi-year average of the snow accumulation rate. The first internal reflection horizon (estimated age is about 130 years, see below) is located at the depth that varies from 3 to 11 m. Thus, mean 130-year snow accumulation rate varies between 1 and 35 mm w.e. over one full dune wavelength, with an average of 21 mm w.e. Thus, the multi-year spatial variability of snow accumulation rate is considerably smaller than that obtained from 2-year stake measurements, but still larger than that reported by (Frezzotti et al., 2002b).

The surface snow density does not show any distinct spatial variability (Fig. 3d). The mean snow density (0.355 g cm^{-3}) is slightly higher than that measured at Vostok stake network (0.33 g cm^{-3}).

During the field- work seasons we also did not observe big difference between snow surface character in leeward and windward slopes of the dunes (Fig. 4). The erosion zone does not demonstrate the dominance of the glaze surface, and no big sastrugi are observed in the accumulation zone, as reported by (Frezzotti et al., 2002b) for the Victoria Land mega-dune field. The small difference in snow morphology between low- and high-accumulation zones of the dune may be related to the relatively small dune size, although it does not explain rather big spatial variability of snow accumulation.

The spatial variability of the accumulation rate covaries well with the surface slope: the smaller is the slope, the higher is accumulation (Fig. 3 f and e), in accordance with the previous observations (Anschutz et al., 2006).

In Fig. 3a-c we show the isotopic composition (δD, dxs and ^{17}O-excess) of the upper 1.5 m of snow sampled twice near each point of our profile. One can see a wave in snow isotopic content (δD) with the magnitude of about 20 25 ‰ and the wavelength similar to that of the mega-dune. The spatial variability of the snow isotopic composition in the mega-dune area is significantly larger than in the area outside the mega-dunes. For example, the standard deviation of the δD values in the samples representing upper 1.5 m of snow and taken along a 40-km profile in the southern part of Lake Vostok, where the glacier is characterized by flat surface, is ±4 ‰ (Ekaykin et al., 2012) against ±6 ‰ in the mega-dune area. Another difference is that outside the mega-dunes the variability of snow isotopic composition is random, with no clear periodicity. At the same time, the average values of δD are similar in both cases, around -440 ‰.

There is a negative covariation between snow isotopic composition and accumulation rate (correlation coefficient, -0.38, is not statistically significant due to the small number of points). A very similar picture was previously observed in the closest vicinity of Vostok, where positive spatial anomalies of isotopic composition correspond to the negative anomalies of snow accumulation, though on the smaller spatial scale (Ekaykin et al., 2002).

We explain this behavior of the snow isotopic composition by different post-depositional alteration of the initial isotopic composition of snow precipitation deposited in the low- and high-accumulation zones of the mega-dunes. Indeed, the erosion zone is characterized by "a long, multiannual, steep temperature-gradient metamorphism" (Frezzotti et al., 2002b), page 8. Thus, the snow here should be enriched in heavy isotopes due to strong post-depositional modification (Town et al., 2008) that may be further facilitated by the increased permeability of the snow in such locations (Albert et al., 2004). We may speculate that in the mega-dunes described by (Frezzotti et al., 2002b), characterized by a very strong modification of the snow physical properties, the isotopic transformation should be even stronger than in the Vostok dunes.

An alternative explanation of negative spatial relationship of isotopic composition and snow accumulation was suggested by (Ekaykin et al., 2002). Since in winter the snow crystals are smaller and wind speed is higher, this snow could be easier re-distributed by wind comparing to snow precipitated in

Примечание [a2]: The reference was eliminated since the cited work does not describe mega-dunes

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Примечание [a3]: Ekaykin A.A., V.Ya. Lipenkov, Yu.A. Shibaev. Spatial distribution of the snow accumulation rate along the ice flow lines between Ridge B and Lake Vostok. – Led i Sneg, 2012, v. 4, p. 122-128.

summer. If so, in the erosion zone of the mega-dunes the proportion of summer snow is larger than in the accumulation zone.

We may use the isotopic data to determine which mechanism, “post-depositional” or “re-distributional” (or both) is mainly responsible for the anomaly of the snow isotopic composition in the mega-dune area.

The observed dxs/δD and ^{17}O-excess/δD slopes (ratios between the standard deviations of the smoothed profiles shown in Fig. 3a, b and c) are, correspondingly, -0.2 ‰/‰ and 0.9 per meg/‰. During the post-depositional changes of the snow isotopic composition these slopes are -0.2 ‰/‰ and 0.4 per meg/‰ (Ekaykin et al., 2016). During the seasonal cycle of the isotopic composition of snow precipitation at Vostok, these parameters are related by slopes -0.1 ‰/‰ and 0.4 per meg/‰ (Landais et al., 2012).

Thus we may conclude that the mixing of the summer and winter precipitation in different proportions cannot explain the variability of snow isotopic composition observed in the mega-dune area, since the variability of ^{17}O-excess and of *dxs* in this case would be significantly smaller. The post-depositional factor would better explain the observed snow isotopic composition in the mega-dunes, but still the variability of ^{17}O-excess seems to be too strong. Note, however, that the data by (Ekaykin et al., 2016) were obtained in laboratory experiments, not in natural conditions, so the ^{17}O-excess/δD slopes reported there may be underestimated.

We should also note that the ^{17}O-excess values positively covariate with the accumulation rate (Fig. 3 c and e), though one would expect a negative covariation in case if the snow isotopic composition variability is due to the post-depositional processes. At present we do not know if this positive covariation is caused by errors in the ^{17}O-excess values, or it suggests another mechanism that creates isotopic anomalies in the mega-dune area.

3.2 Mega-dune drift

We used the GPR data to reconstruct the previous positions of the dunes, and to calculate the velocity of the dunes drift.

In the GPR profile taken across the mega-dunes (Fig. 2), we see several distinct internal reflection horizons (IRH). For 7 of them we defined the depths (Table 1) and, subtracting these depths from the ice sheet elevation, we could define the absolute altitude of each IRH (Fig. 3g). Thus we can see the buried surfaces of our dune and may trace its drift in time.

For this, we first need to date each IRH. We used the density profile obtained from the MD00 core and the average snow accumulation rate in the mega-dune area in order to calculate the depth-age function and determine the age of each IRH (Fig. 3g). The uppermost IRH marks the surface of the dune about 130 years ago, and the lowermost – 530 years ago.

We chose 3 fold hinges (the summit of crests and two lowest points of the fold dips) to trace the dune drift. On average, the dune is drifting upwind with the rate of 4.6 ± 1.1 m yr^{-1}. This corresponds very well with the value reported by (Frezzotti et al., 2002b), 5 m yr^{-1}. With this velocity a dune drifts by ~~1~~ one full wavelength in about 410 years.

As pointed by (Arcone et al., 2005), the apparent dune drift velocity observed in the GPR images is a combination of the real dune velocity and the ice movement, and the real dune velocity is higher than

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the observed one. According to (Richter et al., 2013), ice flow velocities in this region do not exceed 2 m yr^{-1}, so the real dune drift velocity could be up to 6.6 m yr^{-1}. However, the ice is moving almost in parallel with the dune crests (from north-west to south-east). So, the projection of the ice speed vector on the MD profile is close to 0 m yr^{-1}, and the correction to the dune drift velocity due to the ice movement should be close to zero, too. Finally, for the purposes of our study we need not real, but the resultant dune velocity observed by GPR, so in the further calculations we use the apparent dune velocity of 4.6 m yr^{-1}.

3.3 Non-climatic temporal oscillation related to the mega-dune drift

When the dune drifts, the spatial anomalies in snow physical properties, accumulation rate and isotopic composition are drifting accordingly. For example, the point MD00, now located at the leeward side of the dune with reduced accumulation and enriched isotopic composition, about 300 years ago was in the hollow between dunes with increased accumulation and lower heavy isotope content. If one drills an ice core in the mega-dune area, he would see a quasi-periodic (with the period of 410 years) oscillations in snow accumulation and isotopic composition related to the dune drift.

Let us simulate such an oscillation that we would see in a core drilled at MD00 point.

In Fig. 5a we showed a temporal variability of snow accumulation (blue) and isotopic composition (red) that should be seen in point MD00 when the dune crosses this point. To construct these curves, we simply divided the distance of each point in Fig. 3 a and e by the above mentioned velocity of the dune drift. We also showed in Fig. 5a the climatic variability in Vostok region over the same time interval (Ekaykin et al., 2014) in purple. Note that the amplitudes of the both components are similar.

Combining the dune-related and climatic components, we obtain the expected temporal variability of snow isotopic composition in MD00 (Fig. 5b). Then we transform it to a vertical isotopic profile using the depth-age function presented in Fig. 5c. This function takes into account the significant dune-related variability in snow accumulation rate (Fig. 5a), this is why it is essentially non-linear. The resulting simulated vertical isotopic profile is presented in Fig. 5d by red line. In the upper part of the profile the isotopic oscillations are compressed due to the low accumulation rate, and deeper, when the accumulation is higher, they are stretched.

In our simulations we do not take into account that the mega-dune snow may experience enhanced diffusive smoothing due to the increased ventilation of the snow column. In this case the isotopic profile could be substantially smoothed.

In Figure 5d we also showed by the blue line the real isotopic profile from the MD00 core. One can see a good resemblance between them, except for the very bottom part of the MD00 core. Indeed, at the depth of 20 m the core has a δD isotopic composition of -420 ‰. Neither climatic record, nor the isotopic profile from the mega-dunes (Fig. 5a) demonstrate such high isotopic value, this is why we could not reproduce it in our simulations.

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4 Discussion - Non-climatic variability in ice cores

In the previous sections we demonstrated that the snow isotopic composition has significant spatial variability in the mega-dune area, suggested a possible mechanism to explain this variability, and then explained how this "dune-related" signal is transferred to an ice core isotopic profile. We calculated an artificial ice core isotopic profile in the mega-dune area and compared it with the real ice core isotopic profile.

In the case of MD00 core we know that the “signal” we see is mostly related to a dune drift, but how can one separate the climatic signal from non-climatic variability in real ice cores?

Indeed, it is commonly understood that a mega-dune area is an unsuitable place to drill ice for climatic studies, but it does not mean that the locations outside the mega-dune fields are free from non-climatic, “relief-related” variability.

As an example we may mention the South Pole Station region that is not a mega-dune area, but detailed topographic survey shows mega-dune-like features with a typical amplitude of few meters and wavelength of several kilometers – see Fig. 8 in (Van der Veen et al., 1999) and Fig. 2 in (Hamilton, 2004). Unlike the mega-dunes, these snow hills are not elongated, but rather round in shape. The authors suggest these structures are not stationary, but slowly change their locations, which causes temporal non-climatic variability of snow accumulation rate with the period of several hundred or few thousand years. Very similar structures are observed around the Kohnen Station (Eisen et al., 2005) and in West Antarctica (Arcone et al., 2005).

Even the vicinities of the main domes cannot be considered as “dune-safe”. Indeed, the study of the snow isotopic composition profile in two neighboring cores drilled about 55 km to the north-east from the summit ~~at~~ of Dome C showed a very low signal-to-noise ratio likely related to the local ice sheet topography (Benoist et al., 1982).

In Dronning Maud Land the ice cores drilled in relatively short distance one from another demonstrate opposite trends in the snow accumulation rates over the past 200 years (Oerter et al., 2000), which may be considered as the influence of the non-climatic factors.

In general, in low-accumulation sites signal-to-noise ratio in both snow accumulation rate and isotopic composition is very small, being of the order of 0.2 (Ekaykin et al., 2014). The noise, related to the snow re-distribution by wind and/or post-depositional processes, is larger than the climatic signal even at the centennial scale. This means that to study climatic variability with the periods less than 10^3 – 10^4 years in the low accumulation area (which comprises most of the East Antarctica (Arthern et al., 2006)) more than one ice core should be investigated for each location.

The influence of snow topography on snow accumulation is known and to large extent understood on the spatial scale from 10^{-2} to 10^1 m (micro-relief) and from 10^3 to 10^6 m (mega-dunes and continental scale). However, very little is known about the scale from 10^1 to 10^3 m, the range of “meso-dunes” (Ekaykin et al., 2002;Eisen et al., 2008). Meso-dunes are relatively small forms (with typical wavelengths from 200 to 300 m) of snow relief observed in the vicinities of Vostok Station. It was shown that the meso-dunes cause a spatial variability of snow properties: on the bumps the snow accumulation is lower, and its isotopic composition is higher, while in the hollows between the dunes more snow accumulates with lower concentration of heavy isotopologues (Ekaykin et al., 2002). Since these dunes seem to be not stagnant, ~~It~~ it is likely that the drift of the meso-dunes causes the non-climatic temporal oscillations of snow isotopic composition and accumulation rate with a period of few ~~tens of years~~ decades due to mechanisms similar to those described in this paper for the mega-dunes. Further studies of this phenomenon are needed.

Conclusion

The ice cores are priceless source of numerous and diverse paleo-climatic data, and this will hold true even despite the unavoidable limitations. One of the most important limitations is related to a high level of noise which contaminates the climatic signal on relatively short time scales (years to millennia), especially in the low-accumulation areas. The main reason of this noise is a complex snow/ice sheet topography that leads to snow re-distribution due to wind activity, which is further complicated by the post-depositional processes.

In this paper we present the results of the field works carried out during three Antarctic summer seasons in the vicinity of Vostok Station. We mainly deal with the influence of large snow relief forms, mega-dunes, on the snow isotopic composition. We demonstrate that the leeward sides of the dunes are characterized by reduced accumulation and increased concentration of heavy water molecules likely due to post-depositional alteration of the snow isotopic content. In opposite, windward sides of the dunes accumulate more snow that is enriched in light water isotopes.

Using the GPR data, we were able to trace the drift of the dunes and to calculate their velocity, 4.6±1.1 m yr^{-1}. This allowed us to simulate the temporal variability of the snow isotopic composition that would be observed in a given point due to the passing of the mega-dune across this point. Then we compared this artificial vertical profile of the snow isotopic composition with the real isotopic data from a firn core drilled in the mega-dune cite. We showed that the two profiles are very similar.

~~Using the examples published in literature we suggest that similar non-climatic oscillations in snow accumulation rate and isotopic composition are widespread in Antarctica, even beyond the mega-dune fields.~~

As a result of our study we come to the following conclusions:

1) For the first time we demonstrated that snow isotopic composition has significant spatial variability in the mega-dune area in covariance with the snow accumulation rate and surface slope, although the mechanism that forms this variability is yet to be clarified. We also demonstrated how these spatial waves are transformed into the oscillations of snow isotopic composition in a firn/ice core vertical profile.

2) Based on published data we may conclude that significant (periodic or non-periodic) spatial variability is widespread in Antarctica, even outside the mega-dune areas. The drift of different types of dunes across the show/ice sheet surface causes non-climatic temporal variability of snow accumulation rate and isotopic composition, as observed in snow or ice cores, thus considerably reducing the signal-to-noise ratio on the timescales from decades to millennia.

3) The only robust way to obtain a reliable climatic signal is to investigate several ice cores and to construct a stack record of studied parameters.

We also suggest that the mega-dunes are a unique environment that provides the necessary conditions to test different hypothesis. For example, in a short distance one can find locations absolutely different in terms of snow accumulation rate, isotopic composition, physical and (likely) chemical properties, which could be used to study the post-depositional processes, to model glacial conditions (Severinghaus et al., 2010) etc.

In the future studies we plan to investigate the spatial variability of chemical content, the concentration of microparticles and other compounds in the surface snow in the Vostok mega-dune area.

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Figure captions

Figure 1. Vicinities of Vostok Station and the location of the study area.

The mega-dunes are highlighted by hatching. Black line is the route of GPR and geodetic profiles. The location of the glaciological profile is shown in the insert (MD00-MD20). White line is the Vostok lake shoreline adapted from (Popov and Masolov, 2007).

Figure 2. GPR registration recorded along the MD00 profile.

Figure 3. The results of the glaciological, GPR and geodetic survey in the Vostok mega-dune area.

a - c – isotopic content of the surface (1.5 m) layer of the snow thickness, δD (a), *dxs* (b) and ^{17}O-excess (c). For δD the points show the individual samples and the red line is the average of the 58 and 59 RAE samples. For *dxs* only the average is shown. Note that the *dxs* axis is reversed. For ^{17}O-excess we showed the 5-point running means with the error bars (±1σ, where σ is the error of the average of 5 individual values).

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d – surface (20 cm) snow density, individual values (points) and 3-point running mean (line).

e – mean snow build-up in 2013-2014, individual values (points) and 3-point running mean. Dashed lines show the confidence interval (± 1 σ) of 2-year average accumulation value as deduced from Vostok stake network. Note that the Y axis is reversed.

f – surface slope calculated over 20-m intervals of the ice sheet surface. Negative values mean that the local slope is the opposite of the general slope in this region (from south-west to north-east).

g – the elevation of the ice sheet surface and of 7 internal reflection horizons (IRH) above sea level defined by the geodetic measurements and GPR survey.

The gray shading depicts the snow layer (1.5 m) in which the snow isotopic content was measured. The dashed lines connect the fold hinges used to calculate the dune drift velocity. The values to the right are the estimated ages of each IRH relative to January 2015.

The profile is spread from south-west (left part of the figure) to the north-east (right part), see Figure 1. The individual values shown in Figure 3 can be found in Table 1.

Figure 4. Photo of the snow surface in points MD02 (a) – erosion zone, leeward slope of the dune – and MD13 (b) – deposition zone, the hollow between dunes.

Figure 5. Simulated isotope profile in MD00 point.

a – the values of snow accumulation rate (blue) and isotopic composition (red) that could be observed in point MD00 if one would measure them as long as the dune travel across this point. To calculate this we used the data from Fig. 3 a and e, and data on the dune drift velocity. Purple – climatic variability of the snow isotopic composition in the Vostok region taken from (Ekaykin et al., 2014).

b – a combination of climatic and dune-related isotopic variability (red + purple from Fig. 5a).

c – depth-age function for the snow thickness in point MD00.

d – simulated vertical profile of snow isotopic composition calculated using the data from Fig. 5b and depth-age function (Fig. 5c), in red, compared with the real vertical profile of snow isotopic composition measured in the core drilled in point MD00, in blue.

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Table 1. Glaciological, radio-echo-sounding and geodetic data used in this study

Point name	Distance from MD00 (m)	Altitude a.s.l. (m)	Stake height (cm)		Snow build-up (cm)	Mean snow density (g cm^{-3})	Snow accumu-lation (mm w.e.)	Isotope content 58 RAE				Depths of internal reflection horizons (m)						
			58 RAE	60 RAE				δD	$\delta^{18}O$	dxs	^{17}O-excess	1st	2nd	3rd	4th	5th	6th	7th
MD00	0	3424,25	300	292	4	0,358	14	-434,3	-56,04	14,0	-5	4	8	11	14	17	19	24
MD01	88	3424,92	151	152	-0,5	0,311	-2	-437,9	-56,37	13,1	-13	6	9	12	15	18	20	25
MD02	192	3425,75	172	163	4,5	0,330	15	-436,3	-56,30	14,1	-16	7	10	13	16	18	20	25
MD03	291	3426,37	170	170	0	0,338	0	-432,8	-55,76	13,3	-6	8	11	14	17	19	20	26
MD04	393	3427,09	195	190	2,5	0,355	8	-441,5	-56,97	14,3	-9	10	12	15	17	18	19	27
MD05	493	3427,86	175,5	165	5,25	0,367	20	-434,0	-55,97	13,8	-19	11	13	15	17	18	19	28
MD06	592	3428,35	169	167	1	0,335	3	-435,8	-56,36	15,1	-16	11	13	15	16	17	18	28
MD07	690	3428,51	171,5	154	8,75	0,345	32	-444,7	-57,49	15,2	-13	11	13	14	16	17	18	28
MD08	797	3428,73	193,5	177	8,25	0,346	28	-446,9	-57,94	16,5	-13	11	13	14	15	16	17	28
MD09	894	3428,65	187,5	170	8,75	0,345	31	-442,0	-57,29	16,3	-9	10	12	13	14	15	17	27
MD10	992	3428,61	169,5	150	9,75	0,370	34	-441,2	-57,02	15,0	0	9	12	13	14	15	17	27
MD11	1066	3428,44	179	146	16,5	0,363	57	-445,1	-57,47	14,7	-9	8	10	12	14	14	16	26
MD12	1168	3428,18	162	148	7	0,330	21	-442,7	-57,27	15,5	3	7	9	11	13	14	16	25
MD13	1289	3427,64	190,5	158	16,25	0,344	55	-436,5	-56,32	14,0	-12	5	8	11	13	14	16	24
MD14	1394	3427,53	204	188	8	0,360	28	-435,2	-56,08	13,4	2	4	8	11	13	14	17	23
MD15	1493	3427,53	196	178	9	0,337	28	-428,6	-55,17	12,8	-8		8	12	14	15	17	23

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MD16	1593	3427,76	171	165	3	0,385	11	-425,0	-54,62	11,9	0		9	13	15	16	18	23
MD17	1698	3428,17	157	140	8,5	0,435	32	-432,1	-55,51	11,9	-15		10	14	16	17	19	24
MD18	1796	3428,73	188	178	5	0,348	18	-435,5	-56,04	12,8	-9	3	12	15	17	18	19	25
MD19	1901	3429,6	209	201	4	0,420	13	-440,4	-56,72	13,3	8	4	13	16	18	19	20	26
MD20	1983	3430,17	184,5	172	6,25	0,335	19	-437,8	-56,38	13,3	-10	10	15	18				29

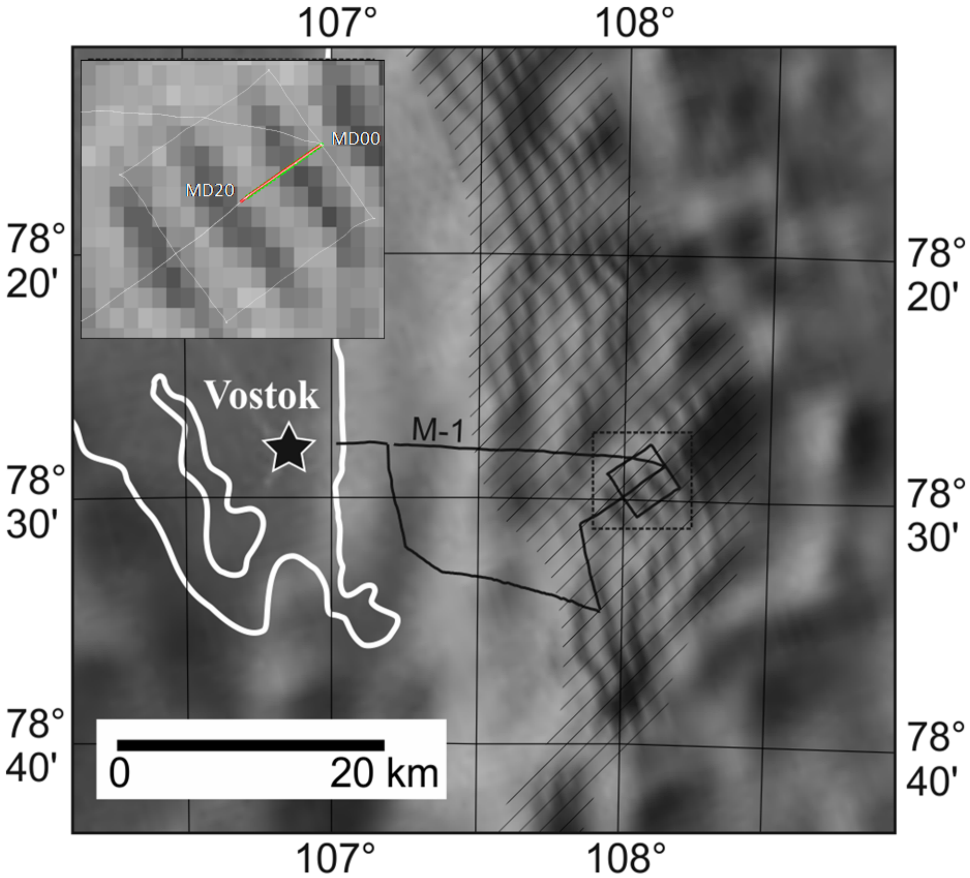


Figure 1.

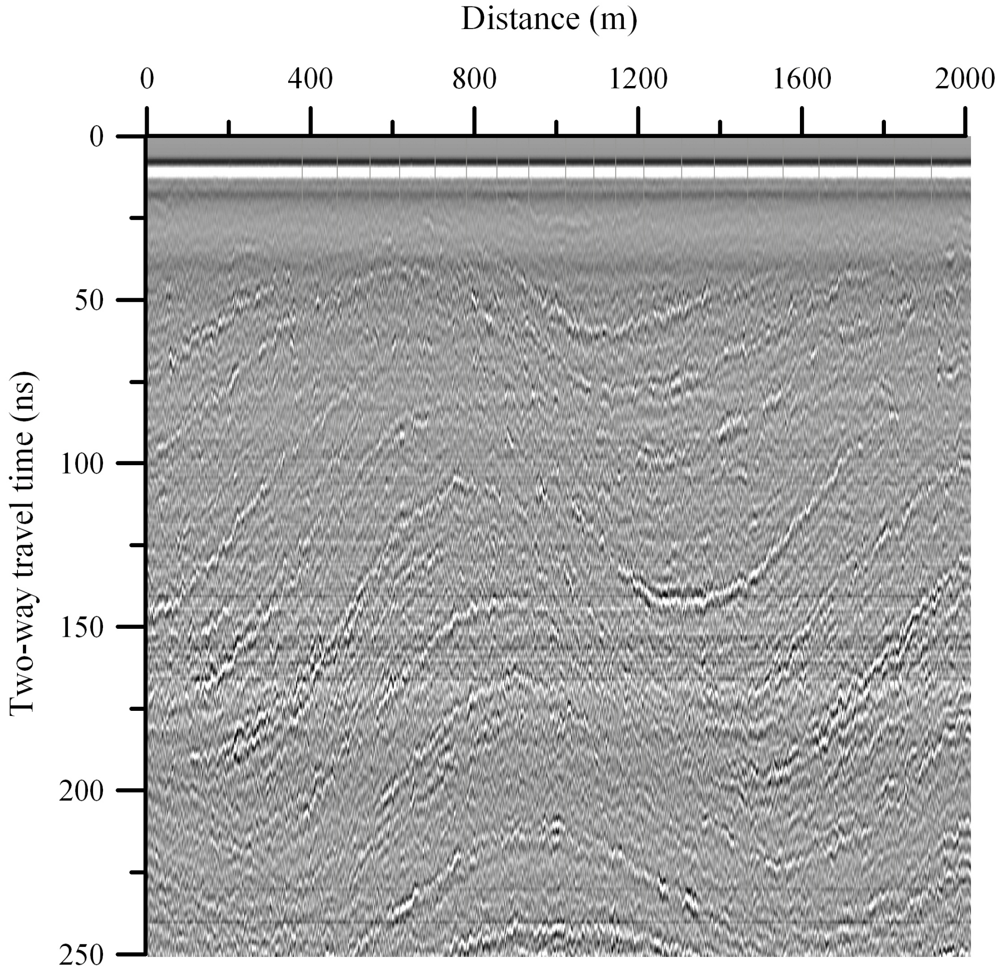
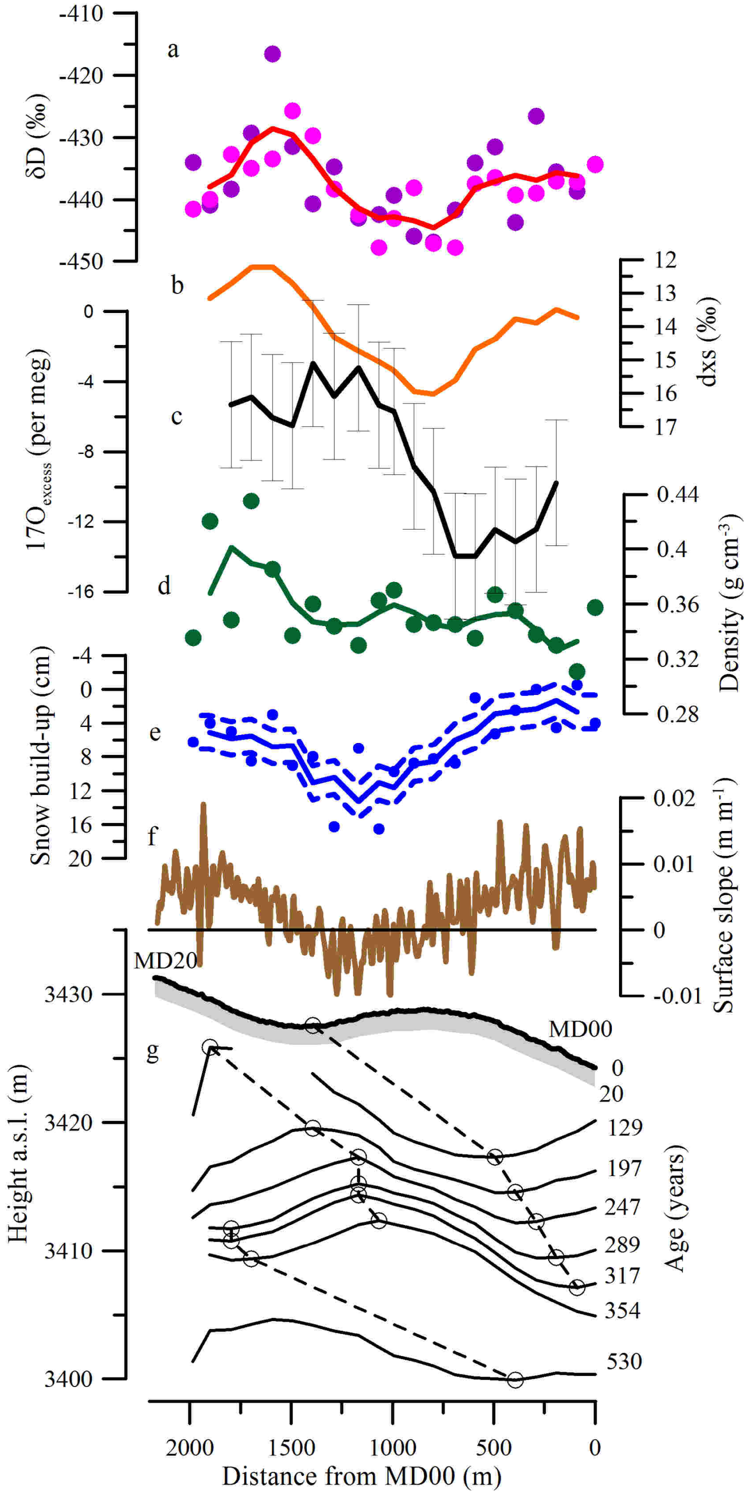

Distance (m)
0
400
800
1200
1600
2000
Two-way travel time (ns)
0
50
100
150
200
250

Figure 2.



a
b
c
d
e
f
g
δD (‰)
-410
-420
-430
-440
-450
dxs (‰)
12
13
14
15
16
17
17O_{excess} (per meg)
0
-4
-8
-12
-16
Density (g cm-3)
0.44
0.4
0.36
0.32
0.28
Snow build-up (cm)
-4
0
4
8
12
16
20
Surface slope (m m-1)
0.02
0.01
0
-0.01
MD20
MD00
Height a.s.l. (m)
3430
3420
3410
3400
Age (years)
0
20
129
197
247
289
317
354
530
2000
1500
1000
500
0
Distance from MD00 (m)

Figure 3.

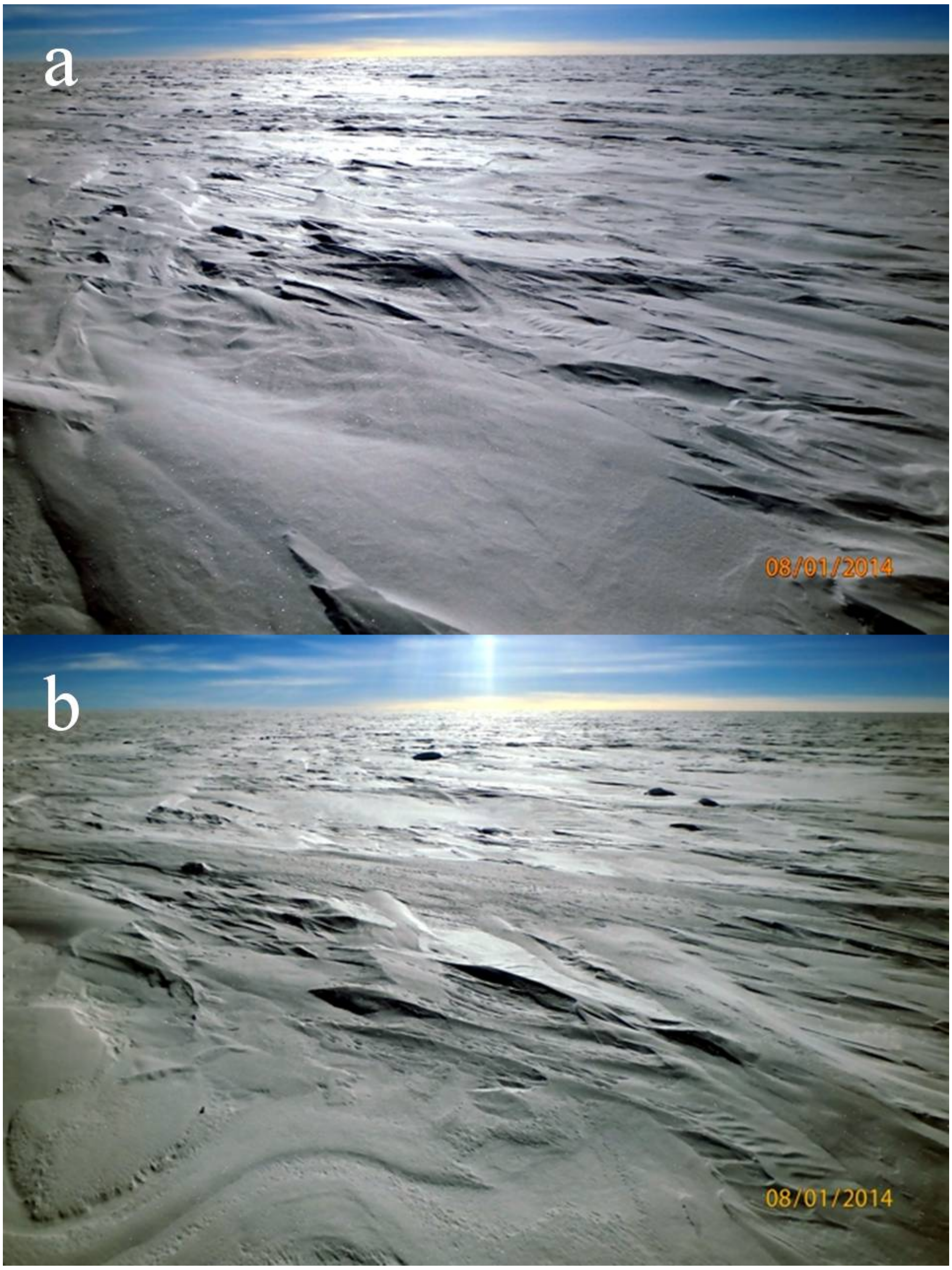


Figure 4.

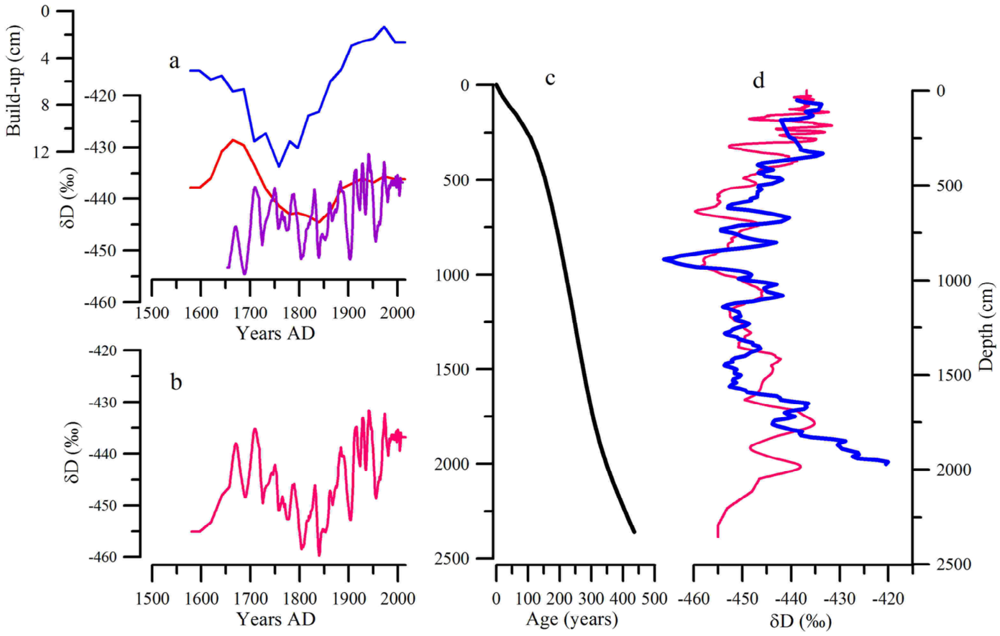


Figure 5