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Ice accumulation rate in Changme-Khangpu glacier, Sikkim

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Abstract. Vertical profiles of ^{137}Cs and ^{210}Pb have been determined in a 9 m column of ice from accumulation zone of Changme-Khangpu glacier in north Sikkim valley. ^{137}Cs activity varies from 4 to 22 dpm/L. In many samples ^{210}Pb occurs at a level of 20 to 65 dpm/L which is much higher than the expected fallout value. ^{137}Cs and ^{210}Pb activities correlate well with each other but not with the dust content. Possibility of ^{210}Pb production in the nuclear explosions is discussed. Several peaks appear in the depth profile of ^{137}Cs and ^{210}Pb which can be matched with Chinese atmospheric nuclear explosions with some phase difference if a uniform ice accumulation rate of 0.7 m per year is assumed since 1969.

Keywords. Glaciers; bomb debris; ice accumulation.

1. Introduction

The estimation of long term mass balance of a glacier constitutes one of the important parameters in understanding glacier dynamics. In the Himalayas, direct measurements of flow rates have been made on a few glaciers but the accumulation rates have been computed only from indirect methods as winter observations are difficult. These estimates fluctuate significantly from year to year and it has not been possible to obtain long term average accumulation rates from such data. The deposition of nuclear debris in discreet events during the second half of this century has provided definite time markers. Tracer techniques on radioactive-labelled ice have provided dynamic parameters of glaciers averaged for several years in the past and have been used extensively in Alps and polar ice caps (Picciotto *et al* 1964; Merlivat *et al* 1975; Lambert *et al* 1975; Koide and Goldberg 1981). Here we report some radiotracer studies on Himalayan glaciers.

Changme-Khangpu, located at 27° N, 88° 42′E at an altitude of 4800–5500 m, is a small (5.6 km long and 0.88 km wide on the average) glacier situated in Sikkim valley (Bhandari *et al* 1982b). Radiometric studies using ^{32}Si and ^{210}Pb isotopes of this glacier and their comparison with other Indian glaciers (Nehnar and Gara) studied previously are discussed elsewhere (Nijampurkar *et al* 1981, 1982; Bhandari *et al* 1982b). Our recent studies on various samples collected during the 1981 expedition show the presence of bomb produced activities such as ^{95}Zr, ^{95}Nb, ^{137}Cs, etc in snow samples which have been attributed to October 1980 Chinese atmospheric test (Bhandari *et al* 1982a). The nuclear tracers can thus be used to provide a chronological frame for deposition and flow of ice. We have chosen the longlived ^{137}Cs and determined its vertical profile in samples taken from accumulation zone for determining ice accumulation rate.

2. Experimental technique

Samples representing vertical and longitudinal profiles were collected in 1981 expedition with a view to study the natural radioactive tracers *e.g.* ^{210}Pb and ^{32}Si and artificial tracers like ^{137}Cs. A total of thirty-two samples (numbered CK-91 to CK-122) in sections of 30 cm were collected from an ice face in a crevasse in the accumulation zone at an altitude of 5250 m. This profile covers 0–9.6 m except for 420–480 cm where two samples CK-105 and CK-106 were lost in transit. Because of the inclination of the crevasse ($\approx 30°$) the 960 cm depth would correspond to a vertical depth of 831 cm, each section representing a vertical depth of 26 cm. The melt waters were brought to the laboratory and processed as follows. The water samples were acidified with 1–2 ml of HCl and the dust was filtered. The ^{210}Pb activity from the water was scavanged by adding $FeCl_3$ carrier and precipitating $Fe(OH)_3$. ^{137}Cs was measured in filtrate as well as the precipitate and dust before it was chemically processed for bismuth. The values given in table 1 represent the total ^{137}Cs activity. The counting system used was a HPGe detector located in 10 cm lead shield. Background in ^{137}Cs peak was 0.11 ± 0.01 cpm and its counting efficiency as determined from ^{137}Cs standard was found to be 3.8%. The procedure for separation and counting of ^{210}Bi — the daughter of ^{210}Pb — has been described in detail earlier (Nijampurkar *et al* 1982). ^{210}Bi was counted on a gas flow GM counter with NaI(Tl) anticoincidence having a background of about 1.4 counts/hr. In most cases, the activity of ^{210}Bi was confirmed by following its decay for a few weeks.

Table 1. Depth profile of ^{210}Pb in ice face samples, Changme-Khangpu glacier.

Sample Number	Depth (cm)	Water processed (L)	^{210}Bi counting rate (cpm) at* $t = 0$	^{210}Pb (dpm/L)	^{137}Cs (dpm/L)
CK-91	0–30	0.490	1.05	24.7	15.2
CK-92	30–60	0.800	3.25	33.3	7.3
CK-95	120–150	0.600	1.02	14.8	9.3
CK-96	150–180	0.750	1.73	17.0	8.5
CK-97	180–210	0.730	1.41	18.5	3.7
CK-99	240–270	0.750	2.10	21.5	7.7
CK-100	270–300	0.600	4.21	66.1	20.8
CK-102	330–360	0.700	3.85	40.9	22.1
CK-103	360–390	0.700	2.82	35.7	17.1
CK-110	570–600	0.650	2.06	24.1	7.5
CK-111	600–630	0.780	0.52	5.9	1.9
CK-112	630–660	0.620	1.22	17.1	4.6
CK-114	690–720	0.840	1.37	14.6	4.0
CK-115	720–750	0.260	0.47	13.7	4.9
CK-117	780–810	0.740	4.24	45.9	13.2
CK-121	900–930	0.950	2.25	27.9	11.3
CK-122	930–960	0.935	2.00	15.2	7.5

*Separation of ^{210}Bi from ^{210}Pb.

3. Results and discussion

The ^{137}Cs activity in thirty core sections varies between 4 and 22 dpm/ L with four main peaks. ^{210}Pb data measured in 17 of these samples are given in table 1 together with ^{137}Cs activity in the same samples. The histogram of ^{137}Cs activity as a function of sample depth is shown in figure 1. An analysis of the data indicated that the dust content does not correlate either with ^{137}Cs or ^{210}Pb activity. In figure 2 we have plotted ^{210}Pb *vs* ^{137}Cs activities. In general, the two activities seem to correlate well with each other.

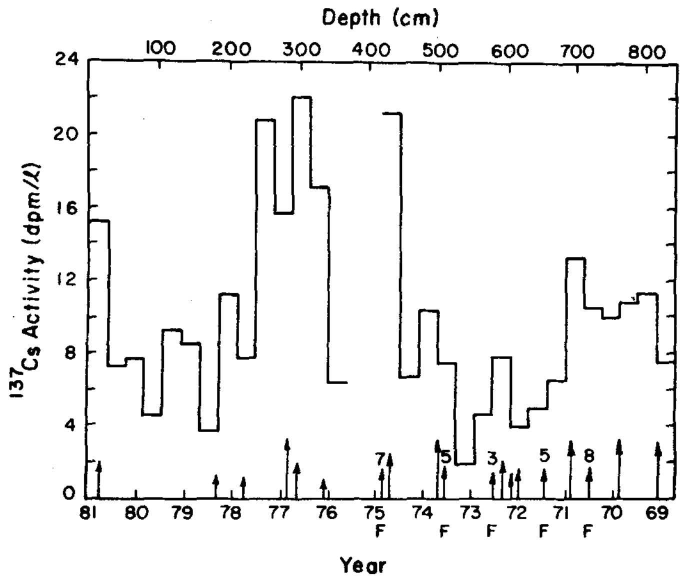

Figure 1. Variation of ^{137}Cs activity with depth of ice. Tests conducted by France are designated by *F* and the total number of explosions in a year are indicated above the arrows.

China and France have conducted several atmospheric nuclear tests since 1964 although since 1975 France has stopped atmospheric detonations. The Indian nuclear explosion of 1974 was carried out underground and was found to be well-contained in the cavity (Bhandari *et al* 1978). Whereas the production of ^{137}Cs in nuclear explosions is well-established, the production of ^{210}Pb is still controversial (Jaworowski *et al* 1979). The values of ^{210}Pb ranging between 6 to 66 dpm/ L suggest one of the following possibilities: (i) the fallout of ^{210}Pb at altitudes of 4–5 km is much higher than 8 dpm/ L assumed by Bhandari *et al* (1982b) and the data represent annual variations in fallout values. In such a case the observed correlation between ^{210}Pb and ^{137}Cs should not be expected. The correlation shown in figure 2 suggests a common origin of ^{137}Cs and ^{210}Pb; (ii) ^{210}Pb is indeed produced in the nuclear explosions. The data shown in figure 2 would support such a conclusion but it has been pointed out by Grotowski *et al* (1977) that production of ^{210}Pb in thermonuclear reactions is improbable. Although Crozaz (1967) did not find any evidence of bomb-produced ^{210}Pb in Antarctic, alpine and Greenland glaciers, Jaworowski *et al* (1978) noted that ^{137}Cs and ^{210}Pb activity

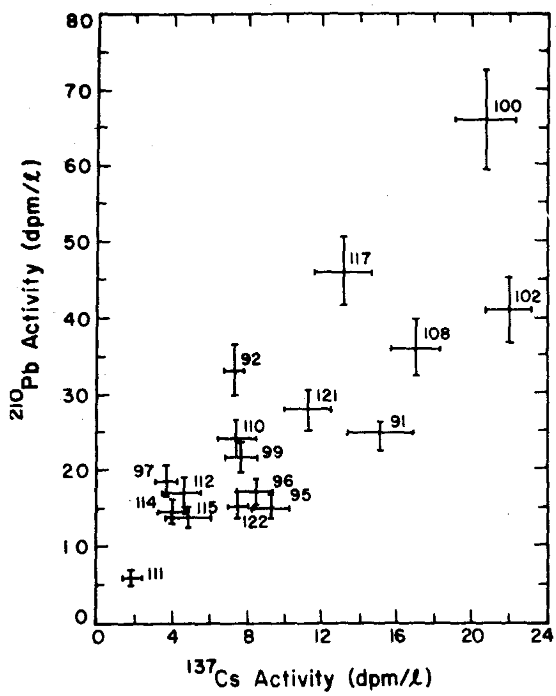

Figure 2. Variation of ^{210}Pb and ^{137}Cs activity in ice samples. Numbers refer to the CK samples as given in table 1.

peaks and troughs occur together for various glaciers including Nepalese Himalaya. However, since ^{210}Pb also correlates with ^{226}Ra and U which are of terrestrial origin, the situation is very complicated. Also for another Himalayan glacier, Nehnar, the horizons containing ^{210}Pb activity above natural levels are also associated with ^{137}Cs activity and a maximum in beta activity (Nijampurkar *et al* 1982). Further, observation of high energy neutron products like ^{54}Mn and ^{88}Y in Chinese nuclear test of 16 October 1980 (Bhandari *et al* 1982a) also seems to support this possibility; (iii) the possibility that the ice concentrates ^{210}Pb and ^{137}Cs identically as water percolates through it cannot be ruled out. Although this phenomenon is not well understood and occurs mostly in ablation zone where melt water is produced profusely (Nijampurkar *et al* 1982), such a process is expected to result in an activity profile without a structure especially towards the deeper depths. The presence of a well-structured profile with several sharp peaks for both the activities does not support this mechanism for concentration of ^{210}Pb. Further, as mentioned earlier, both the activities do not correlate with dust content which should have been the case if they were being concentrated together as a result of percolation and absorption on dust; (iv) lastly there is a contribution of ^{210}Pb from *in situ* decay of uranium series. Again absence of correlation of ^{210}Pb activity with dust content suggests that this contribution is small. Jaworowsky *et al* (1979) have invoked other mechanisms such as atmospheric circulation pattern to explain the correlation of ^{210}Pb and ^{137}Cs, etc. but it is difficult to verify such a mechanism from the present data. Whatever be the origin of ^{210}Pb, from its depth profile one can conclude that the whole core sequence represents a time scale smaller or comparable to the half-life of ^{210}Pb (22 years), which is consistent with accumulation rate of 0.7 m/yr deduced below from ^{137}Cs profile.

The major contribution to the observed ^{137}Cs activity could be from Chinese and early French tests. The cumulative yield of various atmospheric tests carried out by China from December 1968 to 1980 far exceeds the cumulative yields of French atmospheric tests during the same period (Carter and Moghissi 1977; Carter 1979). Most of the French tests were carried out in southern hemisphere at Mururoa and Fangataufa atolls (21° S, 137° W) and hence a major fraction of the radioactive fallout from these tests is expected to be deposited in the southern hemisphere. Only a small fraction will be transported to the northern hemisphere as shown by Rangarajan *et al* (1970) and Gopalakrishnan and Rangarajan (1972) who have continuously monitored different bomb produced activities in Bombay air samples during these periods. Thus only a small contribution of ^{137}Cs activity from French tests is expected in the samples analysed here but because of the geographical proximity between the Chinese tests site (Lop Nor, 40° N, 89° E) and Changme-Khangpu glacier, the major contribution is expected from Chinese tests.

From the list of nuclear explosions carried out by China (G S Murthy, Private Communication, SIPRI Year Book, 1981) we made an attempt to match the peaks in figure 1 with high yield explosions based on an arbitrary but uniform accumulation rate with the uppermost peak attributed to October 1980 Chinese test as discussed elsewhere (Bhandari *et al* 1982a; Sadasivan and Mishra 1982). For Chinese tests the length of the arrow is roughly proportional to the yield, the highest yield being 2–3 MT and lowest being 20 KT or less. Total number of French tests in a particular year is also indicated in figure 1. As can be seen in this figure there is a good correlation between the dates of Chinese explosions and ^{137}Cs peaks if a uniform accumulation rate of 0.7 m/yr is assumed. A phase lag of a few months (2–3 months) is observed for some ^{137}Cs peaks after the explosion which could be partly due to time lapse between the nuclear explosion and precipitation and could partly arise if the accumulation rate is not constant every year.

This estimate of accumulation rate is based on the assumption that the activity once deposited is preserved well. However, in temperate glaciers, such as Changme-Khangpu, this is not strictly true. Melting of snow and refreezing of water in such glaciers can cause some diffusion of the stratigraphy, but the sharpness of various peaks indicate that this process is not important in the accumulation zone.

Changme-Khangpu glacier has been studied by the Geological Survey of India since 1977. By using a network of stakes, the accumulation rates have been computed for brief periods of time. The estimates range between 0.2 mm/day to 6.7 mm/day. The average accumulation rate estimated above falls in this range. The snout of the glacier has also been monitored and is found to retreat at the rate of about 6 m/year for the past five years. Radioactive dating using ^{32}Si and ^{210}Pb indicate that the snout ice is about 100–500 years old. All these parameters together with the topographical information are useful in formulating a model of glacier dynamics which is now in progress.

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