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Interactive comment on "Non-climatic signal in ice core records: lessons from Antarctic mega-dunes" *by* A. Ekaykin et al.

A. Ekaykin et al.

ekaykin@aari.ru

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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:

MF: 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.

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

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

AE: 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

MF: 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?

AE: 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).

MF: Pag 6917 line 27 Anschutz et al., 2006 is not in megadune area, the SMB, slope

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and wavelength is an order of magnitude different from Vostok megadune.

AE: We agree with that, so we eliminated this reference.

MF: 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 ïĄďD isotopic composition is less negative in low accumulation area, and does not appear enriched in heavy isotope, whereas ïĄďO17 appear depleted in the leeward part close to MD00.

AE: 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.

MF: 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.

AE: 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.

MF: 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.

AE: 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).

MF: 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.

AE: 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).

AE: 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 ïĄd'D 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 $\pm$4 ‰ (Ekaykin et al., 2012) against $\pm$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 ïĄd'D 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).

TS: 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.

AE: 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:

TS: 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.

AE: The citation has been removed.

TS: 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

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am not aware of? To me, it should be superscripted.)

AE: I agree with this comment. In all cases 17O-excess was replaced by 17O-excess.

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

AE: Done

TS: 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?

AE: 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.

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

AE: Done

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

AE: In this case we refer to the slopes (or regression coefficients) between changes in isotopic composition, this is why we use ‰‰Ṫhis 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.

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

AE: Done

TS: P6921, L21 "..the core has a ïĄďD isotopic composition of -420%

AE: Done

TS: 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 âĂŤ 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.

AE: 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.

TS: 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?

AE: 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 ïĄďD 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 ïĄďD are similar in both cases, around -440 ‰

TS: 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.

AE: 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.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/9/C3329/2016/tcd-9-C3329-2016-supplement.pdf

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