Records of climatic changes and volcanic events in an ice core from Central Dronning Maud Land (East Antarctica) during the past century

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The depth profiles of electrical conductance, δ^{18}O, ^{210}Pb and cosmogenic radio isotopes ^{10}Be and ^{36}Cl have been measured in a 30 m ice core from east Antarctica near the Indian station, Dakshin Gangotri. Using ^{210}Pb and δ^{18}O, the mean annual accumulation rates have been calculated to be 20 and 21 cm of ice equivalent per year during the past $\sim$ 150 years. Using these acumulation rates, the volcanic event that occurred in 1815 AD, has been identified based on electrical conductance measurements. Based on δ^{18}O measurements, the mean annual surface air temperatures (MASAT) data observed during the last 150 years indicates that the beginning of the 19th century was cooler by about 2° C than the recent past and the middle of 18th century. The fallout of cosmogenic radio isotope ^{10}Be compares reasonably well with those obtained on other stations (73° S to 90° S) from Antarctica and higher latitudes beyond 77°N. The fallout of ^{36}Cl calculated based on the present work agrees well with the mean global production rate estimated earlier by Lal and Peters (1967). The bomb pulse of ^{36}Cl observed in Greenland is not observed in the present studies – a result which is puzzling and needs to be studied on neighbouring ice cores from the same region.

1. Introduction

Long ice cores from polar ice sheets provide information on continuous records of past volcanic eruptions and accumulation rates of ice, climatic and environmental changes, atmospheric and nuclear fallout, and solar and terrestrial variability for several thousands of years (Orheim *et al* 1986; Delmas *et al* 1992; Nijampurkar and Rao 1993a; Beer *et al* 1994; Stuiver *et al* 1995 and Hammer *et al* 1997). In recent years, there has been considerable interest to study short term (a few centuries), high resolution records of climate and environment from archives such as glaciers, ice sheets, tree rings and lake sediments (Orheim *et al* 1986; Ramesh *et al* 1989; Nijampurkar and Rao 1993a and Petterson *et al* 1993) These records often show interannual variations in global surface air temperature, sea surface temperature and precipitation which appear to correlate with 11 year solar cycle, heavy rainfall and flood events (Seleshi *et al* 1994 and Currie 1994).

Measurements of the DC electrical conductivity of solid ice (EC) is a quick and powerful tool for obtaining historical records of volcanic eruptions in terms of deposition of strong acids H_2SO_4, HCl and micro particles. These records also provide precise accumulation rates of ice, giving accurate time index during the past several thousands of years (Hammer *et al* 1997). Stable isotopes of oxygen (δ^{18}O) are excellent time markers and climatic indicators (Jouzel *et al* 1987). Natural radio isotopes of different half-lives (^{210}Pb, ^{10}Be and ^{36}Cl) give information about their fallout and depositional history during different time scales. Whereas

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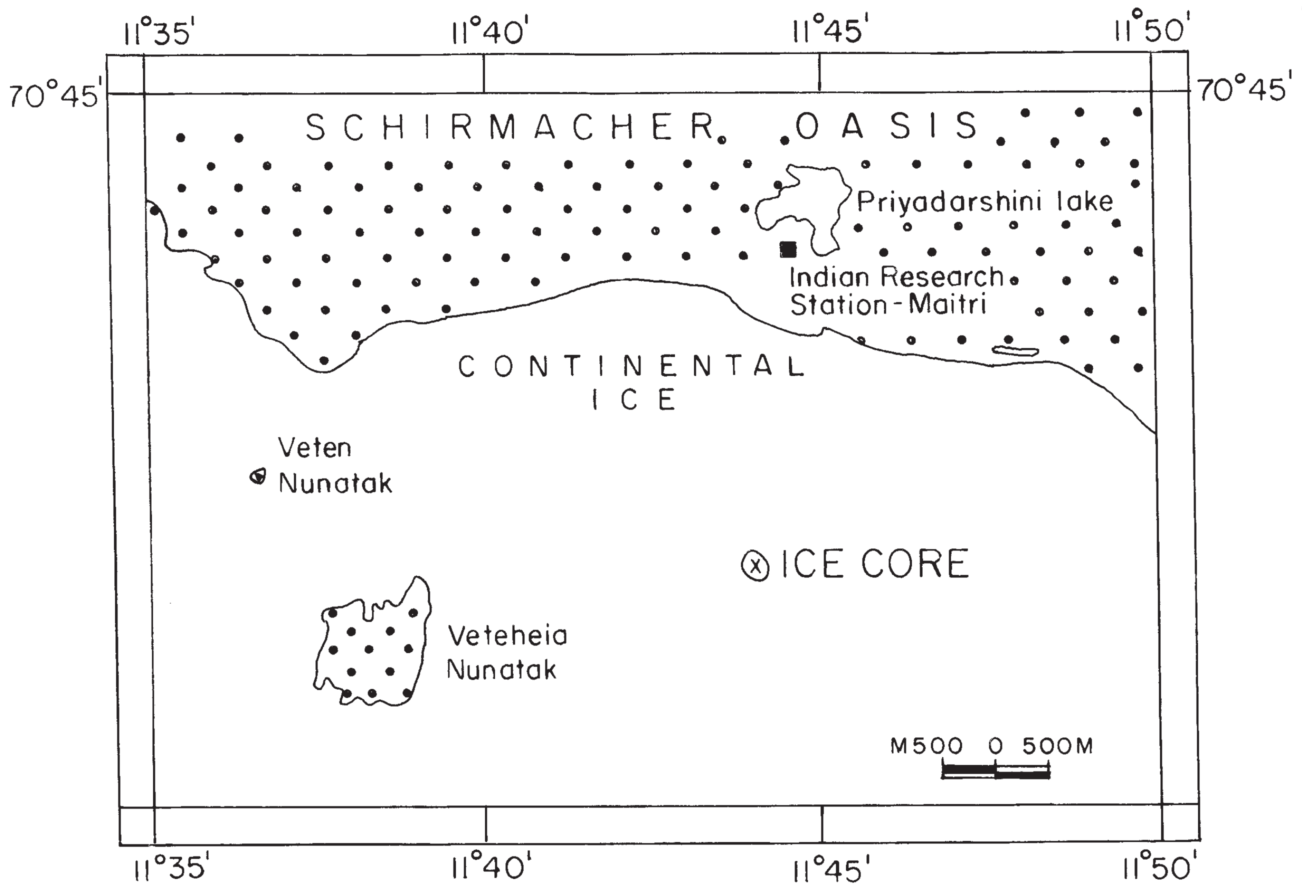

Figure 1. Location map of the site from where 60 m ice core was raised during the Indian expedition to Antarctica in 1992.

^{210}Pb ($t_{1/2} = 22.3$ a) gives accumulation rates of ice during the last century (Gaggeler *et al* 1983), the cosmogenic radio isotope ^{10}Be ($t_{1/2} = 16$ Ma) with a much longer half-life gives long term accumulation rates of ice during millions of years and information on climatic changes, solar cycles and sun spot activities during different time scales (Beer *et al* 1991). Another cosmogenic isotope ^{36}Cl ($t_{1/2} = 0.3$ Ma) also produced during testing of nuclear weapons from 1950–1980, is a useful tracer to study transport process in the atmosphere and hydrology (Synal *et al* 1990). These two cosmogenic isotopes are promising proxies to reconstruct solar and terrestrial variability on the scales longer than a few centuries (Beer, personal communication, 1998). The ^{10}Be/^{36}Cl ratio is very useful for dating older ice (Nishiizumi *et al* 1983). Since the data, until this date, for these isotopes is sparse on the southern hemisphere (Antarctica) in comparison to that from Greenland and other Polar regions from northern hemisphere, we present in this paper the results of the part of the ice core (3–10 m) for ^{10}Be and ^{36}Cl concentrations during the last 35 years. Recently Aldahan *et al* (1998) have published data for ^{10}Be in a core from Antarctica in a nearby site spanning a period of 60 years B.P. The main objective of this study is to compare the levels of concentrations of ^{10}Be and ^{36}Cl during the past few decades with available data (Aldahan *et al* 1998) from other locations and to compare our data with the bomb pulse of ^{36}Cl observed in Greenland from 1940–1980.

In view of the above, we discuss the data of our analysis of the first 60 m ice core raised from east Antarctica near the Indian station, Dakshin Gangotri, in 1992 in terms of short term climatic changes (δ^{18}O), volcanic eruptions (ECM), accumulation rates of ice (^{210}Pb, δ^{18}O, ECM) and fallout of cosmogenic ^{10}Be and ^{36}Cl during the last 150 years. Due to technical constraints, measurements were carried out only on part of the 30 m top core ($\sim$ 150 years).

2. Location and sample collection

The 60.46 m ice core was raised in the continental ice by the Geological Survey of India (G.S.I) south of the Indian Research Station, Maitri, in Central Dronning Maud Land, East Antarctica during the austral winter of the 12th Indian scientific expedition to Antarctica in 1992 (Chaturvedi *et al* 1996). The drilling site was $\sim$ 3 km east of the Nunatak Vateheia at location 70°47′S, 11°44′E south of Schirmachar Oasis (figure 1).

Table 1. *Various parameters, techniques used in the present study and their applications.*

S.No	Parameter	Technique	Importance
1.	$\delta^{18}O$	Mass spectrometry	Climatic changes Accumulation rates
2.	^{10}Be, ^{36}Cl	Accelerator mass spectrometry	Solar and terrestrial variability Atmospheric transport Climatic variations Dating of polar ice
3.	^{210}Pb Total β	Radiation detectors (α, β)	Accumulation rates
4.	Solid conductance	Indigeneous conductometer	Past volcanic records Accumulation rates
5.	Density	Conventional technique	Study of densification

The lowest minimum air temperature recorded during the period was $-34.5°$ C in the month of August 1993. Scanty snow fall and wind-borne snow was witnessed intermittently all round the year, particularly during winter and the spring months and was generally associated with blizzards. Out of the total 60.46 m of the ice core, more than 95% was recovered in unshattered columns. The average length of each column was about 60 cm; though, at times, individual core of 2 m length have also been obtained. The physical logging of the core was done in the field.

The entire core was cut into 302 sections of about 20 cm each at the sampling site and kept frozen in ultra clean wide mouth plastic bottles. These samples for all sections were photographed and later subjected to density stratigraphic studies in the field. However, these measurements could not be carried out on the first thirteen samples from the top 2.9 m because they were collected as broken ice bits.

The complete core was transported from Antarctica to Goa by ship in a frozen condition and preserved at $-20°$ C in a cold storage and later transported in a refrigerated vehicle to Ahmedabad and stored in a refrigerator till the time of analysis.

3. Analytical procedures

After obtaining the photographic records of the various sections of the core and density stratigraphy in the field, the core sections were subjected to analysis for the different parameters (EC, $\delta^{18}O$, ^{210}Pb, ^{10}Be, ^{36}Cl) in different laboratories (see sections 3.1 and 3.2). Table 1 gives the various parameters, techniques used in the present study and their applications.

3.1 *Electrical conductivity (EC) measurements*

About 20 cm cylindrical sections of the core from 3–30 m depth was cleaned by scraping off a few mm of the surface ice using an ultra clean stainless steel knife. The electrical conductivity of the cleaned solid ice core section was measured at $-18°$ C in a vertical model deep freezer using the Electrical Conductivity Method. The acidity of the core was monitored in terms of the current using an EC system developed at PRL on similar lines following those available (Hammer 1980).

3.2 *$\delta^{18}O$, ^{210}Pb, ^{10}Be and ^{36}Cl measurements*

After EC measurements, each section of 20 cm core was subsampled in 2–3 cm interval for $\delta^{18}O$ measurements and preserved frozen until analysis. The remaining part of each 20 cm section ($\sim$ 2L) was preserved in a frozen condition before analysis for ^{210}Pb, ^{10}Be and ^{36}Cl.

The $\delta^{18}O$ measurements were made at the Department of Geophysics, Copenhagen, Denmark by two authors using an auto mass spectrometer as per standard procedures (Dansgaard 1964). We obtained a continuous low resolution record of $\delta^{18}O$ measurements from 0–3 meters representing ice melt waters (not in frozen condition) each of 20 cm ice fractions. However these samples were probably subjected to evaporation, melting and refreezing disturbing their original $\delta^{18}O$ signatures during sampling, transporting and storage before measurements. These results, therefore, are not included in the text for the discussion of comparison of their $\delta^{18}O$ concentrations and interpretation of accumulation of ice and climatic variations.

^{210}Pb activities in the melt water samples ($\sim$ 1L) were measured as per the standard procedures using α spectrometry (Sarin *et al* 1992). In brief, these samples were acidified with 6N HCl so as to maintain the pH $\sim$1–2 and were spiked with known activity of ^{209}Po. After equilibration of spike, samples were evaporated to dryness and the residue was dissolved in 50 ml of 0.6 N HCl. From this solution, polonium isotopes were plated on silver planchet and their activities were assayed by alpha spectrometry using silicon surface barrier detectors. From the measured activity of ^{210}Po, the *in situ* ^{210}Pb activity in the samples were calculated.

^{10}Be and ^{36}Cl activity measurements were made at the AMS facility of ETH/AST in Zurich, Switzerland. Be and Cl spikes (supplied by J Beer) were added to bi-annual samples during melting of the ice. The samples in the ultra clean, leak proof plastic bottles were sent to the AMS laboratory of Prof. J Beer for ^{10}Be and ^{36}Cl analysis. The samples cover approximately the time period of nuclear testing from 1980–1940 AD, and they were analysed as per the standard procedures published earlier (Beer *et al* 1994).

4. Results and discussion

4.1 *Physical examination of the core*

Photographic and density stratigraphy studies were conducted in the field by G.S.I. (Geological Survey of India) scientists. The photographic record of the core did not reveal any specific information regarding trapped dust particles. No dust horizon was observed in any section of the core. The density of the solid sections of the core varied from 890 to 910 kg/m^3 (Chaturvedi *et al* 1996) from 3 to 60 m depth with a variation of ~2% up to 60 m depth. However the density of the top sections of the core from 0–3 m could not be measured as these samples were recovered in broken bits.

4.2 *Electrical Conductivity (EC) measurements*

The EC profile shown in figure 2 indicates that the high background of the instrument ($2 \pm 2\,\mu$amp) is probably due to non-ideal laboratory conditions (like non availability of cold room facility generally maintained at $-18°$ to $-20°$ C for such measurements) during the course of EC measurements of all the samples. The sharp peaks of magnitude $>10\,\mu$amp (saturated values of currents due to limitations of the instrument) at few depths (time) could be related to historical volcanic eruptions during the past 150 years and can be subsequently used for dating older ice. A sharp peak of $>10\,\mu$amp occurring at a depth of about 30 m could be related to the major eruption 'TAMBORA' that occurred in Indonesia (10° S) in 1815 AD. The other sharp peak observed at 5 m depth around 1963–64 which can be attributed to volcanic eruption that occurred at 1° S (AUGUNG) in 1963. Four unidentified peaks of similar magnitudes were observed at depths between 3 and 4 m probably due to major eruptions that might have occurred recently (i.e., after 1963) in the southern hemisphere. They, however, could not be related to any specific known volcanic events.

The volcanic eruption of 'TAMBORA' that erupted in 1815AD has been used to calculate an accumulation rate of $\sim 17 \pm 0.08$ cm/yr which agrees reasonably well with those obtained by ^{210}Pb and δ^{18}O (see discussion 4.3 and 4.4).

Due to some constraints in the logistic facilities in storage and transportation of the ice cores, the data are interpreted with caution.

4.3 *^{210}Pb activities*

The ^{210}Pb activities up to a depth of 20 m have been measured (by combining 8 sections of the core each of 160 cm to obtain easily measurable signals of ^{210}Pb activities). The results of 7 samples is plotted on figure 3, The best fit line of the data gives an average accumulation rate of 20 ± 2 cm/yr during the past 100 years. It appears from figure 3 that the accumulation rate of ice has not remained constant during the last century and varies from 12.5 to 26.6 cm/yr with a mean value of 20 ± 2 cm/yr. Figure 3 shows that the ^{210}Pb activity at a depth of ~10 m is decreased by a factor of ~4 (about 2 half-lives of ^{210}Pb) relative to that at 3 m. This indicates that the depth interval from 3–10 m covers a time span of ~50 years (1990–1940)—a period of nuclear tests. This also suggests an age of 150 years at the depth 30 m. The fallout of ^{210}Pb calculated from the present work (2.6×10^{-2} dpm/cm^2 yr) agrees well with the mean fallout of 3×10^{-2} dpm/cm^2 yr for different locations in 60°–90° belt in southern hemisphere (Crozaz *et al* 1964; Picciotto *et al* 1964; Nijampurkar and Rao 1993b). However, the mean value of ^{210}Pb fallout estimated in the 60°–90° belt in the northern hemisphere is higher by a factor of ~2 (5×10^{-2} dpm/cm^2 yr, Crozaz and Langway 1966).

4.4 *δ^{18}O measurements*

δ^{18}O records in the polar ice cores have often been used to determine the accumulation rates of ice and the mean annual surface air temperatures (MASAT) at the site of precipitation (Dansgaard 1964). δ^{18}O measurements carried out in the present work are discussed in the light of these parameters.

The depth profile of the continuous record of δ^{18}O measurements for 3–6 m depth of the core is given in figure 4. The continuous high resolution δ^{18}O record shows clear cyclic variations and annual cycles with summer and winter peaks. These data have been used for calculation of

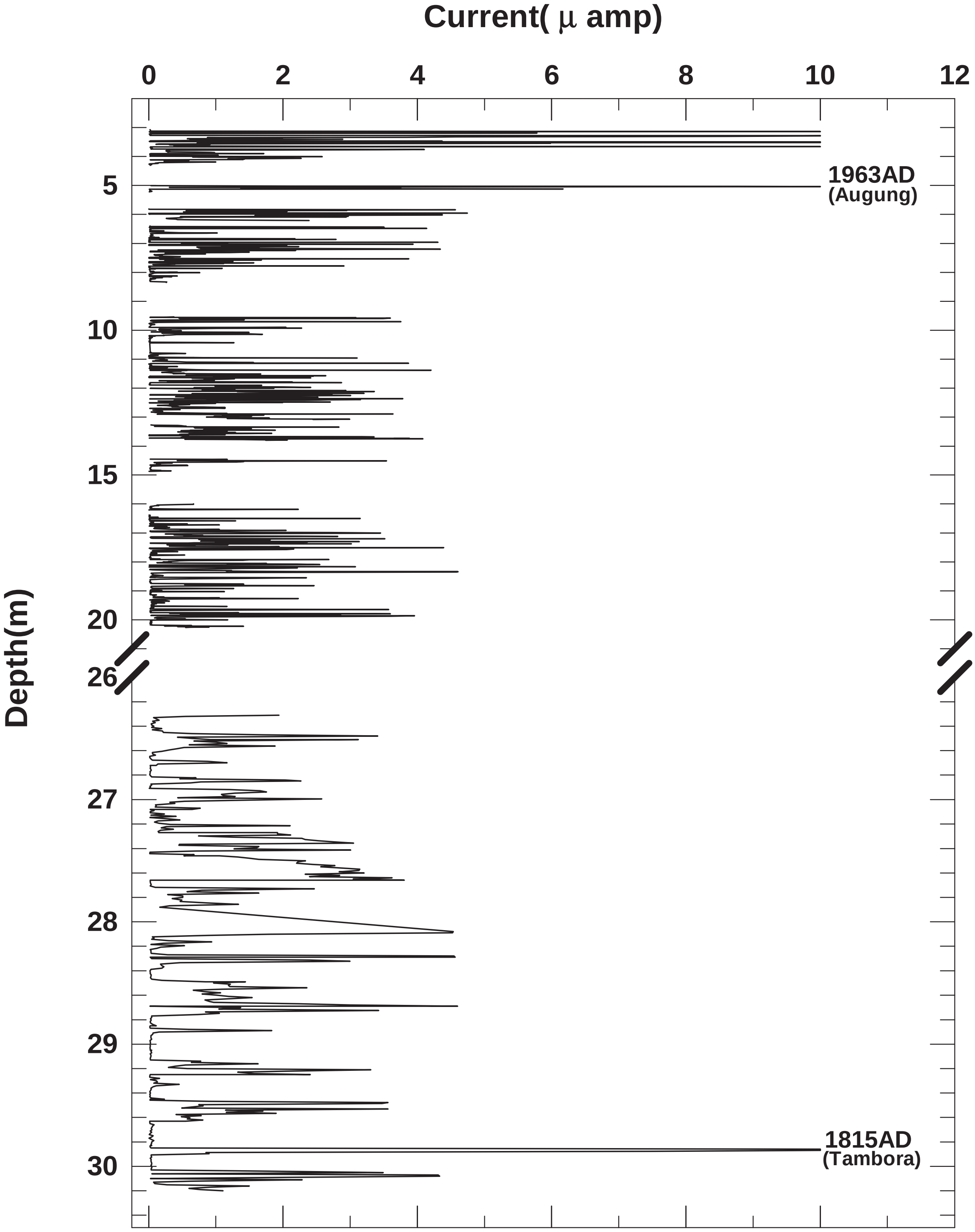

Figure 2. Electrical conductivity measurements of the solid ice core samples from 0–30 m depth at an interval of 20 cm. The peak saturated values of currents (μ amp) at about 5 and 30 m depths identify the past volcanic episodes Augung (1963AD) and Tambora (1815 AD) respectively. For unidentified peaks between 3 and 4 m depth, please refer section 4.2

(i) accumulation rates of ice and (ii) MASAT at the site of precipitation using empirical linear relationship established between mean annual δ^{18}O and MASAT (Dansgaard 1964). In the absence of any other good time marker (e.g., ^{137}Cs) ^{210}Pb has been used to calculate and compare the ages of ice samples and used as time index to study the depositional history of the ice core and climatic variations at the site of precipitation.

The δ^{18}O values for the depth 3–6 m (figure 4) equivalent to 1977–1962 AD, vary from −21.4 to −26.5%. The accumulation rate of ice during this period is not uniform and varies from 8 to 46 cm/yr and the mean has been calcu-

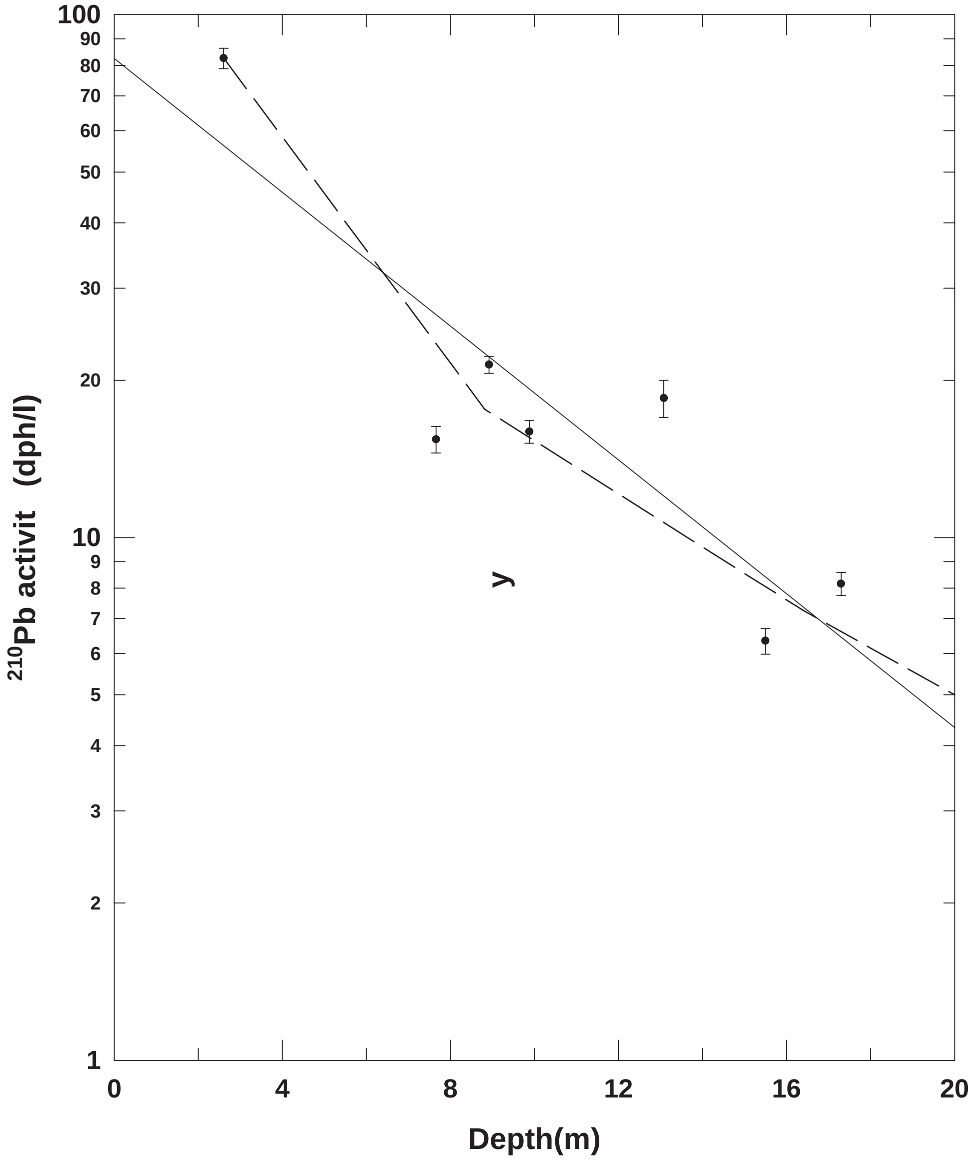

Figure 3. Depth profile of ^{210}Pb specific activities in the ice core up to 18 m depth. The past average accumulation rate of ice has been calculated to be 20 ± 2 cm/yr using the best-fit line of these data. The depth profile, however, shows that the accumulation rate has varied during the past century.

lated to be 21 ± 0.10 cm/yr. The accumulation rate of ice during the first two years (corresponding to 3–4 m depth) are observed to be higher by a factor of two compared to the calculated mean value. Similarly the discontinuous cyclic record of δ^{18}O concentrations shows that the accumulation rate of ice varies from 16 to 26 cm/yr during the time period equivalent to 6-30 m (1960–1840AD). The average MASAT value for the period equivalent to 3–6 m has been calculated to be −15° C (table 2). Figure 5 shows the average MASAT values verses depth of 3–30 m. The individual MASAT values for the different periods have been calculated which vary from −15 to −17.6° C and shows lowest MASAT of −17.6 ± 0.2°C at ∼ 1900AD. More measurements are needed to confirm the trend and minima at ∼ 1900 AD. Table 2 shows the mean annual δ^{18}O, average MASAT, age (yr) and time (AD) for the different periods corresponding to different depths from 3–30 m. It is clear from table 2 and figure 5 that the MASAT for the period equivalent to 17.8 to 18.0 m depth (i.e., beginnning of the 19th century) was lower by ∼ 2°C compared to other time periods.

The data therefore indicate that the average accumulation rate at this site during the last 150 years is about 20 cm/yr and that a few decades at the beginning of the century (1920–1890 AD) were cooler by ∼ 2° C than the other periods during the recent past (1977–1920 AD) and middle of 18th century (1890–1840 AD). The accumulation, however, is not uniform during this period and shows large interannual and decadal variations.

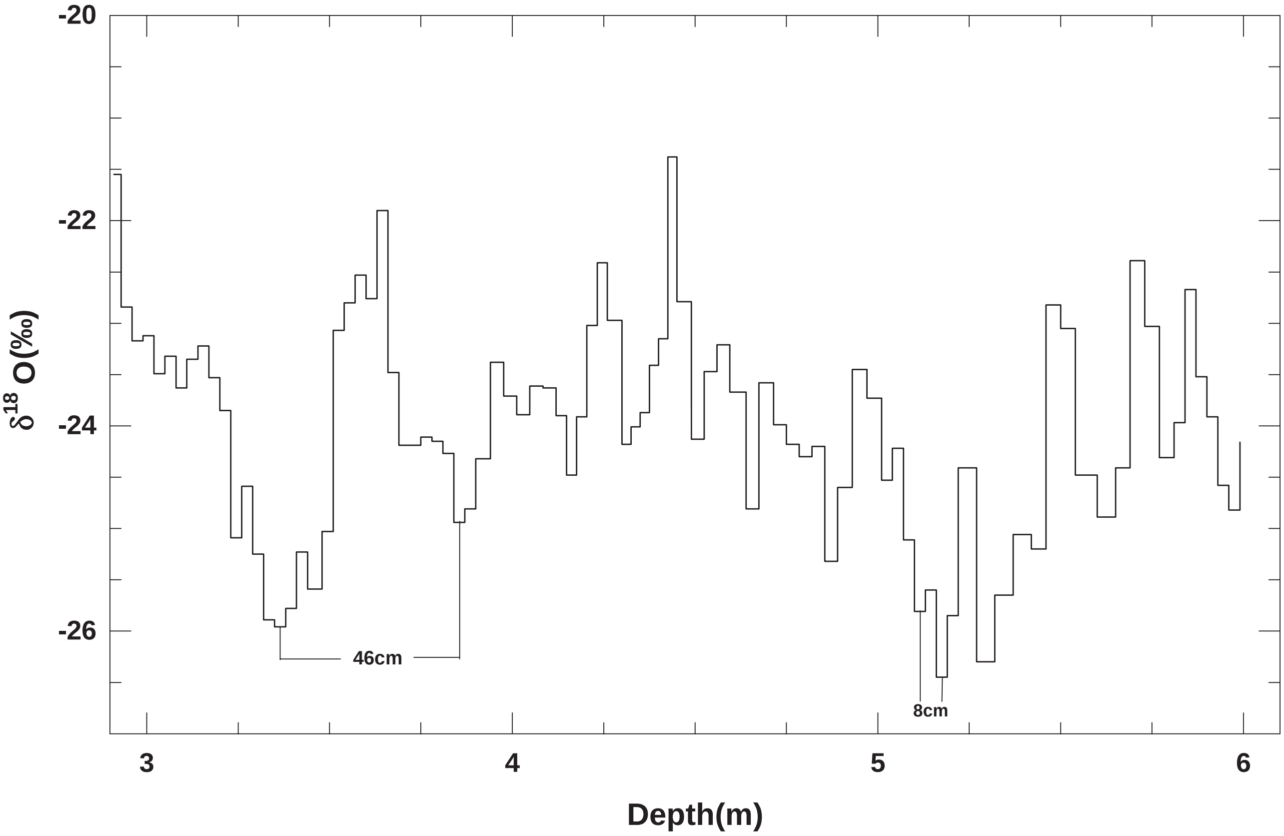

Figure 4. Variation in δ^{18}O between 3 and 6 m depth is drawn on expanded scale. Using their cyclic variations, an accumulation rate for ice has been estimated which varies from 8 to 46 cm with an average value of 20 cm/yr.

Table 2. *Mean annual $\delta^{18}O$(°/₀₀), average MASAT (°C) values at different periods derived from 60 m ice core raised at Dakshin Gangotri from east Antarctica.*

Sl.No.	Depth (m)	Mean annual δ^{18}O(°/₀₀)	Mean MASAT temp (°C)	Age (yr)	Time (AD)
1	3.1–5.8	−24	−15	22	1970
2	9.8–10.0	−24.6	−15.8	49.5	1942
3	13.1–13.2	−24.5	−15.7	65.8	1926
4	17.8–18.0	−25.8	−17.6	89.6	1902
5	27.7–27.9	−24.6	−15.8	139	1853

δ^{18}O values from DMI (74°S 12°W), east Antarctica closer to our station vary from −14 to −26°/₀₀ during the last 50 years (Aldahan *et al* 1998) but the accumulation rate is higher by a factor of two than that estimated from the present work.

4.5 *^{10}Be and ^{36}Cl studies*

The importance of polar fallout of cosmogentic isotopes ^{10}Be and ^{36}Cl (also produced artificially during nuclear detonations) has been discussed briefly in the introduction (see section 1). ^{10}Be and ^{36}Cl measurements have been made for the ice samples which represent a time period of 1940–1975AD. The ^{10}Be values (table 3) range from 0.56 to 2.58 × 10^4 atoms/g with a mean value of 1.16 × 10^4 atoms/g which agrees well with those calculated at Renland ice core from Greenland and DML ice core from Antarctica (Aldahan *et al* 1998). Among the ^{10}Be concentrations, only one sample had ^{10}Be in excess of 1.5 × 10^4 atoms/g, at 500 cm depth with a value of 2.58 × 10^4 atoms/g.

The deposition of ^{10}Be (2 × 10^5 atoms/cm^2 yr) determined in the present work agrees reasonably well with those derived for other regions at higher latitudes in Antarctica (73°S to 90°S). The ^{10}Be fallout at locations in northern hemisphere, however, are higher by factors of 2–3. The ^{10}Be deposition values have smaller variance and lower annual

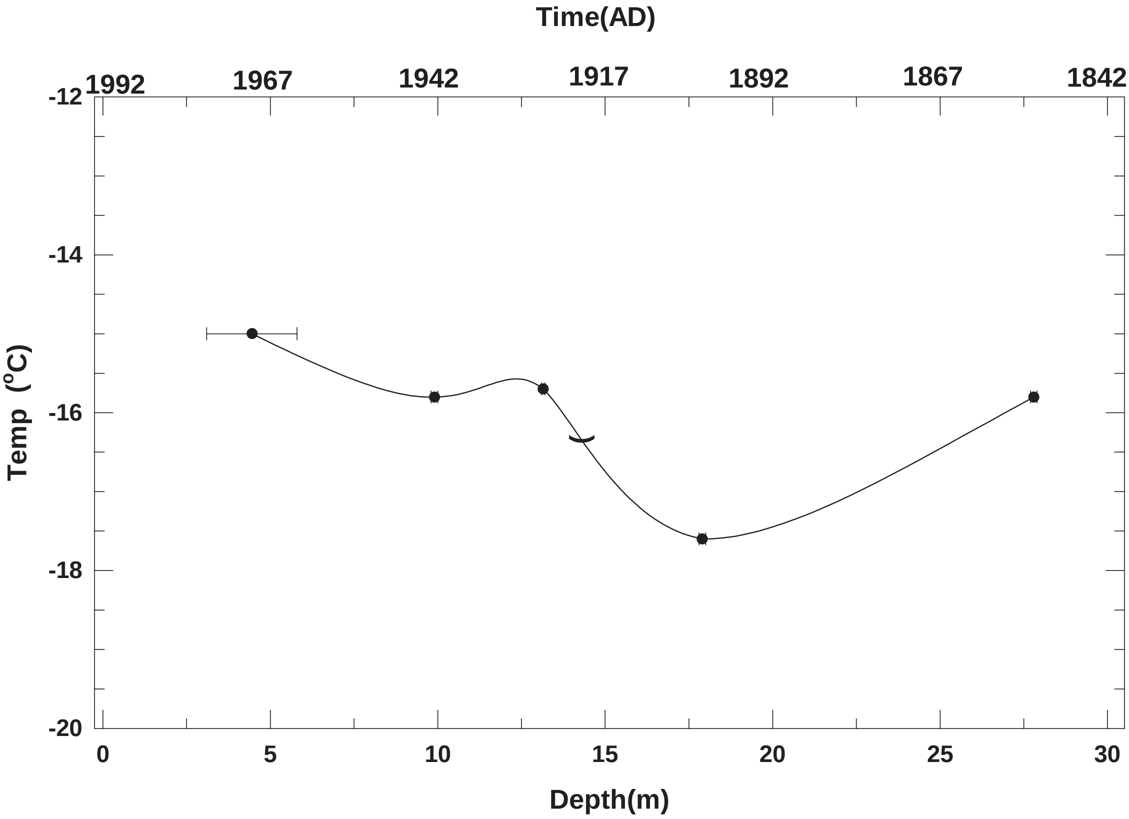

Figure 5. Average MASAT (°C) values calculated during different time periods are plotted against depth (m) and time (AD). The lowest value is recorded around the beginning of the century and is cooler by ~ 2° C than the recent past.

Table 3. *Concentrations of ^{10}Be and ^{36}Cl in ice samples collected from 60 m ice core raised at Dakshin Gangotri from east Antarctica.*

Sl.No	Depth (cm)	Volume (ml)	Concentration ($\times 10^4$ atoms/g)		^{10}Be/^{36}Cl
			^{10}Be	^{36}Cl	
1.	328	630	1.38	0.219	6.30
2.	369	680	1.15	0.208	5.53
3.	410	1060	0.86	0.107	8.04
4.	447	920	1.13	0.207	5.46
5.	479	650	1.16	–	–
6.	508	680	2.58	0.200	12.90
7.	541	1000	0.82	0.151	5.43
8.	580	100	1.11	0.239	4.64
9.	620	1070	1.07	0.209	5.12
10.	660	1070	1.15	0.211	5.45
11.	694	570	0.79	0.154	5.13
12.	728	1145	1.26	0.235	5.36
13.	798	880	1.32	0.226	5.76
14.	833	1065	1.30	0.166	7.83
15.	968	900	0.85	0.245	3.47
16.	1026	1130	0.56	0.137	4.09

Note: The errors on the ^{10}Be measurements are in the range of 6–9% whereas those for ^{36}Cl are within 25%.

average in Antarctica than in Greenland (Raisbeck and Yiou 1985 and Steig *et al* 1996; Aldahan *et al* 1998). The ^{10}Be deposition flux calculated for Antarctic ice core by Aldahan *et al* (1998) and the estimates of ^{10}Be made by Lal *et al* 1987 are higher by a factor of 2 than that measured in the present work and that on Greenland ice core by a factor of 1.5 (Baumgartner *et al* 1997) probably due to the difference in the annual precipitation.

^{36}Cl measurements have been made for the time period (1980–40) which cover nuclear-weapon tests (see section 4.2). The ^{36}Cl values vary from 0.1 to 0.25×10^4 atoms/g (table 3) with a mean value of 0.2×10^4 atoms/g. The mean deposition of ^{36}Cl has been estimated to be 3.91×10^4 atoms/cm^2 yr which agrees reasonably well with the global production rate of 4.09×10^4 atoms/cm^2 yr(i.e., 1.3×10^{-3} atoms/cm^2 sec) by Lal and Peters (1967). The fallout of ^{36}Cl (based on a single measurement available prior to this work) in Antarctica is higher by a factor of ~10 (Finkel *et al* 1980) and that in Greenland for the cosmic ray component is higher by a factor of 2–6 compared to that in the present work.

Figure 6 shows variations in bi-annual (see section 3.2) concentrations of ^{10}Be and ^{36}Cl and their ratios (^{10}Be/^{36}Cl) and δ^{18}O for the period 1980–1940, a period of atmospheric nuclear tests. The ^{36}Cl concentrations unexpectedly do not show any variation throughout the period of bomb tests and the bomb pulse appears to be missing or diluted to cosmic ray background ^{36}Cl level at this loca-

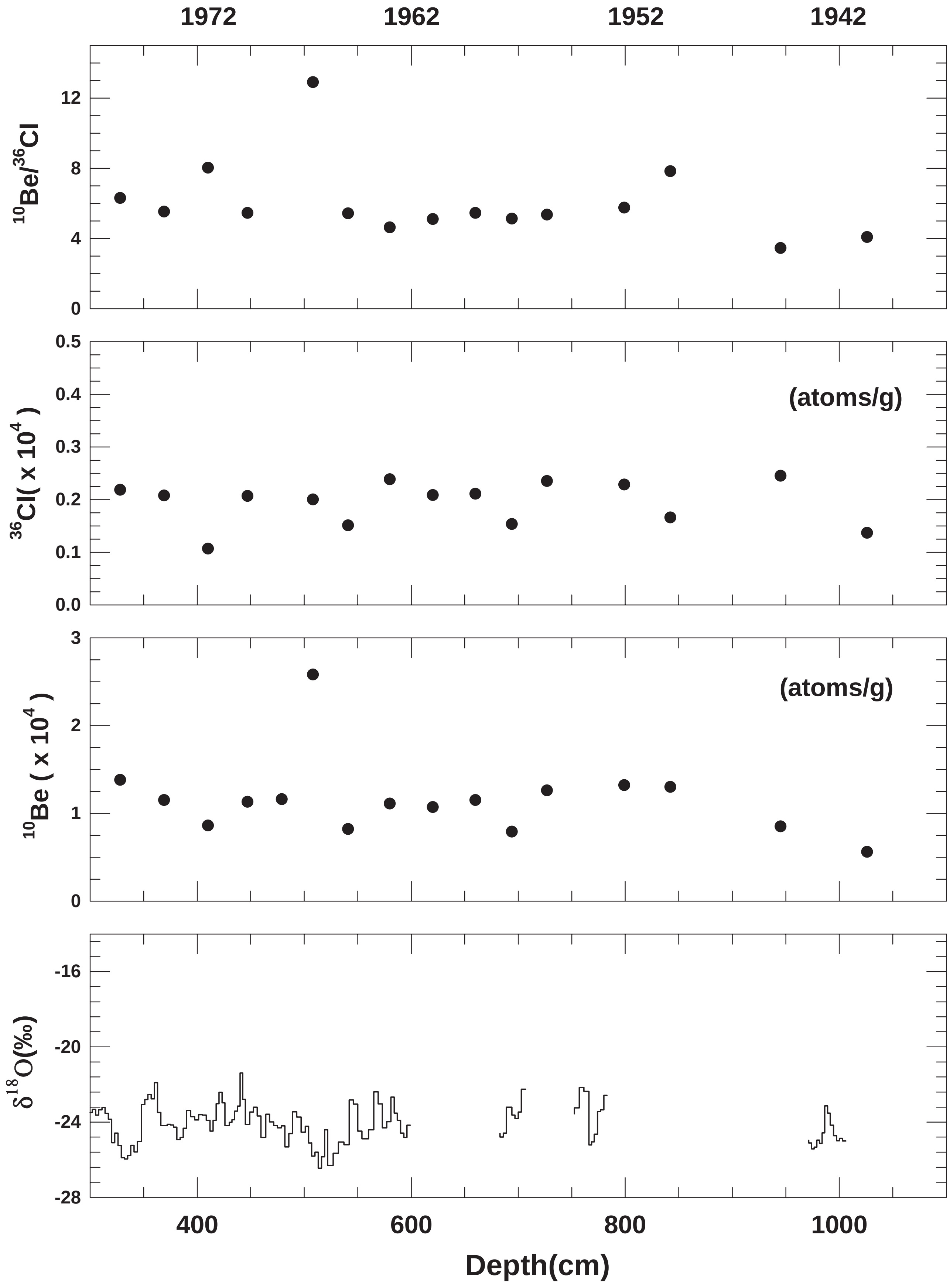

Figure 6. The concentrations of ^{10}Be and ^{36}Cl (atoms/g) and their ratios plotted against depth and time. The bomb pulse of ^{36}Cl could not be detected in the core section of 1940–1980 (see section 4.5 for discussion). These data are also plotted for δ^{18}O which are good climatic indicators.

tion. The cause for the "missing" ^{36}Cl is unclear, it probably could be due to its dilution during transport from the northen hemisphere to Antarctica. Earlier work in Greenland shows a bomb pulse of ^{36}Cl concentration during 1980–1940, with concentrations by an order of magnitude higher than its cosmogenic contribution (Beer 1998, personnel communication; Synal *et al* 1990; Elmore *et al* 1982; Conard *et al* 1989). ^{10}Be/^{36}Cl ratios measured in the present work for the last $\sim$ 40 years though show a wide range 3.5–13, bulk of the samples have values 5 ± 1 (table 3) with one sample > 8. The mean ^{10}Be/^{36}Cl in all samples is 7 which agrees well with that calculated to be 6.7 (Nishiizumi *et al* 1983) in surface ice from Yamato hills in Antarctica (71°10′S, 35°07′E). We therefore suggest that the mean ^{10}Be/^{36}Cl ratio of 7 measured in the present work for the last $\sim$ 40 years can be used as the initial ratio to date older ice from central Dronning Maud Land, east Antarctica (as indicated by Nishiizumi *et al* 1983 to date older ice from the Allan hills). The biannual data on ^{10}Be and ^{36}Cl for a short period in the present work are not sufficient to find out their correlations with solar activity, sunspot numbers and cosmic ray intensities etc. to draw meaningful conclusions.

The present limited data set does not give any explanation for the strange observation of the missing ^{36}Cl pulse at this location and more systematic measurements need to be carried out at the same or at neighbouring locations to justify the present observation.

5. Conclusions

- The mean accumulation rate of ice based on ^{210}Pb (20 ± 2 cm/yr), δ^{18}O (21 ± 0.02 cm/yr) and conductance (17 ± 0.05 cm/yr) has been estimated to be $\sim$19 cm/yr in polar ice near the Indian station, east Antarctica for the past 150 years. The accumulation rate however shows significant interannual and decadal variations.
- The mean annual surface air temperature (MASAT) data observed during the last 150 years showed that the beginning of the 19th century was cooler by about 2°C than the recent past and middle of 18th century.
- It is intriguing that, unlike in Greenland, ^{36}Cl bomb pulse during the nuclear testing period (1980–1940 AD) is missing in the present location of East Antarctica.
- The mean ^{10}Be/^{36}Cl ratio of 7 for the last $\sim$ 40 years may be used as the initial value to date older ice from east Antarctica.

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