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High resolution 900 yr volcanic and climatic record from the Vostok area, East Antarctica

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Abstract

~~Detailed~~ volcanic record of the last 900 yr (1093–2010 AD) has been ~~received~~ using high resolution (2–3 samples per accumulation year) sulfate measurements in four snow/firn cores from the Vostok station area, East Antarctica. Totally, 33 volcanic events have been identified in the record, including well-known low latitude eruption signals found in many polar ice cores (e.g., Pinatubo 1991, Agung 1963, Krakatoa 1883, Tambora 1815, Huanaputina 1600, Kuwae 1452), however in comparison with other Antarctic sites the record has more events covering the last 900 yr. The strongest volcanic signals occurred during mid-13th, mid-15th and 18th centuries. The largest volcanic signal of Vostok (both in sulfate concentration and flux) is the 1452 AD Kuwae eruption. Average snow accumulation rate calculated for the period 1093–2010 AD is 21.3 ± 2.3 mm H_2O. Accumulation record demonstrates a slight positive trend, however sharply increased accumulation rate during the periods from 1600 to 1815 AD (by 11 % from long-term mean) and from 1963 to 2010 AD (by 15 %) are typical features of the site. Na^+ record shows strong decadal-scale variability probably connected with coupled changes in atmospheric transport patterns over Antarctica (meridional circulation change) and local glaciology. The obtained high resolution climatic records suggest a high sensitivity of the Vostok location to environmental changes in Southern Hemisphere.

1 Introduction

Polar ice cores contain ~~high resolution~~ information about atmospheric aerosols over continuous time intervals. Studies of these ice cores allowed reconstructing global environmental change over the past several hundred thousand years (e.g. Petit et al., 1999; EPICA community members, 2004). High-resolution (years to decades) climate records from ice cores characterize environmental changes in more detail, although the mechanisms of these changes are not fully understood (Mosley-Thompson et al., 1993). Volcanic sulfate aerosol in the atmosphere is a possible factor of climatic fluctuations over relatively short time intervals. Explosive eruptions eject to the stratosphere huge amounts of gas (mainly sulfur dioxide) and solid particles (usually silicate ash) and have the capability of cooling global climate by 0.2–0.3 °C for several years after the eruption (Zielinski, 2000). However, to obtain a complete picture of links between climate and volcanism we need more high resolution records of climate and volcanic changes which can be easily obtained from ice cores. Volcanic events clearly fixed in these cores by horizons with higher acidity and electrical conductivity, by peaks of non-sea salt sulphates, as well as particles of volcanic origin (tephra).

Climatic variations of the last millennium include both ~~worm~~ (Medieval ~~Worm~~ Period of 10–12th centuries and recent ~~worming~~ since mid-20th century) and cold (Little Ice Age of 15–19th centuries) episodes and detailed study of ice cores taken in different sites allow to better understand regional peculiarities of past climate, including mechanisms of atmospheric circulation (Russel and McGregor, 2000). At the present, there are a few high resolution volcanic records from Antarctica covering at least the last millennium (e.g., Delmas et al., 1992; Cole-Dai et al., 2000; Castellano et al., 2005; Ferris et al., 2011; Jiang et al., 2012). Here we try to extend this list and present a ~~composed~~ high-resolution volcanic and climatic record of the past 900 yr from the Vostok station area (East Antarctica), which is one of the lowest snow accumulation sites in Antarctica.

2 Data and methods

2.1 Ice and snow cores

In this study we analyzed some snow/firn core sections from four sites located in the vicinity of Russian Vostok station (Table 1, Fig. 1). The cores were taken in the course of Russian Antarctic Expeditions (RAE) during the summer seasons of 1990, 2007 and 2010. In the field electrical conductivity was continuously measured over the cores and some sections containing suspected volcanic events were chosen for detailed chemical analysis. These cores were transported frozen in pre-cleaned plastic package from Vostok station to ~~Irkutsk~~ laboratory.

2.2 Sample preparation and analysis

Chemical analysis of the core was carried out in the Laboratory of Hydrochemistry and Chemistry of Atmosphere (Limnological Institute SB RAS, Irkutsk). Core sections were mechanically cleaned by removing external part (about 2 cm) and cut with 2–3 cm step under ~~sterile~~ conditions (in laminar box). Then samples were melted and filtered through a membrane filters (with 0.2 µm cell size) pre-washed by deionized water. Concentrations of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (NO_3^-, Cl^-, SO_4^{2-}) were measured in the filtrate using ion chromatograph ICS-3000 (Dionex). Totally 1730 samples have been analyzed. In this article only data of Na^+ and SO_4^{2-} measurements is presented. In order to identify the signals of volcanic eruptions the concentration of non-sea salt (nss) SO_4^{2-} were calculated using SO_4^{2-}/Na^+ concentration ratio in bulk sea water. Based on snow accumulation data (see below) sampling resolution for ion measurement is estimated to be from 1.8 (5G) to 3.0 (VK-55) samples per year.

2.3 Core dating

Snow depths were converted in water equivalent with using density data. Here we used synthesis linear density-depth relationship calculated at Vostok area (Ekaykin et al., 2004) for 5G, VK-07 and VKT-55 cores and individual linear relationship derived from direct density measurements for VK-55. For dating of the cores we used several well-known large volcanic signals previously identified in other sites of Antarctica (Legrand and Delmas, 1987; Moore et al., 1991; Delmas et al., 1992; Cole-Dai et al., 1997, 2000; Zhang et al., 2002 and others). ~~Formerly,~~ the most important volcanic eruptions of XIX century, Tambora (1815) and Krakatoa (1883) have been found in two cores of the Vostok station area, VK-07 and VFL-1 (Khodzher et al., 2011). Totally eight volcanic stratigraphic markers from eruption of unknown volcano in 1259 to Pinatubo eruption in

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1991 have been used in this study (Table 2). It has been taken into consideration that time lag between the actual time of eruption and aerosol accumulation on the snow surface in Antarctica seems to be 1–2 yr (Delmas et al., 1985). Average annual accumulation rate between two adjacent volcanic markers were calculated and intermediate horizons dated. Below the lowest stratigraphic marker in each core the average accumulation rate of overlaying horizons has been used. Age of the oldest sample (5G core) is attributed to 1093 AD. Thus the ion concentration profiles synthesized from four separate cores covers at least the last 900 yr.

Na^+ concentration profile of VK-55 demonstrates quasi-cyclic variations (Fig. 2). Previously, similar variations observed in Antarctic cores have been explained by annual/seasonal changes in the sources of chemical components (e.g., Li et al., 2009). Using 2010 summer snow surface as a time reference we have counted the number of annual layers. Because it is believed that Na^+ peaks as a rule belongs to winter season (Legrand and Delmas, 1987) a calendar year can be defined between two adjacent hollows. Totally, 32 ± 2 annual layers were calculated along the firn core. Uncertainties of layer counting are due to ambiguity of bends manifestation. In accordance with the counting prominent sulfate peak of Pinatubo (1991) at 42.5 cm H_2O was calculated by 1993 AD that demonstrates a striking accuracy of annual dating of this snow core.

2.4 Identification of volcanic events

In order to exclude sulfates of non-volcanic origin or background sulfates we primarily estimated background value of sulfate concentration in the cores by analogy with other works (e.g., Cole-Dai et al., 2000). The value has been calculated for each core as average of the nss-sulfate concentration. Respectively, non-volcanic background for 5G core was estimated as 176 $\mu g L^{-1}$, for VK-07 as 235 $\mu g L^{-1}$, for VKT-55 as 118 $\mu g L^{-1}$ and for VK-55 as 155 $\mu g L^{-1}$. Followed Cole-Dai et al. (1997, 2000) we also calculated the volcanic threshold as average nss-sulfate concentration plus 2σ. The threshold was used in this study as a criterion for distinguishing explosive volcanic events from the background (421 $\mu g L^{-1}$ for 5G, 462 $\mu g L^{-1}$ for VK-07, 249 $\mu g L^{-1}$ for VKT-55 and

349 µg L^{-1} for VK-55). Moreover excess nss-SO_4^{2-} concentration above the threshold for not less than two successive samples was additional criterion for detecting of volcanic event.

For each volcanic event its duration (in yr) and sulfate flux (in kg km^{-2}) were calculated. As it is known in areas dominated by dry sulfate deposition (low accumulation areas) effect of variability of snow accumulation rates could be smoothed by considering the sulfate flux (Legrand and Delmas, 1987; Castellano et al., 2005). The volcanic sulfate flux was obtained for each sample within the event by multiplying the net sulfate concentration (difference between nss-sulfate concentration and background) by the sample length in water equivalent. The volcanic sulfate flux of an event was obtained as the cumulative sum of sulfate fluxes of separate samples.

3 Result and discussion

3.1 900 yr Vostok volcanic record

In general, nss-SO_4^{2-} profile demonstrates a strong variability over the past 900 yr (Fig. 3). Mean long-term sulfate concentration is 197 ± 121 µg L^{-1}. Increased sulfate content was established for intervals of 1230–1270 AD, 1410–1460 AD and 1590–1890 AD with mean concentrations exceeded the long-term mean by 25 %, 42 % and 19 %, respectively.

Totally 33 volcanic events over the last 900 yr has been detected in the Vostok record (VR). These events and their parameters are listed in Table 3 and shown on Fig. 3. Most of the events (24 of 33) are attributed (sometimes tentatively) to historically known eruptions (e.g. Simkin and Siebert, 1994) from the earliest in 1260 AD to the latest in 1998 AD. The largest number of volcanic eruptions occurred in 18th (10 events) and 19th (9 events) centuries. The strongest sulfate signals appeared in 13th, 15th and 18th centuries. The largest volcanic event recorded in Vostok area both by sulfate concentration (1266 µg L^{-1}) and flux (57.4 kg km^{-2}) is the 1452 AD eruption of Kuwae, Vanuatu, South

Pacific (17° S, 168° E). The largest event of XIII century was event dated in 5G core as 1260 AD. The eruption has been tentatively attributed to El Chichon (17° N, 93° W) in Mexico (Palais et al., 1990; Cole-Dai et al., 2000). Langway et al. (1988) used this signal as a bipolar stratigraphic ice core marker. The duration of the events vary from 0.33 to 7.42 yr. The longest events were 1600 AD Huaynaputina (7.4 yr) and 1452 AD Kuwae (6.8 yr).

Besides VR, a few other volcanic records covering at least the last 900 yr are known. Here we used for comparison the records from South Pole (SP, Delmas et al., 1992), Plateau Remote (PR, Cole-Dai et al., 2000) and Dome C (DC, Castellano et al., 2005). Locations of these sites are shown at Fig. 1 and correlation of volcanic events with VR listed in Table 4. In general, VR contains more volcanic events in comparison with any other (particularly after 1700 AD). Only 19 events were found in PR and 21 events in DC and SP for the comparable period. Seven events (V3, V5, V11, V12, V26, V29, and V33) of VR were found in other three records. These include the well-known eruptions of the last millennium: Agung (1963), Krakatoa (1883), Tambora (1815) with unknown eruption (1809), Huaynaputina (1600), Kuwae (1453) and Unknown (1259, El Chichon?).

On the other hand, sixteen events of VR (V1, V4, V7, V8, V14, V15, V17–21, V24, V27, V28, V30, and V31) were not found in any of the three other cores. Some of the events are characterized by very high sulfate concentrations, for example, very prominent peaks V21 (1085 $\mu g L^{-1}$, 1712 AD) and V31 (1124 $\mu g L^{-1}$, 1427 AD). It should be noted that though some sulfate peaks of VR (Fig. 3) do not exceed the calculated threshold but some of them could be attributed to a "volcanic event". For example, the peak dated ~~by~~ 1195 AD ($F = 6.4\,kg\,km^{-2}$) is in good correlation with the events detected in PR (PR19–20, 1191–1197 AD) and in Greenland GISP 2 core (Zelinski et al., 1994) and can be linked with eruption of a low latitude volcano. A similar "event" is 1270 AD ($F = 2.8\,kg\,km^{-2}$) correlated with PR16 (1269 AD) and DC15 (1271 AD). Unlike ~~to~~ the other cores ~~in~~ the ~~VR~~ so-called "1259 sequence" is presented by only one event 1260 AD (V33). Probably it can be explained by presence of core gaps (approximately 42 yr for the interval 1093–1290 AD). At the same time VR contains more large to moderate events concentrated near 1452 AD Kuwae event (V29–V31). The ~~double of~~ volcanic eruptions of Krakatoa SP3 (1883) and Tarawera SP2 (New Zeland, 1886) found in SP record (Delmas et al., 1992) is presented in VR by single although more prolonged (3.4 versus 2.2 yr) event V5 dated as 1884 AD. On the other hand events V12 (1808 AD) and V11 (1816 AD) of VR are also separately presented in other cores (5 and 4 at Dome C, PR5 and PR4 at Plateau Remote and SP8 and SP7 at South Pole, respectively). It ~~means~~ that mixing of snow layers in Vostok area is estimated to be not more than 7–8 yr at least in the beginning of the nineteenth century.

Volcanic sulfate fluxes recorded in Vostok have also some differences with other cores (Fig. 4). The fluxes from Agung (1963), Krakatoa (1883) and Huaynaputina (1600) over Vostok area are more than over DC and PR. However the Tambora (1815) flux in VR is more than in PR and less than in DC. The flux from Kuwae (1453) in VR is much less significant than in PR and more than in DC. Moreover VR flux of Kuwae is more than 1259 AD similar to PR although in SP (Delmas et al., 1992) and Dome C (Castellano et al., 2005) records the Kuwae volcanic flux is significantly less than that of the 1259 AD eruption. Cole-Dai et al. (2000) explained the lower sulfate flux of the “1259 event” in the PR by possible loss of the volcanic mass due to snow drift and redistribution (impact of local glaciology). On the other hand, ~~as well~~ as in VR the Kuwae eruption in the Talos Dome ice core is the largest volcanic signal of the last 800 yr (Stenni et al., 2002).

In order to compare volcanic fluxes among the different sites we also used normalized values of the fluxes with respect to the 1815 AD Tambora eruption (Table 3, Fig. 5) as ~~it was previously~~ proposed by Cole-Dai et al. (1997). Normalized fluxes are expected to be less dependent on glaciological features of sampling sites (e.g. accumulation rate, snow redistribution etc.). Tambora-normalized values (F/F_T) in VR vary from 0.04 to 1.82 although most of them are lower than 1.0 (Fig. 5). The exceptions are two events, 1452 AD Kuwae (1.82) and 1259 AD Unknown (1.37). It means the Tambora eruption (1815 AD) was the strongest event over the last 600 yr.

~~Found~~ differences between mentioned volcanic records are probably caused by both differences in atmospheric circulation which affects the aerosol fallout and local accumulation conditions (e.g. snow redistribution). In low accumulation areas sulfate fallout is dominated by dry deposition with very small dilution effect in comparison with high accumulation areas (Legrand and Delmas, 1987). Apparently weak dilution could explain more prominent volcanic signals in VR.

3.2 Snow accumulation rate

Long term average snow accumulation rate over the past 900 yr (1093–2010 AD) was calculated from the volcanic stratigraphic record as 21.3 ± 2.3 mm H_2O (Fig. 6). In general, the accumulation rate demonstrates a general positive trend (0.006 mm yr^{-1}). The intervals of low~~er~~ accumulation were 1093–1600 AD (18.9 ± 0.5 mm or −11 % from the long-term mean) and 1883–1963 AD (20.8 mm or −2 %). Increased rates of accumulation are observed at 1600–1815 AD (23.7 ± 0.1 mm or +11 %) and 1963–2010 AD (24.5 ± 0.9 mm or +15 %). The results support the earlier conclusion about a slight increase of snow accumulation at the Vostok site during the last 200 yr (Ekaykin et al., 2004). In particular, increasing trend for the period of 1810–2010 AD was calculated as 0.009 mm yr^{-1}. In general, sharp increase of snow accumulation during 17–18th centuries and approximately since mid-1900s are typical features of the Vostok site.

According to some Antarctic proxies the period approximately from 1400 to 1900 AD is characterized by cooler climate conditions related to the Little Ice Age (LIA) cold stage (e.g. Li et al., 2009; Bertler et al., 2011). Orsi et al. (2012) estimated that the temperature in West Antarctic during 1400–1800 AD was on average 0.52 ± 0.28 °C colder than the last 100-yr average. ~~In accordance with~~ Simms et al. (2012) Neoglacial advance in the South Shetland Islands (northern Antarctic Peninsula) occurred between 1500 and 1700 AD. It is considered that during the cold intervals the snow accumulation rates were decreased. Li et al. (2009) have revealed sharply reduced snow accumulation rates between 1450 and 1850 AD in the core from Princess Elizabeth Land (East Antarctica). A reduction in accumulation rate during the time period of 1500 to 1900 AD has been, recently, found in the 1830 yr South Pole record (Ferris et al., 2011). However Mosley-Thompson et al. (1993) reported that net accumulation at South Pole and central Greenland was below the long-term mean from 1600 to 1700 AD and above from 1700 AD onward while at Siple prior to 1700 AD accumulation was above average. The authors believed that such spatial differences result from minor shifts in preferred locations for large-scale circulation features.

Positive accumulation anomaly at Vostok from 1600 AD (final phase of the LIA) is likely ~~to reflect rather~~ regional peculiarities in atmospheric transport over Antarctica than temperature changes. Udisti et al. (2004) ~~have revealed~~ relative changes in snow accumulation rates at Vostok and Dome C sites during the last 45 kyr. They concluded that the changes could be related with variations in regional atmospheric circulation. Recent measurements of snow accumulation along the northern and southern ice flow lines passing through ~~the~~ Lake Vostok have shown that this area is characterized by a strong latitudinal gradient of the snow accumulation rate (Ekaykin et al., 2012). It is likely the Vostok site is very sensitive to changes in atmospheric circulation. An alternative interpretation of increased accumulation may be firn transfer from a higher accumulation site along the flow line from Dome B to Vostok (VFL). Although the averaged rates along the VFL have very little change (21–24 mm H_2O) there is a sharp spatial variability in accumulation rates along the VFL (Ekaykin et al., 2012). Most probably, these anomalies are related to a snow re-deposition as a result of the wind interplay with the glacier surface relief. However, previously, Petit et al. (1982) have showed that spatial variability of the accumulation rate at the Dome C area becomes small at a 10 yr scale. Sulfate volcanic record of the Vostok also suggests (see above) the local snow depositional noise is smoothed over a longer-term scale (Fig. 6). For example, despite ~~of~~ high interannual variability of accumulation rate during 1977–2010 AD due to a local glaciology its mean value (24.7 ± 8.7 mm) ~~perfectly~~ corresponds to that estimated for the same period from volcanic horizons (24.9 mm).

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3.3 Na^+ record

Na^+ is the most suitable marine aerosol indicator in Antarctica (Legrand et al., 1988). The main source of Na^+ in antarctic snow ~~are~~ considered to be either open sea surface (e.g. Legrand and Delmas, 1984; Legrand and Mayewsky, 1997; Wagenbach et al., 1998) or sea ice surface (e.g. Wolff et al., 2003). The Vostok Na^+ record demonstrates strong decadal-scale variability over the last 900 yr with long-term mean concentration of $57.6 \pm 48.7\,\mu g\,L^{-1}$ (Fig. 6). In particular, from 1200 to 1500 AD Na^+ content has a greater variability. Positive Na^+ anomalies are observed at intervals of 1090–1180 AD (mean concentration is $66.4\,\mu g\,L^{-1}$, +15 % from the long-term mean), 1220–1340 AD ($71.1\,\mu g\,L^{-1}$, +23 %), 1400–1510 AD ($82.2\,\mu g\,L^{-1}$, +43 %). During 1630–1920 AD Na^+ demonstrates slight increase ($61.6\,\mu g\,L^{-1}$, +7 %) although some intervals are marked as more prominent spikes. For example, the mean concentrations calculated for 1810–1860 AD and 1670–1710 AD exceed the long-term mean by 30 % and 20 %, respectively. During 1980–2010 AD Na^+ concentration is significantly decreased ($12.6\,\mu g\,L^{-1}$, −78 %). It should be noted that mean Na^+ concentration and its variability at Vostok are significantly increased in comparison with a higher accumulation site (e.g. Sommer et al., 2000).

It is ~~considered~~ that changes of Na^+ concentrations are controlled by local and global factors. On the one hand, Na^+ ~~content is due to~~ a snow accumulation rate ~~effect~~ linked with dry deposition process (Legrand, 1987). On the other hand, Na^+ is highly sensitive to the intensity of meridional circulation as it is supported by prominent seasonal variations (Legrand et al., 1988). However quantitative ~~ratio~~ of both factors at Vostok ~~is~~ still unknown. Although local glaciology (such as snow redistribution by wind etc.) is most efficient in low accumulation sites (Ekaykin et al., 2004) we assume that a large part of Na^+ variability at Vostok is related to atmospheric circulation changes. The increase of meridional (ocean-Antarctica) thermal gradient during the cold stages should lead to enhance of atmospheric circulation and cyclonic activity by analogy with the modern winter conditions (Petit et al., 1999). At Vostok the most pronounced increase of Na^+

concentration during about 1400–1450 AD coincides with the beginning of the LIA, while the second half of the LIA stage (1630–1860 AD) is characterized by a slight Na^+ increase (Fig. 6). Kreutz et al. (1997) found the increase of Na^+ in annually dated Siple Dome ice core at the beginning of the LIA (1400 AD) caused by enhanced meridional circulation intensity. Similarly, increased meridional circulation over Antarctica with increased Na^+ content in snow is determined, for example, during the coldest stage of the last climatic cycle, the Last Glacial Maximum (Legrand et al., 1988). At the same time Li et al. (2009) pointed decreased Na^+ concentrations during the LIA (1450–1850 AD) in ice core from the Princess Elizabeth Land (East Antarctica). The authors suggest the concentration decrease was linked with increased distance to the open water during the LIA cold time. We assume that the above mentioned differences of Na^+ loading between Vostok and other sites reflect complex changes in atmospheric circulation coupled with local glaciological features. However, detailed mechanisms of such interaction need~~s in~~ further development.

4 Conclusions

Four snow and firn cores taken at the Vostok site have been analyzed for chemical composition (major ions). Analysis of nss-SO_4^{2-} profile ~~allowed~~ identif~~ying~~ 33 volcanic events within the last 900 yr (1093–2010 AD). They include both well-known major eruptions of the last millennium (e.g. Agung 1963, Krakatoa 1883, Tambora 1815, Huaynaputina 1600, Kuwae 1452) and those of more moderate intensity. Decreased sulfate deposition occurred during 13th, 15th and 18th centuries. The largest volcanic event in the Vostok record was the 1452 AD Kuwae eruption. The sulfate volcanic record from Vostok ~~unlike~~ those from other sites (e.g. South Pole, Plateau Remote, Dome C) contains more events (particularly after 1700 AD). The differences between the records probably reflect atmospheric circulation pattern differences coupled with local glaciological effects (e.g. wind redistribution of snow).

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Average snow accumulation rate during 1093–2010 AD was calculated as 21.3 ± 2.3 mm H_2O. In general, accumulation record demonstrates a slight positive trend for the last 900 yr (0.006 mm yr^{-1}). Increased snow accumulation rate during 1600–1815 AD and 1963–2010 AD are typical features of the Vostok site. The Vostok Na^+ record demonstrates strong decadal-scale variability over the last 900 yr. It is probably the changes of snow accumulation and sea-salt aerosol fallout recorded at Vostok site reflect rather regional peculiarities of climate variations over Antarctica of both local and global scale which requires further study.

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References

Bertler, N. A. N., Mayewski, P. A., and Carter, L.: Cold conditions in Antarctica during the Little Ice Age – implications for abrupt climate change mechanisms, Earth Planet. Sc. Lett., 308, 41–51, 2011.

Castellano, E., Becagli, S., Hansson, M., Hutterli, M., Petit, J. R., Rampino, M. R., Severi, M., Steffensen, J. P., Traversi, R., and Udisti, R.: Holocene volcanic history as recorded in the sulfate stratigraphy of the European Project for Ice Coring in Antarctica Dome C (EDC96) ice core, J. Geophys. Res., 110, D06114, doi:10.1029/2004JD005259, 2005.

Cole-Dai, J., Mosley-Thompson, E., and Thompson, L. G.: Annually resolved Southern Hemisphere volcanic history from two Antarctic ice cores, J. Geophys. Res., 102, 16761–16771, 1997.

Cole-Dai, J., Mosley-Thompson, E., Wight, S. P., and Thompson, L. G.: A 4100-year record of explosive volcanism from an East Antarctica ice core, J. Geophys. Res., 105, 24431–24441, 2000.

Delmas, R. J., Legrand, M., Aristarain, A. J., and Zanolini, F.: Volcanic deposits in Antarctic snow and ice, J. Geophys. Res., 90, 12901–12920, 1985.

Delmas, R. J., Kirchner, S., Palais, J. M., and Petit, J. R.: 1000 years of explosive volcanism recorded at the South Pole, Tellus, 44 B, 335–350, 1992.
Ekaykin, A. A., Lipenkov, V. Ya., Kuzmina, I. N., Petit, J. R., Masson-Delmotte, V., and Johnsen, S. J.: The changes in isotope composition and accumulation of snow at Vostok station, East Antarctica, over the past 200 years, Ann. Glaciol., 39, 569–575, 2004.
Ekaykin, A. A., Lipenkov, V. Ya., and Shibaev, Yu. A.: Spatial distribution of the snow accumulation rate along the ice flow lines between Ridge B and Lake Vostok, Ice Snow, 4, 122–128, 2012.
EPICA community members: Eight glacial cycles from an Antarctic ice core, Nature, 429, 623–628, 2004.
Ferris, D. G., Cole-Dai, J., Reyes, A. R. and Budner, D. M.: South Pole ice core record of explosive volcanic eruptions in the first and second millennia AD and evidence of a large eruption in the tropics around 535 AD, J. Geophys. Res., 116, D17308, doi:10.1029/2011JD015916, 2011.
Jiang, S., Cole-Dai, J., Li, Y., Ferris, D. G., Ma, H., An, C., Shi, G., and Sun, B.: A detailed 2840 year record of explosive volcanism in a shallow ice core from Dome A, East Antarctica, Ann. Glaciol., 58, 65–75, 2012.
Khodzher, T. V., Golobokova, L. P., Osipov, E. Yu., Artemieva, O. V., Maslennikova, M. M., Lipenkov, V. Ya., Shibaev, Yu. A., Belozerova, O. Yu., and Likhoshway, E. V.: Evidence of volcanic eruptions of the Tambora and Krakatoa (XIX century) according to the chemical and electron-microscopic studies of the snow-firn cores from the area of Vostok station (Antarctica), Ice Snow, 1, 105–113, 2011 (in Russian).
Kreutz, K. J., Mayewski, P. A., Meeker, L. D., Twickler, M. S., Whitlow, S. I., and Pittalwala, I. I.: Bipolar changes in atmospheric circulation during the Little Ice Age, Science, 277, 1294–1296, 1997.
Langway, C. C., Clausen, H. B., and Hammer, C. U.: An inter-hemispheric volcanic time-marker in ice cores from Greenland and Antarctica, Ann. Glaciol., 10, 102–108, 1988.
Legrand, M.: Chemistry of Antarctic snow and ice, J. Phys. Colloq., 48, 77–86, 1987.
Legrand, M. R. and Delmas, R. J.: The ionic balance of Antarctic snow: a 10-year detailed record, Atmos. Environ., 18, 1867–1874, 1984.
Legrand, M. and Delmas, R. J.: A 220-year continuous record of volcanic H_2SO_4 in the Antarctic ice sheet, Nature, 327, 671–676, 1987.

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Legrand, M. and Mayewski, P. A.: Glaciochemistry of polar ice core: a review, Rev. Geophys., 35, 219–243, 1997.

Legrand, M. R., Lorius, C., Barkov, N. I., and Petrov, V. N.: Vostok (Antarctica) ice core: atmospheric chemistry changes over the last climatic cycle (160,000 years), Atmos. Environ., 22, 317–331, 1988.

Li, Y., Cole-Dai, J., and Zhou, L.: Glaciochemical evidence in an East Antarctica ice core of a recent (AD 1450–1850) neoglacial episode, J. Geophys. Res., 114, D08117, doi:10.1029/2008JD011091, 2009.

Moore, J. C., Narita, H., and Maeno, N.: A continuous 770-year record of volcanic activity from east Antarctica, J. Geophys. Res., 96, 17353–17359, 1991.

Mosley-Thompson, E., Thompson, L. G., Dai, J., Davis, M., and Lin, P. N.: Climate of the last 500 years: high resolution ice core records, Quaternary Sci. Rev., 12, 419–430, 1993.

Orsi, A. J., Cornuelle, B. D., and Severinghaus, J. P.: Little Ice Age cold interval in West Antarctica: evidence from borehole temperature at the West Antarctic Ice Sheet (WAIS) Divide, Geophys. Res. Lett., 39, L09710, doi:10.1029/2012GL051260, 2012.

Palais, J. M., Kirchner, S., and Delmas, R. J.: Identification of some global volcanic horizons by major element analysis of fine ash in Antarctic ice, Ann. Glaciol., 14, 216–220, 1990.

Petit, J. R., Jouzel, J., Pourchet, M., and Merlivat L.: A detailed study of snow accumulation and stable isotope content in Dome C (Antarctica), J. Geophys. Res., 87, 4301–4308, 1982.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzmank, E., and Stievenard, M.: Climate and atmospheric history of the past 420 000 years from the Vostok ice core, Antarctica, Nature, 399, 429–436, 1999.

Russell, A. and McGregor, G. R.: Southern Hemisphere atmospheric circulation: impacts on Antarctic climate and reconstructions from Antarctic ice core data, Clim. Change, 99, 155–192, 2010.

Simkin, T. and Siebert, L.: Volcanoes of the World, 2nd Edn., Geoscience Press, Tucson, 349, 1994.

Simms, A. R., Ivins, E. R., DeWitt, R., Kouremenos, P., and Simkins, L. M.: Timing of the most recent Neoglacial advance and retreat in the South Shetland Islands, Antarctic Peninsula: insights from raised beaches and Holocene uplift rates, Quaternary Sci. Rev., 47, 41–55, 2012.

Sommer, S., Wagenbach, D., Mulvaney, R., and Fischer H.: Glacio-chemical study spanning the past 2 kyr on three ice cores from Dronning Maud Land, Antarctica: 2. Seasonally resolved chemical records, J. Geophys. Res., 105, 29423–29433, 2000.

Stenni, B., Proposito, M., Gragnani, R., Flora, O., Jouzel, J., Falourd, S., and Frezzotti, M.: Eight centuries of volcanic signal and climate change at Talos Dome (East Antarctica), J. Geophys. Res., 107, ACL 3-1–ACL 3-13, doi:10.1029/2000JD000317, 2002.

Udisti, R., Becagli, S., Castellano, E., Delmonte, B., Jouzel, J., Petit, J. R., Schwander, J., Stenni B., and Wolff, E. W.: Stratigraphic correlations between the European Project for Ice Coring in Antarctica (EPICA) Dome C and Vostok ice cores showing the relative variations of snow accumulation over the past 45 kyr, J. Geophys. Res., 109, D08101, doi:10.1029/2003JD004180, 2004.

Wagenbach, D., Ducroz, F., Mulvaney, R., Keck, L., Minikin, A., Legrand, M., Hall J. S., and Wolff, E. W.: Sea-salt aerosol in coastal Antarctic regions, J. Geophys. Res., 103, 10961–10974, 1998.

Wolff, E. W., Rankin, A. M., and Röthlisberger, R.: An ice core indicator of Antarctic sea ice production?, Geophys. Res. Lett., 30, 2158, doi:10.1029/2003GL018454, 2003.

Zhang, M. J., Li, Z. Q., Xiao, C. D., Qin, D. H., Yang, H. A., Kang, J. C., and Li, J.: A continuous 250-year record of volcanic activity from Princess Elizabeth Land, East Antarctica, Antarctic Sci., 14, 55–60, 2002.

Zielinski, G. A.: Use of paleo-records in determining variability within the volcanism-climate system, Quaternary Sci. Rev., 19, 417–438, 2000.

Zielinski, G. A, Mayewski, P. A, Meeker, L. D, Whitlow, S., Twickler, M. S, Morrison, M., Meese, D. A., Gow, A. J., and Alley, R. B.: Record of Volcanism Since 7000 B.C. from the GISP2 Greenland Ice Core and Implications for the Volcano-Climate System, Science, 264, 948–952, 1994.

Table 1. Short description of ice and firn cores used in this study (see also Fig. 1).

Site	Type of site	Location	Depth intervals, m
5G	Deep borehole (started in 1990 ∼ snow surface age)	Vostok station (78.465° S, 106.835° E)	15.50–36.00 (with few gaps)
VK-07	shallow borehole (RAE-52, summer 2007)	∼ 350 m to the SW from 5G	3.80–19.30
VKT-55	shallow borehole (RAE-55, summer 2010)	∼ 150 m from VK-07	2.50–7.80
VK-55	snow pit (RAE-55, summer 2010)	∼ 1.4 km to the SW from 5G	0.00–2.00

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Table 2. Volcanic stratigraphic markers and their ages.

Core	Volcano (Year of Eruption, AD)	Depth in core, m	Depth in H_2O, m	Year in core, AD	Period covered	Mean accumulation, mm $H_2O\,yr^{-1}$
5G	Long Island (1660)	15.63	7.28	1661		
					1601–1661	23.7
	Huaynaputina (1600)	18.60	8.70	1601		
					1453–1601	18.3
	Kuwae (1452)	23.93	11.41	1453		
					1260–1453	18.9
	El Chichon (1259)	30.52	15.06	1260		
					< 1260	19.6
VK-07	Krakatoa (1883)	6.36	2.43	1884		
					1816–1884	22.5
	Tambora (1815)	10.08	3.96	1816		
					1661–1816	23.7
	Long Island (1660)	18.16	7.64	1661		
					< 1661	23.4
VKT-55	Agung (1963)	2.82	1.03	1964		
					1884–1964	20.8
	Krakatoa (1883)	7.12	2.70	1884		
					< 1884	20.8
					1993–2010	24.9
VK-55	Pinatubo (1991)	1.09	0.43	1993		
					< 1993	24.9

Table 3. Volcanic events for last 900 yr in Vostok area (combined).

Core	Eruption (year)	Event	Year, AD	Duration, yr	Depth in core, m	Peak nss-sulfate, µg L^{-1}	Volcanic flux (F), kg km^{-2}	$F/F_{Tambora}$
VK-55	Semeru (1996)	V1	1998	0.3	0.77	471	2.7	0.09
	Pinatubo (1991)	V2	1993	5.0	1.09	535	20.3	0.64
VKT-55	Agung (1963)	V3	1964	3.3	2.82	430	12.5	0.40
	Ritter Island (1888)	V4	1889	0.8	6.84	223	1.7	0.05
VK-07	Krakatoa (1883)	V5	1884	2.5	6.36	515	8.9	0.28
	Makian (1861)	V6	1861	0.5	7.64	649	5.5	0.18
	Kelut (1848)	V7	1849	0.4	8.29	494	2.3	0.07
	Tinakula-Savo (1840)	V8	1840	1.1	8.78	497	4.7	0.15
	Cosiguina (1835)	V9	1836	1.5	9.00	544	3.9	0.12
	Merapi (1832)	V10	1829	0.7	9.38	484	2.1	0.07
	Tambora (1815)	V11	1816	5.7	10.08	676	31.5	1.00
	Unknown (1809)	V12	1808	1.8	10.53	471	6.9	0.22
	Kilauea (1790)	V13	1796	1.1	11.21	767	6.2	0.20
	?	V14	1787	0.4	11.65	529	2.9	0.09
	Gamalama (1775)	V15	1772	0.7	12.48	518	4.4	0.14
	Taal (1754)	V16	1756	0.3	13.31	485	2.1	0.07
	?	V17	1742	0.8	14.06	578	6.1	0.19
	?	V18	1741	0.8	14.12	463	5.3	0.17
	?	V19	1735	0.8	14.46	543	3.3	0.11
	Raung (1730)	V20	1728	1.9	14.81	578	13.3	0.42
	Taal (1716)	V21	1712	2.4	15.61	1085	23.7	0.75
	Cotopaxi (1698)	V22	1700	2.4	16.25	565	8.6	0.27
	Gamkonora (1673)	V23	1676	0.8	17.43	463	5.1	0.16
	Long Island (1660)	V24	1661	3.3	18.16	502	6.8	0.22
5G	Parker+Deception (1641)	V25	1633	2.0	17.03	443	12.0	0.38
	Huaynaputina (1600)	V26	1601	7.4	18.60	489	24.7	0.78
	?	V27	1552	0.5	20.41	560	3.8	0.12
	?	V28	1527	0.6	21.33	470	3.8	0.12
	Kuwae (1452)	V29	1453	6.8	23.93	1266	57.4	1.82
	?	V30	1442	2.2	24.33	483	8.2	0.26
	?	V31	1427	2.3	24.87	1124	22.8	0.72
	?	V32	1290	0.8	29.53	714	7.7	0.24
	El Chichon (1259)	V33	1260	6.0	30.52	1097	43.1	1.37

Table 4. Correlation of volcanic events of Vostok record with other cores in East Antarctica.

Volcanic eruption (year)	Vostok (this study)		Plateau Remote (Cole-Dai et al., 2000)		Dome C (Castellano et al., 2005)		South Pole (Delmas et al., 1992)	
	Event	Year, AD	Event	Year AD	Event	Year AD	Event	Year AD
Semeru (1996)	V1	1998						
Pinatubo (1991)	V2	1993			A	1992		
Agung (1963)	V3	1964	PR1	1968	B	1964	SP1	1964
Ritter Island (1888)	V4	1889						
							SP2	1886
Krakatoa (1883)	V5	1884	PR2	1884	1	1887	SP3	1884
					2	1881	SP4	1880
Makian (1861)	V6	1861			3	1861		
Kelut (1848)	V7	1849						
Tinakula-Savo (1840)	V8	1840						
Cosiguina (1835)	V9	1836	PR3	1836			SP5	1836
Merapi (1832)	V10	1829					SP6	1831
Tambora (1815)	V11	1816	PR4	1816	4	1816	SP7	1816
Unknown (1809)	V12	1808	PR5	1810	5	1807	SP8	1809
Kilauea (1790)	V13	1796					SP9	1795
?	V14	1787						
Gamalama (1775)	V15	1772						
Taal (1754)	V16	1756			6	1758		
?	V17	1742						
?	V18	1741						
?	V19	1735						
Raung (1730)	V20	1728						
Taal (1716)	V21	1712						
Cotopaxi (1698)	V22	1700	PR6	1694	7	1696		
Gamkonora (1673)	V23	1676	PR7	1671	8	1675		
Long Island (1660)	V24	1661						
			PR8	1653				
Parker+Deception (1641)	V25	1633	PR9	1639	9	1624	SP10	1641
							SP11	1621
Huaynaputina (1600)	V26	1601	PR10	1600	10	1601	SP12	1601
			PR11	1595			SP13	1596
?	V27	1552						
?	V28	1527						
					11	1480		
Kuwae (1452)	V29	1453	PR12	1454	12	1460	SP14	1450
?	V30	1442						
?	V31	1427						
			PR13	1343	13	1347	SP15	1340
?	V32	1290	PR14	1285	14	1288		
			PR15	1277			SP16	1279
			PR16	1269	15	1271	SP17	1269
El Chichon (1259)	V33	1260	PR17	1260	16	1259	SP18	1259
			PR18	1234	17	1230		
			PR19	1197	18	1190	SP19	1191
					19	1170	SP20	1177
							SP21	1118

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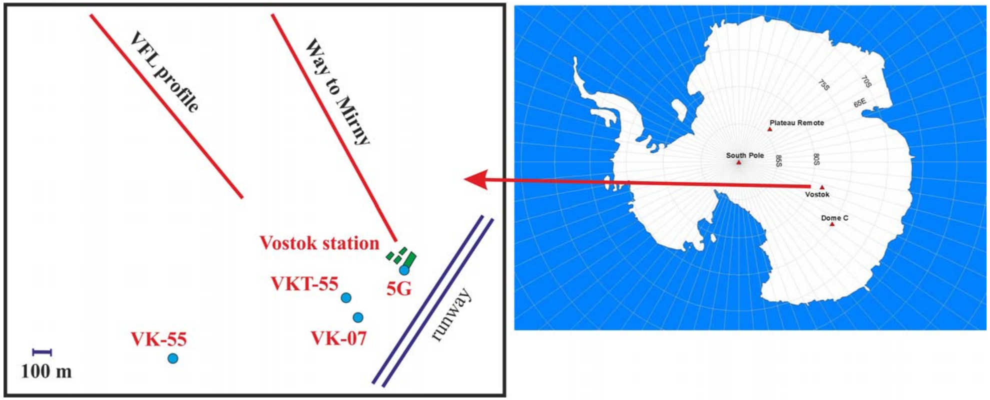

Fig. 1. Locations of the Vostok station and core sites used in this study (left side). Also other Antarctica core sites mentioned in text are indicated (right side).

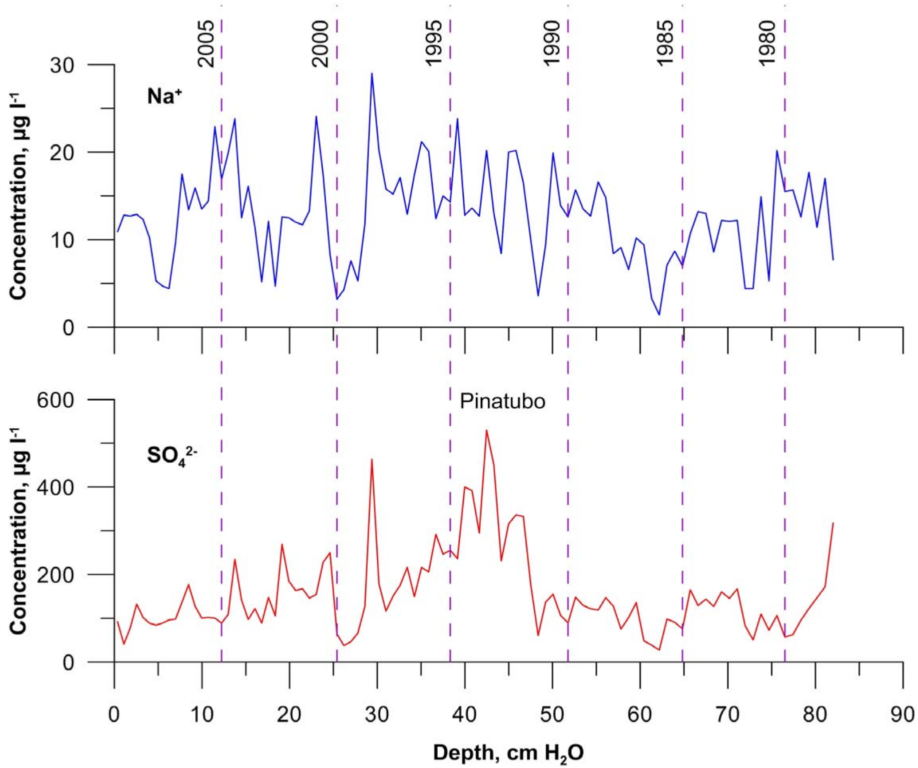

Fig. 2. Variation of Na^+ and SO_4^{2-} concentrations used for counting of annual layers in snow pit VK-55. The peak on sulfate profile at 42.5 cm H_2O corresponds to Pinatubo eruption of 1991 (in the core 1993). Zero depth corresponds to 2010 summer snow surface.

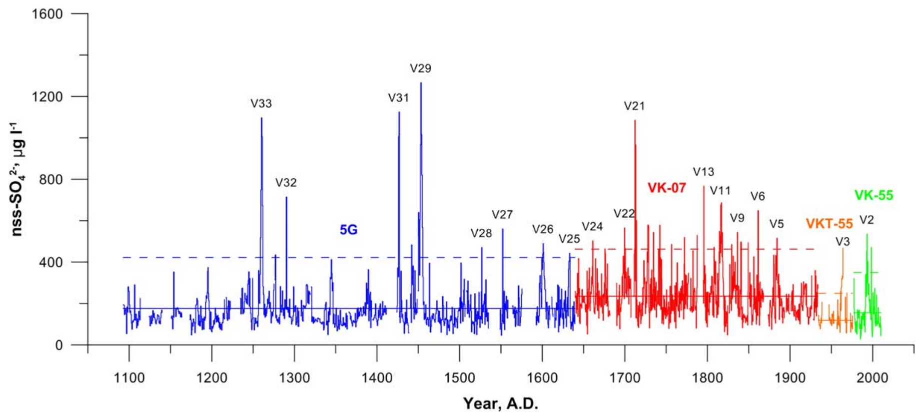

Fig. 3. Composed nss-SO_4^{2-} 900 yr volcanic record for the Vostok area. Each of used four cores is shown by different color (5G, VK-07, VKT-55 and VK-55). Some volcanic eruptions are labeled (for more details see Table 3). Solid horizontal lines indicate non-volcanic background and dashed lines show the detection threshold (explanations are in text).

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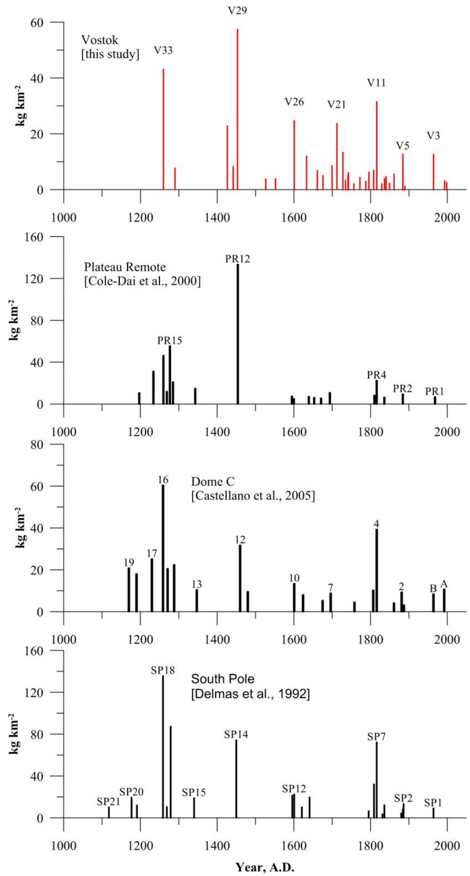

Fig. 4. Comparison of sulfate fluxes of volcanic eruptions recorded in four Antarctic cores. Explanations are in text.

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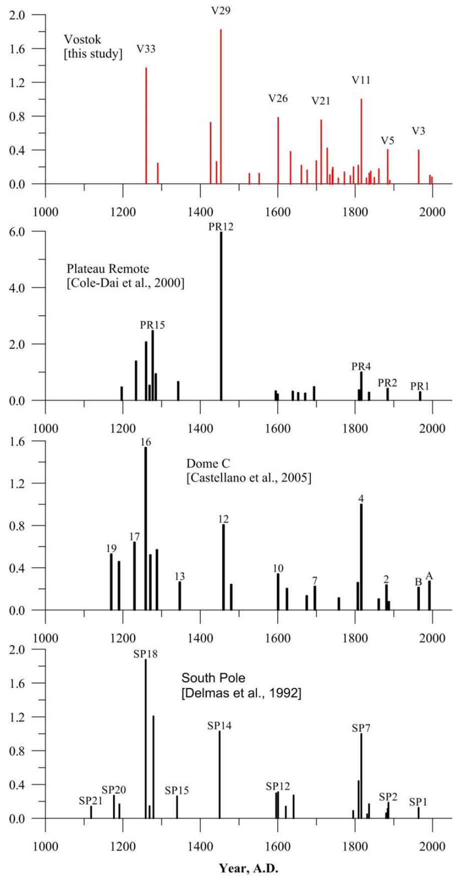

Fig. 5. Comparison of Tambora normalized sulfate fluxes of volcanic eruptions recorded in four Antarctic cores. Explanations are in text.

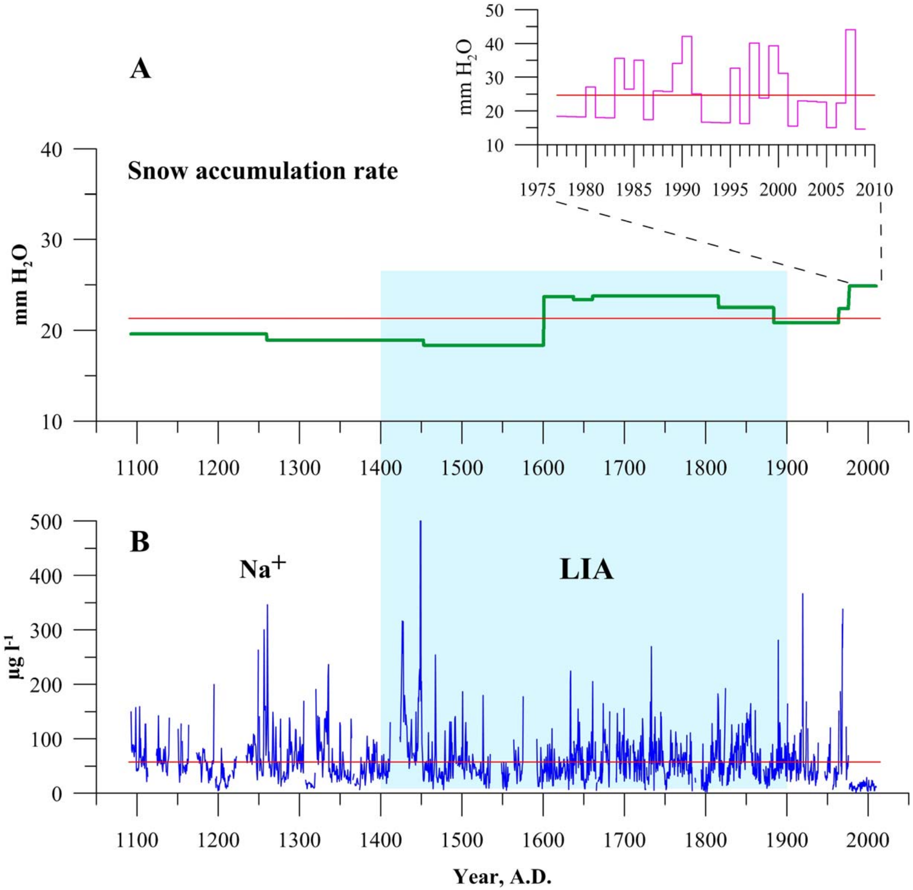

Fig. 6. (A) Snow accumulation rates during 1093–2010 AD. Annually resolved data for the period 1977–2010 AD were calculated based Na^+ values in snow pit VK-55 (insert). **(B)** Na^+ concentration profile of the Vostok record for the last 900 yr. Horizontal red lines represent average value, filled rectangle shows the Little Ice Age period.