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Spatial distribution of the snow accumulation rate along the ice flow lines between Ridge B and Lake Vostok

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Antarctica, ice flow lines, snow accumulation, snow density, snow isotope content, spatial variability.

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During the 45th–57th Russian Antarctic Expeditions (1999–2012) an intensive program of glaciological and geophysical observations have been carried out in the region between the subglacial Lake Vostok and the Ridge B, Central Antarctica. In this work we present the instrumentally obtained snow accumulation data along the northern (*NVFL*) and southern (*VFL*) ice flow lines passing through the Lake Vostok. The mean accumulation rate at the *NVFL* and *VFL* profiles is 29–37 kg m^{-2} yr^{-1} and 21–24 kg m^{-2} yr^{-1}, respectively. Thus, this region is characterized by a strong latitudinal gradient of the snow accumulation rate, while the longitudinal one is an order of magnitude less. The spatial distribution of the accumulation rate along the *VFL* is characterized by a sharp variability attributed to the snow re-deposition due to the wind interplay with the local glacier surface slope anomalies. The new data on the stable water isotope concentration (δ^{18}O) along the *VFL* profile are also presented.

Introduction

Interpretation of the climatic information recorded in the Vostok deep ice core is related to a number of methodological difficulties, one of them is due to the fact that the Vostok station is situated about 300 km from the nearest ice divide. It means that ice found at certain depth was deposited not at the drilling site, but some distance upstream along the ice flow line. To account for this ice advection effect, sophisticated two-dimensional ice flow models are employed [15]. The parameters needed to run the models are bedrock relief, glacier thickness, basal conditions, as well as spatial distribution of snow properties and accumulation rate along the ice flow line. Nevertheless, until recently the glaciological data in the region of interest, located between the Ridge B and the Lake Vostok (Fig. 1), were rather scarce. The data on the snow density, accumulation rate and isotope content (concentration of deuterium, δD, and/or oxygen 18, δ^{18}O) were available along the Vostok—Mirny route [4] and at the site of Dome B deep drilling [12]. An attempt to calculate the spatial distribution of the long-term accumulation rate values along the Vostok flow line using the radio echo sounding data on internal glacier layering was made in [13]. To fill up the data gap, an intense program of glaciological and geophysical investigations in the region of interest was launched during the 45th summer season (December 1999 — January 2000) of Russian Antarctic Expedition (RAE) by the specialists of Arctic and Antarctic Research Institute and Polar Marine Geosurvey Expedition (PMGE) with the logistical support from the RAE.

Aside from collecting data along the ice flow lines needed to interpret the deep ice core data, this activity was aimed at following: 1) to study the spatial distribution of the snow properties, isotope and chemical content, and accumulation rate, as well as ice thickness, in the regions of Lake Vostok and between the lake and the Ridge B; 2) to reconstruct the climate variability in this region over the past 200—300 years; 3) to define the site of a future deep ice drilling to obtain the undisturbed climatic record for the past 1—1.5 million years.

In 1999—2004 the glaciological and geophysical (radar echo and seismic soundings) investigations were mainly restricted to the area of lake Vostok, which allowed to describe in detail the lake's morphology [14] and collect a vast dataset of glaciological information (to be published elsewhere). During the 50—55 RAE summer seasons (2004—2010) the glaciological works were extended to the region between Lake Vostok and the Ridge B with the focus on the Vostok ice flow line and the northern Vostok flow line (profiles *VFL* and *NVFL* in Fig. 1), as well as to the larger sector of East Antarctic ice sheet located between the sites Progress, Dome B, Vostok, Komsomolskaya and Mirny. Some preliminary results of these studies are summarized in [2]. In particular, in this work the spatial distribution of the ice thickness, snow density and isotope content along the *VFL* is presented. The isotopic analyses of the snow samples from shallow hand-drilled cores and deep pits accompanied by the dating of the snow-firn thickness has allowed to reconstruct the regional (for the southern part of Lake Vostok) climate history over the past 350 years [3].

Finally, during the last Antarctic summer season (December 2011 — January 2012) the snow stakes installed at the *VFL* and *NVFL* profiles were revisited having made possible to measure instrumentally the present-day spatial distribution of the snow accumulation rate along the flow

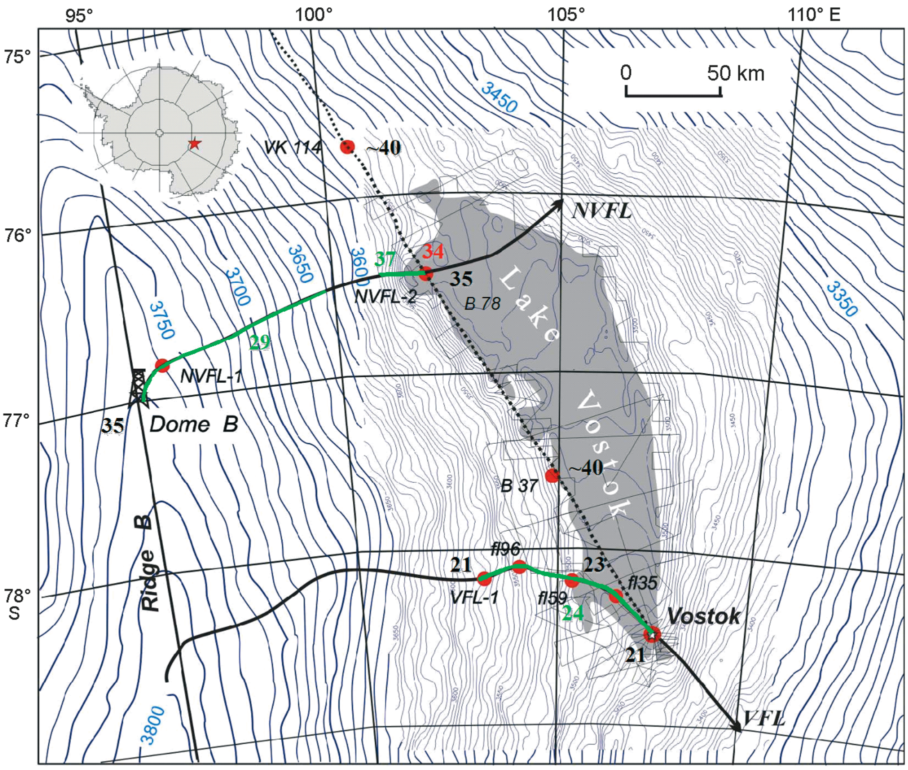

Fig. 1. The map of the area of study. The red dots are the pits and snow cores mentioned in the paper. The green color depicts the studied intervals of the northern and southern ice flow lines (*NVFL* and *VFL*) passing through the subglacial Lake Vostok. The numbers are the snow accumulation rate values (kg m^{-2} yr^{-1}): previously published (black) [4, 12] and obtained as a result of this study (red and green).
The dotted line is the route of the old Vostok–Mirny logistical traverse

Рис. 1. Карта района исследований. Красные кружки – расположение шурфов и скважин, упомянутых в настоящей работе. Зелёным цветом выделены исследованные участки северной и южной линий тока льда (*NVFL* и *VFL*), проходящих через подледниковое озеро Восток. Цифрами показаны скорости снегонакопления (кг м$^{-2}$ год$^{-1}$): опубликованные ранее (чёрным) [4, 12] и полученные в ходе настоящего исследования (красным и зелёным). Точечная линия – старая трасса транспортного похода Восток–Мирный

lines passing through the Lake Vostok, which is the main subject of this paper. The present work is a Russian contribution to the International Polar Year projects N 301 TASTE-IDEA (Trans-Antarctic Scientific Traverses Expedition – Ice Divide of East Antarctica) and N 205 IPICS-IPY (International Partnership in Ice Core Science – International Polar Year Initiatives) [6].

Methods and results

During the 50th RAE summer season (January 2005) glaciological observations were carried out along the Vostok ice flow line (*VFL* profile in Fig. 1) from Vostok to 96th km uphill towards the Ridge B. In total, 78 snow stakes were set up (every 1 km in the interval 0–60 km from Vostok and every 2 km in the interval 60–96 km). Three shallow pits were excavated (*fl35, fl59* and *fl96* as indicated in Fig. 1) followed by snow stratigraphy description and snow sampling for isotope content and total beta-activity. The latter allowed to define the 1955 high beta-activity layer and thus to absolutely date the snow thickness. The snow samples of the upper 1.5 m of snow were also taken near each stake to define the isotope composition. Next year the *VFL* profile was prolonged until the 107th km from Vostok with the snow stakes set up every 1 km. In the end of the profile (point *VFL-1* in Fig. 1) a snow core was retrieved to the depth of 14.8 m. The methods of these works are described in details in [2].

In January 2012 (57th RAE summer season) the glaciological works at the *VFL* profile were repeated. For the first time in the history of Russian Antarctic Expedition it was made using ski-doo snow-mobiles (Fig. 2). The height of each snow accumulation stake was re-measured, which allowed to calculate the total snow build-up over the 7-year period, from 2005 to 2011 (or over 6-year period, 2006–2011, for the stakes 80–90 located at the distance of 97–107 km from Vostok). The average measured total snow build-up is 44.4 cm for stakes 1–79 and 41.3 cm for stakes 80-90.

The build-up data were first corrected for the snow settling as described in [1] (see also [7]). The mean value of the correction is 0.7 cm, or about 1.5% of the total snow build-up.

In order to transform the snow build-up into the accumulation rate, the snow density data were applied. During the RAE57 traverse, two types of density measurements were made: near each stake the density of the upper 20 cm snow layer was defined (Fig. 3) according to the routine technique used at Vostok station [1], and also the upper 50-cm density was measured at each 10th stake. Between 20-cm (ρ_{20}) and 50-cm snow density (ρ_{50}) a linear relationship was found ρ_{50} = 0,226 ρ_{20} + 286 (significant with 90% probability), which was then applied to calculate the snow density in the upper 50 cm for each *VFL* point. We should note that choosing 20-cm or 50-cm density changes the final accumulation values by about 5%, and that the variability of the accumulation rate along the *VFL* depends almost entirely on the snow build-up and only to minor extent on the density.

Fig. 2. Glaciological traverse along the *VFL* profile, 57th RAE (January 2012) with the use of ski-doo snowmobiles. Photo by V. Zarovchatsky
Рис. 2. Гляциологический поход по профилю *VFL*, 57-я РАЭ (январь 2012 г.), на базе снегоходов Ski-doo. Фото В. Заровчатского

Thus, the average (for the 6–7 year period) snow accumulation rate for every stake is calculated as the total snow build-up corrected for snow settling, multiplied by the 50-cm snow density and divided by the number of years passed since the stake set-up (see Fig. 3). Also, during the 57th RAE summer season samples of the surface snow were collected near 24 stakes (at the distance of 11, 12, 17, 31, 34, 44, 48, 55, 56, 59, 72, 74, 76, 97–107 km from Vostok) in order to confirm the spatial distribution of the isotopic content.

The *NVFL* stake profile was set-up during the 53rd RAE summer season (January 2008). The beginning of the profile (point *NVFL*-00, without stake) corresponds to the crossing of the north Vostok ice flow line with the route of the old Vostok–Mirny logistic traverse. The stakes were installed every 2 km, and the last stake (*NVFL*-94) is located at the Ridge B, near the Dome B drilling site, 188 km from *NVFL*-00. The density in the upper 20 cm snow layer was defined every 10 km. Near the point *NVFL*-91 (182nd km of the profile) the 21-m snow core was retrieved that is still has to be analyzed (site *NVFL-1* in Fig. 1).

Stakes 1–10 of the *NVFL* (2–20 km of the profile) were revisited during the RAE 55 summer season (early February 2010). Mean snow build-up for the two years (2008–2009) is 20.7 cm that after the snow settling correction equals to 21.2 cm. The snow density was measured near each stake in the upper 20 cm snow layer with the average over the 10 stakes being 346 kg m^{-3}. Thus the accumulation rate at this interval of *NVFL* is estimated at 36.8 kg m^{-2} yr^{-1}. Late in January 2010 a 3-m snow pit (named *NVFL-2*, as indicated in Fig. 1) was dug in the beginning of the *NVFL* profile followed by the snow stratigraphy description, snow density measurements and sampling for isotope and chemical content. In the SO_4^{2-} profile measured on the pit samples a pick was found at the depth of about 160 cm that is interpreted as the Pinatubo volcano signature (T.V. Khodzher, personal communication, 2012). In central Antarctica the layer containing the Pinatubo products is dated as year 1993 [5]. The mean density of 0–160 cm snow thickness in *NVFL-2* is 357 kg m^{-3}, which gives the average accumuation rate for the period 1993–2009 equal to 33.6 kg m^{-2} yr^{-1}, i.e., very similar to the value from the snow stakes given above.

Stakes 28–94 (56–188 km of the profile) were re-measured during RAE 57 (January 2012) by the scientific geodesic traverse. Mean snow build-up for the period 2008–2011 is 35.0 cm (35.7 cm after the snow settling correction). The snow density was not measured, thus the RAE 53 density data were used. Since the density was not defined near each stake, for the points with no available data the density was calculated from the regression line (Fig. 4)

$$\rho_{20} = -4.8 \times 10^{-2} D + 336,$$

where D – distance along the profile (km).

In order to estimate the mean density in the upper 36 cm snow layer we used the density data from the *NVFL-2* snow pit. The densification rate is 62 kg m^{-4}. A very close value is produced by a simple densification model by Herron and Langway [11] using the following input values: mean annual firn temperature −57 °C, accumulation rate 30 kg m^{-2} yr^{-1}, surface snow density 340 kg m^{-3}. Keeping in mind a limited applicability of the model to the upper snow layer, we nevertheless consider this result as a confirmation of the densification rate used for our calculations. If so, the density of the upper 20 cm and 36 cm differs negligibly, so to calculate the accumulation rate we use the ρ_{20} data without correction. The average accumulation rates (for the period 2008–2009, stakes 1–10, and 2008–2011, stakes 28–94) are shown in Fig. 4.

Discussion

In general, the spatial distribution of the accumulation rate along the *VFL* profile is characterized by a slight increasing trend, from 22.8 kg m^{-2} yr^{-1} in the beginning (Vostok station) to 24.0 kg m^{-2} yr^{-1} in its end. The first figure is very close to the mean accumulation rate as observed at the Vostok stake farm, 23.2 kg m^{-2} yr^{-1} (Fig. 5). In Fig. 3 we also showed the long-term average accumulation values in sites *fl35, fl59* (for the period 1955–2004) and *VFL-1* (1815–2005) [2]. These values are noticeably lower than the corre-

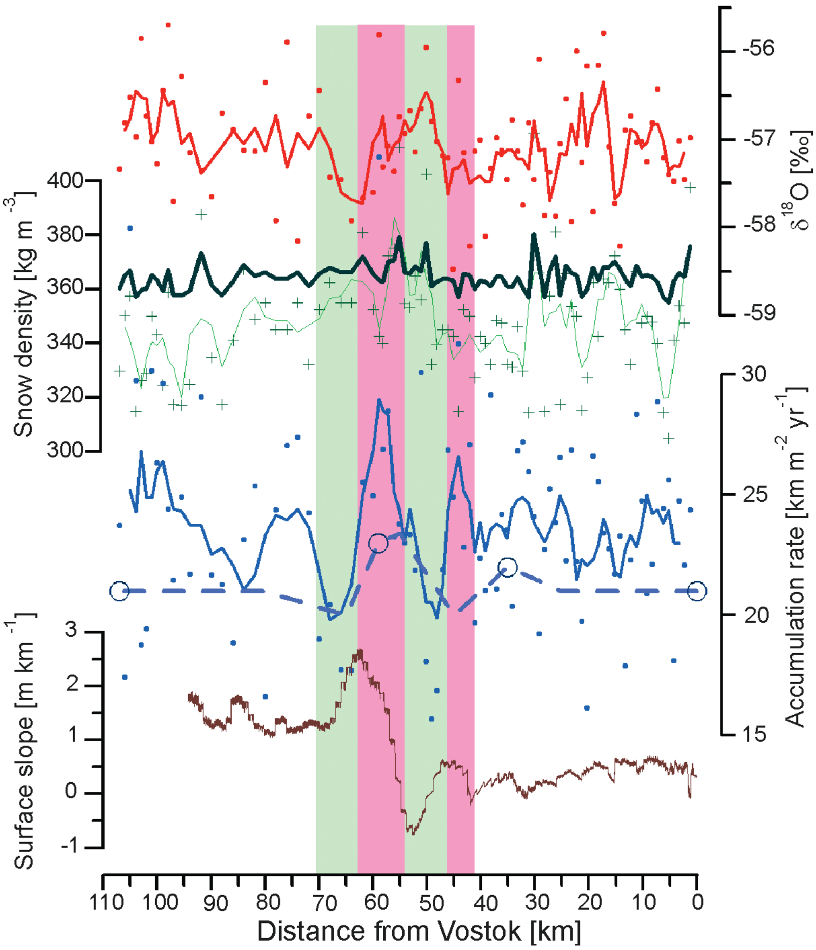

Fig. 3. Spatial distribution of the snow isotope content, density and accumulation rate along the *VFL* profile.
From the top to the bottom:

data on the isotope content ($\delta^{18}O$) of the surface 1–1.5 m snow layer. The dots are individual values near each stake of the profile, and the solid curve is the 3-point running mean. The graph represents the results of the isotope analyses of the samples collected during the 50th RAE summer season [2] near each stake, and 57th RAE (near 24 of 90 stakes);

the snow density values of the upper 20 cm of snow are shown as averaged of the 50th and 57th RAE measurements. The crosses are the values at individual points, while the thin line is the 3-point running mean. By the thick green line the calculated density of the upper 50-cm of snow is shown;

the average (2005–2011 for interval 0–96 km and 2006–2011 for interval 96–107 km) values of the snow accumulation rate for each stake (the dots), and the same data smoothed by 5 stakes (the solid line). The circles are the mean long-term accumulation rates from the snow pits and cores data [2], and the dashed line is the prediction of the accumulation rate distribution along the profile [2];

the data on the glacier surface slope. The general slope is from the west to the east, and the negative values means the opposite slope (from the east to the west) (from [2]);

the color shading highlights the positive (pink) and negative (blue) anomalies of the accumulation rate; note that the horizontal axis (the distance from Vostok Station) is reversed, so that the west is on the left and the east is on the right

Рис. 3. Распределение изотопного состава, плотности и скорости накопления снега по профилю *VFL*.
На рисунке представлены (сверху вниз):

данные об изотопном составе (концентрации $\delta^{18}O$) поверхностного (1–1,5 м) слоя снега – индивидуальные значения для каждой вехи профиля (точки) и осреднённые по трём соседним точкам (сплошная линия). График построен по результатам анализа образцов, отобранных в сезоны 50-й РАЭ [2] около каждой вехи и 57-й РАЭ (около 24-х из 90 вех);

осреднённые по результатам измерений 50-й и 57-й РАЭ данные по плотности снега в верхнем 20-сантиметровом слое – индивидуальные значения в каждой точке профиля (крестики) и сглаженные по трём соседним вехам (тонкая линия). Жирной зелёной линией показаны рассчитанные значения плотности верхнего 50-сантиметрового слоя снега;

средние (за период 2005–2011 гг. для интервала 0–96 км и 2006–2011 гг. для интервала 96–107 км) значения снегонакопления на каждой вехе. Точки – индивидуальные значения, сплошная линия – те же данные, сглаженные по пяти соседним вехам. Кружки – средние многолетние значения снегонакопления по данным снежных шурфов и кернов [2], пунктирная линия – прогноз распределения снегонакопления по профилю, выполненный до начала полевых работ 57-й РАЭ [2];

распределение угла наклона поверхности ледника (по [2]). Общий уклон поверхности – с запада на восток; отрицательные значения обозначают обратный уклон (с востока на запад);

цветовой заливкой выделены зоны с положительными (розовым) и отрицательными (голубым) аномалиями снегонакопления; горизонтальная ось (расстояние от станции Восток) перевернута таким образом, что запад расположен слева, а восток – справа рисунка

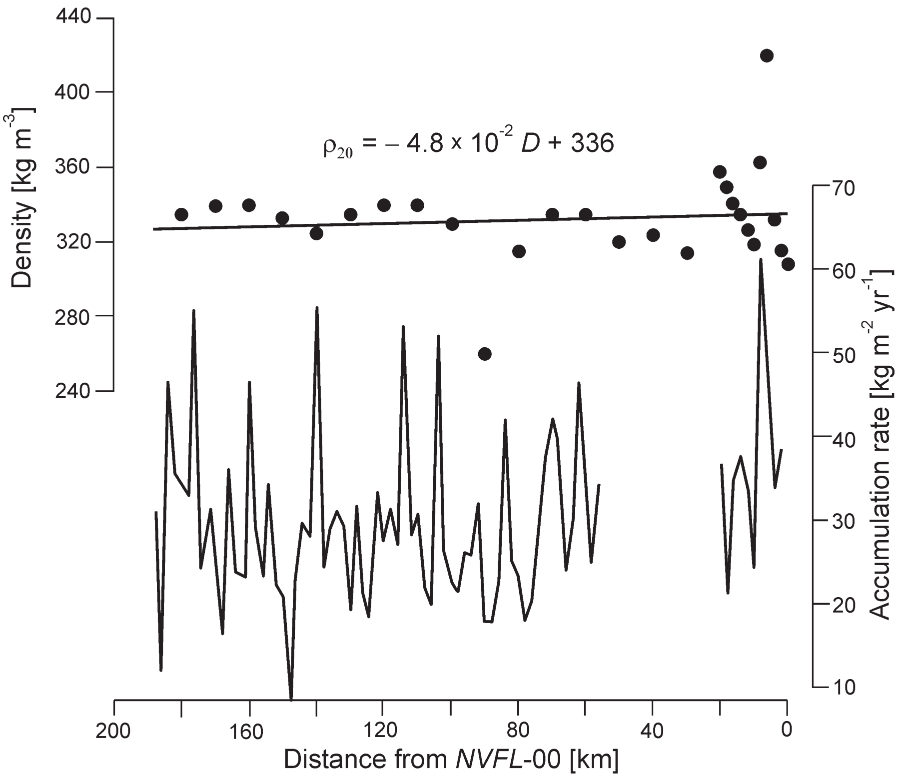

Fig. 4. The spatial distribution of the snow density and accumulation rate along the *NVFL* profile.
The black line on the density plot is a linear approximation of the individual values. Note that the horizontal axis (the distance from the beginning of the profile) is reversed, so that the west is on the left and the east is on the right

Рис. 4. Распределение плотности и скорости накопления снега по профилю *NVFL*.
Чёрная линия на графике плотности – линейная аппроксимация отдельных значений; горизонтальная ось (расстояние от начала профиля) перевёрнута таким образом, что запад располагается справа, а восток – слева

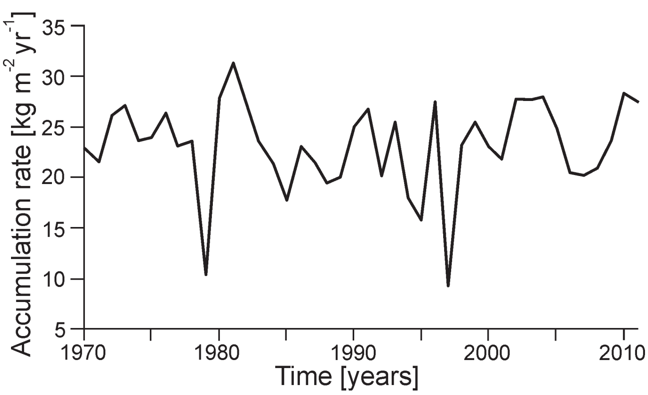

Fig. 5. The time series of the snow accumulation rate as obtained at the Vostok accumulation-stake farm (1970–2011)
Рис. 5. Ряд снегонакопления на снегомерных полигонах станции Восток (1970–2011 гг.)

sponding stake data in accordance with the evidence of increasing accumulation since the 1950s [8].

More interesting feature of the *VFL* profile is a sharp spatial variability at the smaller scale: in a distance of less than 10 km the accumulation rate may change by 8 $\mathrm{kg\,m^{-2}\,yr^{-1}}$. These variations were previously noticed in the spatial distribution of snow density and isotope content [2] (see Fig. 3). In particular, it was reported that the $\delta^{18}O$ concentration in snow may vary by more than 1‰ (that is equivalent to apparent change of the air temperature of about 1 °C) within 10 km, which is unlikely. An alternative explanation is that these anomalies are due to the snow re-deposition as a result of the wind interplay with the glacier surface relief.

Indeed, the influence of the snow (glacier) surface relief anomalies on the snow accumulation rate has been repeatedly observed on various scales, from micro-relief (tens of centimeters – meters) to mega-dunes (first kilometers) (see the review in [2]). However, there is a very small evidence of such effects on the scale of 10 km. In Fig. 3 we showed the data on the surface slope along the *VFL* profile [2]. It is evident that the positive accumulation anomalies (highlighted by the pink shading) correspond to the zones of a sharp slope decrease, while negative anomalies (shaded in blue) do to the locations with an increasing slope. It could be interpreted as follows: the increasing tilt of the glacier surface causes the acceleration of the katabatic wind speed and, thus, the enhanced snow erosion. When the surface slope decreases, the energy of the flow drops, and the «excess» snow falls out causing the observed increased snow build-up. This scheme was used in [2] to predict the spatial distribution of the snow accumulation along the *VFL* (the dashed line in Fig. 3). Since the position of the predicted maxima and minima of the accumulation rate corresponds well with the observed ones, we believe that the proposed scheme is a very likely explanation of the accumulation spatial distribution.

The mechanism of the influence of the snow re-deposition by wind on the snow isotope content is much less clear. One may think of two possible scenarios:

1) intensity of the snow drift by wind may vary between summer and winter due to the varying wind speed and snow properties (size and shape of crystals) causing different portion of summer and winter snow deposited in different locations [2] (i.e., an effect similar to «wind scouring» [10]);

2) the observed isotope effect may appear after the snow is deposited due to the fact that the isotopic post-depositional alteration strongly depends on the accumulation rate [9].

The *NVFL* profile is characterized by a different accumulation rate for the intervals 0–20 and 56–188 km (37 and 29 kg m^{-2} yr^{-1}). Three alternative (or complimentary) explanations for this could be proposed:

1) the observed pattern reflects the climatologically driven regional distribution of the snow precipitation rate. In this case, the regional minimum of the accumulation (precipitation?) is located about 120 km from the beginning of the *NVFL* profile;

2) the increased snow accumulation in the 0–20 km interval is caused by the influence of the glacier surface slope anomalies close to the western shore of the lake Vostok similar to what happens around the 60th km of the *VFL* profile;

3) the observed difference could be time-dependent taken into account that the 0–20 km data represent 2-year average of accumulation (2008–2009), while the 56–188 km interval does 4-year average (2008–2011). However, this version is not supported by the accumulation rate data from the Vostok stake farm (see Fig. 5) since the average 2008–2009 accumulation (22.2 kg m^{-2} yr^{-1}) is significantly lower than the one for the 2008–2011 period (25.1 kg m^{-2} yr^{-1}).

Thus, further investigations, including the snow stake re-measuring in the 20-56 km of the *NVFL* profile, are needed.

Conclusion and outlook

As a result of the long-lasting project of glaciological investigations in the Lake Vostok – the Ridge B region in central Antarctica, the robust instrumental data on snow accumulation rate were obtained for the two ice flow lines passing through the southern and northern parts of the lake. The mean accumulation rate for the southern flow line (the *VFL* profile) is 21–24 kg m^{-2} yr^{-1}, while for the northern one (*NVFL*) it is about 1.5 higher, 29–37 kg m^{-2} yr^{-1}. Thus, a strong latitudinal gradient of this parameter is observed, while in the west-east direction the accumulation rate is relatively constant. It was stated in [2] that the *VFL* profile correspond to the axis of the minimum values of the snow accumulation rate and isotope content, and thus likely is a divide between the two air masses feeding this region with precipitation (from Indian and Pacific oceans). This preliminary conclusion needs however further investigations.

The short-term variability of the glaciological parameters along the *VFL* profile demonstrates sharp oscillations that could hardly be explained by the local climate, but rather are due to the snow properties alteration caused by the wind activity. In particular, positive (negative) accumulation anomalies covary with the decreasing (increasing) glacier surface slope. The future studies in the frames of this project will be focused on the following:

1) the study of the snow properties, isotope content and accumulation rate in the interval of the *VFL* between the *VFL-1* site and the Ridge B (see Fig. 1). This area is likely characterized by a low snow accumulation rate, substantial ice thickness and relatively flat bedrock relief (see Fig. 5 in [15]), which makes it a good candidate for a future deep drilling to get a 1–1.5 million year climate record;

2) the completion of the analyses and interpretation of the numerous snow pits and cores samples and data from the flow lines and Lake Vostok area to detail the spatial distribution of the snow characteristics and to reconstruct the regional past climate changes;

3) the extension of the study area to the south of the *VFL* profile in order to define the region of the minimum values of the snow isotope content and accumulation rate;

4) to carry out the glaciological investigations in the mega-dune area located about 25 km to the east–south-east from Vostok with the aim to study the relationship between the snow characteristics with the glacier relief anomalies.

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Пространственное распределение скорости снегонакопления вдоль линий тока льда между Ледоразделом B и озером Восток

В течение летних полевых сезонов 45-й – 57-й Российских антарктических экспедиций (1999–2012 гг.) сотрудниками Арктического и Антарктического НИИ и Полярной морской геологоразведочной экспедиции была выполнена обширная программа гляциологических и геофизических (радиолокационных и сейсмических) исследований в районе Центральной Антарктиды между подледниковым озером Восток и Ледоразделом B. Цели программы – сбор данных, необходимых для интерпретации палеоклиматической информации по глубокому керну со станции Восток, поиск места нового глубокого бурения льда, изучение которого позволит восстановить историю климата Антарктиды за последние 1–1,5 млн лет, а также изучение регионального палеоклимата в масштабе времени 200–300 лет. В настоящей работе представлены инструментальные (полученные путём реечных снегомерных наблюдений) данные о распределении скорости снегонакопления вдоль двух линий тока, проходящих через северную (профиль *NVFL*) и южную (профиль *VFL*) части оз. Восток. Среднее накопление на профиле *NVFL* составило 29–37 кг $м^{-2}$ $год^{-1}$, тогда как на *VFL* – 21–24 кг $м^{-2}$ $год^{-1}$. Таким образом, данный район характеризуется значительным широтным градиентом снегонакопления. При этом изменение данного параметра с запада на восток приблизительно на порядок меньше. Распределение снегонакопления по профилю *VFL* характеризуется резкими колебаниями, достигающими 8 кг $м^{-2}$ $год^{-1}$ на расстоянии менее 10 км, что едва ли можно объяснить местной изменчивостью количества осадков. Наиболее вероятная причина этих колебаний – перераспределение свежего снега в процессе отложения вследствие взаимодействия снеговетрового потока с рельефом подстилающей поверхности. Данное предположение подтверждается чётким совпадением положительных (отрицательных) аномалий снегонакопления с участками профиля, характеризующимися резким понижением (повышением) угла наклона поверхности. Ранее [2] подобные аномалии были обнаружены в распределении изотопного состава и плотности поверхностного снега. Дальнейшие полевые работы по данной программе будут сосредоточены в верхней части профиля *VFL* (непосредственно примыкающей к Ледоразделу B), а также к югу от *VFL* и к востоку–юго-востоку от станции Восток в районе так называемых «мега-дюн».