International Symposium on
Hydrology of Mountainous Areas
Shimla (INDIA) May 28-30, 1992

# Instrumentation and Measurement Techniques for the Study of Water Equivalent of Snow & Snow Pack and Glacier Using Isotope Techniques

**Bhishm Kumar and A.K. Dwivedi**

National Institute of Hydrology,
Roorkee - 247 667 (INDIA)

ABSTRACT

The study of the formation of snow cover and measurement of its water is of great scientific and practical importance for land which is covered with snow for a large part of the year. Information on snow cover is required to evaluate the rate of stream flow of river during the snow melt period, the amount of water available for reservoirs and irrigation systems and water content of the soil and to forecast possible natural disaster such as flooding, mud flows, land slides and snow avalanches.

Hydrological investigations related to snow and ice are mostly directed to water balance studies in basin with temporary snow cover or with glaciers. They require good knowledge of processes involving accretion and melting of snow covers, transition from snow to ice, water movement and storage in glaciers, and long term variations in the kryosphere of the earth. Isotope methods have been proved useful for solving many detailed questions in the frame of these problems. This paper deals with the instrumental techniques used for the measurement of water equivalent of snow using isotopes and methods based on the analyses of environmental isotope contents (primarily Deuterium, Tritium , Oxygen-18) in snow and ice for the study of snow pack and glacier.

## 1. INTRODUCTION

Snowfall is a very common phenomenon observed on the high mountains. It becomes more frequent above of the snow line, where its accumulation with time forms glacier. According to an estimate about 80 % of the area of the earth is covered with either snow or ice [Bahadur et al. (1989)]. Information on snow cover ,which serves as natural storage reservoir from which a major part of the requirement of water supply of an area may be derived. Its knowledge helps the hydrologists to evaluate the seasonal runoff of a basin owing to snow melt. It is possible to have the estimates of water that may be available for the reservoirs, irrigation systems and hydel projects. This will help in possible forecast of some of the natural disasters e.g. flood, mud flows, land slides and snow avalanches. There is marked variations in the depth and density of the snow cover in the representative area concerned. Therefore, getting the representative data on large area is extremely difficult and requires a lot of expenditure on the resources.

Isotopic methods have been proved useful for giving solution of many problems. The methods discussed, are based on measurement of nuclear radiation or isotopic contents in snow and ice. Work carried out in India, on applications of isotopes and impact of various changes affecting its contents in snow and glaciers, are also discussed.

## 2.NUCLEONIC GAUGES / TECHNIQUES

The following four types of the nucleonic gauges are in use.

I) The Gamma Attenuation Method.
II) The Neutron_Neutron Method.
III) The Airborne Gamma Survey Method.
IV) The Cosmic Radiation Absorption Method.

### I) The Gamma Attenuation Method.

Radioactive gamma sources are used in various ways to measure water equivalent of snow. Attenuation of gamma to measure water equivalent of a snow cover between source and detector, two types of installations are in common use: **1. Vertical 2.Horizontal**. Vertical type is used to measure total water equivalent above or below a point source. Horizontal installation measures water equivalent between two vertical types and selected distances above the ground. Guillot et al. (1968) have discussed about moving horizontal beam radiometeric snow gauge. Gamma rays pass through the snow of thickness h and density $\rho$, the emerging intensity of the gamma rays or the counting rate I is given by

$$I = I_o \exp. (-\mu \rho h) \qquad (i)$$

Where

$\mu$ is the mass attenuation coefficient
$I_o$ is the intensity or the counting rate in absence of the snow.

Mass per unit area of the snow ($g/cm^2$) is also the water equivalent of the snow in cm. The calibration of the gauge is done by measuring the ratio of the countings in presence and absence of different snow layers.

Amongst different type of the snow gauges; stationary gamma snow gauges **(fig.1)** have been reported by Fischmester (1956), Duncan (1963), Abal'van et al (1971),and Martinec (1975) and with telemetry type by Doremus(1951), Danilin (1957) and Ferronsky et al. (1968). Portable type of gamma snow gauges have been reported by Danilin (1957), Ferronsky et al.(1968) and Danilin et al. (1983). These gauges are automatic and simple ,but, have a shortcoming with the traditional methods that give measurements of localised points (fig.2). Danilin (1970) has reported a maximum possible error of 10% or less. Cs-137 or Co-60 are used as source and Scintillation or Geiger- Muller counters as detectors.

Installation of this type of gauges are relatively expensive and complex. Also adequate safety measures in the heavy snow areas require high energy source. Extra precaution is needed while such type of sources are used. This method is valuable tool and provide the possibility of continuous recording useful in inaccessible regions. Various type of modifications made in USA and France in telemetry type of horizontal snow gauges have been reported. [Randolph et al. (1972)].

II) The Neutron_Neutron Method.

The principle of this method is based on the slowing down of the fast neutrons in the snow cover [Danilin et al.(1970)]. In this, a mixture of Pu-Be or Am- Be of activity grater than 10 neutrons per second , is taken as the source and Scintillation detector in a pipe capable of being inserted in the snow. The probe **(fig.3)** is calibrated in the field for snow density measurements and a calibration relation of the type $\varrho=f(I/I_o)$,is obtained, where I is the normal neutron counting rate at the place of measurement, $I_o$ is the counting rate in water in shielded container and $\varrho$ is the snow density.

**III) The Airborne Gamma Survey Method.**

Ferronsky et al. (1968), Abal'yan et al. (1971), Kogan et al. (1965) ,Zotimov have stated that this type of the method was first proposed and tested in USSR in 1962. Abalyan et al. (1971), [Avdyushin et al.(1971),Cork et al.(1979),Dmitriev et al.(1974), Fritzsche (1979) ,Getker et al.(1979), Kuittinen et al.(1979), Loijens(1979), Nikiforov et al.(1979), Peck et al.(1979),Tollan et al.(1979),Vershinina et al.(1979)], Danilin (1983) and Zotimov have reported about its further developments which took place in USSR, USA, Canada, Norway and Finland subsequently.

In this method, changes in the natural gamma ray intensity in the layer of the atmosphere earths surface is recorded. This field is created by gamma radiation of radio- active elements and their decay products contained in the rocks of surface sediments. A reduction in the intensity of this gamma field is caused mainly by snow cover, which acts as an absorbing shield.

The method is intended for mapping the water equivalent of snow in flat country, or in hilly country,rising nearly up to 400 meter. In regions with more than 10% of their areas in marsh land, the measurements of water equivalent of snow cover are made only for those areas without marshes and the integrated characteristics are applied to the area of the entire basin. The usual height for making air-born gamma survey is 25- 100 meter. The water equivalent of snow is determined by the formula

$$W_n = \frac{\ln (I_s/I_\omega)}{\alpha} \qquad \ldots.(2)$$

Where $I_s$ - Intensity of soil ground gamma radiation at height Z in absence of snow.

$I_\omega$ - Intensity of gamma radiation with water equivalent $W_n$

$\alpha$ - Constant of sensitivity of the instrument.

The accuracy of an areal gamma survey of snow cover depends on the limitations of the radiation measuring equipment (e.g. uniformity of operation of the measuring instruments), fluctuations in the intensity of the cosmic radiation and radio activity in the layer of the atmosphere near the ground, soil moisture variations in top 15 cm, uniformity of snow distribution, absence of extensive thawing etc. (e.g. steady flying conditions, errors in setting course of successive flights). The expected error ranges between ±10%, with a lower limit of approximately 10mm of water equivalent. Experiments have shown that the standard deviation of water equivalent measurements of snow made from the aircraft over a course of 10-20 Km, is about 8 mm.

Kogan (1965), Dmitriev et al.(1971) and Endresstol (1979) have reported four types of air borne techniques:

i) The measurements are taken either from the aeroplane or helicopter, flying each time along an ideal routine at almost the same height. Duncan et al. (1963), Kogan et al. (1965), Dmitriev (1971), Kogan (1976) and Nikiforov et al. (1979) have shown that the results are reproducible within an error of 10%.

ii) The intensity of the gamma radiation is taken at two fixed heights, the effect of changes in moisture and the extraneous background is insignificant.

iii) It is a two angle method in which the gamma radiation is measured simultaneously and independently by two radiometers within two different angular apertures. The dependence of the technique on variation in cosmic and random background and in good moisture, is reduced. The readings are highly dependent on the degree of unevenness of the topography and non uniformity of the snow cover.

iv) Simultaneous measurements of the intensity ratios at two, or more fixed gamma radiation energy intervals,generally chosen within the region of photopeaks, recorded by a scintillation spectrometer,is taken. Nikiforov et al. (1979) has estimated a maximum error of 10% in such experiments.

Dmitriev et al. (1974) have reported that such type of surveys started in USSR from 1971. This technique has been extensively used in other countries also e.g. USA,Canada, and the Scandinavian [Cork et al.(1979), Endrestol (1979), Fritzsche (1979), Getker et al.(1979), Kuittinen (1979), Loijens (1979), Peck (1979) and Tollan (1979)]. Many of the theoratical aspects-application technology,equipment design, measurements and processing, and results have been described by Dmitriev et al. (1971) and in WMO (1979). Abal 'yan et al.(1971) have shown the suitability of the airborne technique for the mountainous regions. Here also, there are difficulties of calibration ,comparison and linking of the ground and aerial measurements. Automatic acquisition, processing and taking in to account the changes taking in different parameters affecting the data, has been discussed by Dmitriev et al.(1971), Endrestol(1979) and Nikiforov et al. (1979). A portable, hand held instrument provides a means for measurement of averaged water equivalent for a band width of approximately 8 meters for the length of the course. The appearance of snow cover is calculated by means of the formula:

$$R_i = [(N-32)/R_t]-R_r \qquad ....(3)$$

where

$R_i$ - the mean intensity of gamma radiation

$R_o$ - the initial intensity of the gamma radiation

$R_t$ - the final intensity of the gamma radiation

N - the pulses recorded by the counter of instrument after a time t in minutes of flying along the course.

32 - a coefficient of division of the recalculating circuit

$R_{\gamma *}$- Residual background of the instrument determined from the atmospheric pressure

Then by means of the table of graduations of the instrument giving the details of attenuation coefficient of the gamma radiation, $R_t$ / $R_o$ is approximately the mean value of the water equivalent Wn mm , of the snow cover are found for the course. Correction is applied for getting the true value of the water equivalent. The effect due to variations in the cosmic background and terrestrial background is not considered. The water equivalent Wn=KW; where $K=R_1/R_2$ and $R_1$ is the local background radiation for measurement for 10 minutes duration before the experiment is started; $R_2$ is the local background radiation, before the appearance of the snow cover for the same time of measurement i.e. 10 minutes. By this, water equivalent from 10 to 300mm may be measured. The accuracy of the measurement ranges from ± 2 mm to ± 6 mm , which may vary in accordance with the changes in the soil moisture and distribution of the snow in the area and also the stability of the instrument. The occurrence of the precipitation which carries in it considerable gamma ray material to the snow cover and measurements during and after precipitation are affected by this additional radiation. Decay of the radiating material permits accurate readings of the water equivalent nearly 4 hours after the precipitation stops. Comparison of reading before and after occurrence of precipitation will provide information on the change in the water equivalent of the snow cover.

IV) **The Cosmic Radiation Absorption Method.**

This method was first proposed in the USSR [Fridman, (1968)]. The method is based on determining the ratio of the intensities of natural cosmic radiation, before and after the snow cover. The water equivalent of snow is measured remotely at a number of points in the area concerned. The radiation detector is kept at the level of the earth's surface. This method is best suited to the mountainous areas and for the measurement of a large snow water equivalent. The method has the superiority over the other methods having limitations for uses. The cosmic radiation absorption follows almost linearity for snow cover thickness less than 1000 gram/$cm^2$ and in some cases it is suitable for water equivalent in the range of 300-10,000 mm. Fridman (1979) has proposed a modification, whereby only the neutron component of the cosmic radiation is recorded.

Tests carried out with an instrument developed in the USSR have shown that, for the range 10-1000 mm of water equivalent of snow, the standard deviation of measurement is 34 mm.

## 3.ISOTOPIC CONTENT OF FRESH SNOW-

The isotopic content of the snow cover gives valuable information about the isotopic variation of the snow, which falls down to the mountains and contributes to the snow cover accretion. primarily, the isotopic contents of the fresh snow are Deuterium, Tritium and Oxygen-18; out of these three contents, two contents -Deuterium and Oxygen-18, are stable isotope.

## 4.EFFECT OF VARIOUS CHANGES ON THE ISOTOPIC CONTENTS OF A SNOW COVER

Measurements of isotopic contents in temperate snow covers does not change during the melting periods even if rainwater and melt water percolates. In case a considerable amount of water percolates with a $\delta$-value ,which does not correspond to the equilibrated $\delta$-value of the snow; the mean value of deuterium and Oxygen-18 values of the snow cover is changed. After a long time the isotopic content of water makes a homogeneous mixture with the isotopic contents of the snow and ,thus, there is an increase in the $\delta$ value of the entire snow cover. After a strong rainfall, significant changes have been noticed in the isotopic content [Stichler et al. (1976), Krouse et al. (1972), Herrmann et al. (1981)]. Therefore, the study of the isotopic content can also be used for distinguishing meltwater and rain, allowing a detailed observation of the water movement.

The transition in snow and glacier ice also brings about changes in the isotopic content. It is observed that the original isotopic distribution on account of the seasonal and climatic variations in the isotopic contents of precipitation will be changed within the glacier either between polar (cold) as well as ice fields and temperate glaciers (with percolating meltwater during the ablation period) also between the firn zone and the compact glacier ice. It is observed that the course from different polar regions , the damping of Oxygen-18 seasonal variations as a function of the resident time of the respective layer in the field. [Dansgaard et al. (1973)]. The station differing in the accumulation rates show that the diffusion will be more effective with decreasing accumulation rate. The value of Oxygen-18 becomes more in the firning process up to the ice formation, than the annual accumulation rate of the isotopic contents. In certain conditions either percolating meltwater, formation of ice lenses or slow molecular diffusion processes govern the changes in the homogeneity of the isotopic contents. In temperate glacier ice, diffusion processes do not play significant role, because, they relatively stay for less than a few thousand years. At such places , isotopic contents of ice and meltwater get intermixed within the body of the glacier. These isotopic contents are affected by any or the combination of the following:

i) The change in the isotopic concentration in snow also, is observed. This has been documented by measurements of deuterium and oxygen-18 contents in the snow samples collected from different parts of the world.Fig.4 shows that the -values differ not only in their absolute values, but, also in the slopes of the mostly linear relation between the $\delta$-value and the altitude due to the local climatic conditions. It is observed that the fractionation factor for deuterium to Hydrogen and that of oxygen-18 to Oxygen-16 ratios between ice and liquid water at 0 $^{o}$C are 1.020 and 1.003 respectively. This means that $\delta$-D and $\delta$-D Oxygen-18 of glaciers are higher by 20% and 30% respectively, than those of the glacier meltwater.

ii) Continental effect also influences the $\delta$-values. an altitude effect as measured in Greenland for tritium concentration in Antarctica [Merlivat et al.(1973) and (1977)] can be explained by a tritium exchange with tritium-rich water vapour in the atmosphere.

iii) Seasonal variations in polar regions of Deuterium, Oxygen-18 and tritium concentration in snowfall can be safely stored within the snow cover for a considerable time [Moser et al.(1975)]. Changes in the large scale weather patterns can be visible in the isotopic profile of a snow cover [Friedman et al.(1972)]

iv) Wind drift can change the original isotopic profile of a snow cover especially in the case of dry snow, in areas with little accumulation and strong wind exposure, as in the case in the Antarctica, and on the steep slopes. This complicates the interpretation of the isotope concentration from the snow profile.

v) Condensation of the atmospheric moisture at the snow surface (hoar-frost) have not been investigated in details, however, they are important for understanding transport phenomenon of water vapour and snow metamorphosis. Fig.5 indicates that the increase in the deuterium values at the snow surface during the day time, caused by the evaporation of the snow, is compensated in the night by condensation of the available water in air. The same is effected in the fluctuation of the deuterium excess. The absolute value of the deuterium variations has been changed as new air masses with different humidity and deuterium concentrations were carried into the area. Judy et al. (1970) have found deuterium variations in an annual snowpack.

vi) Moser and Stichler (1970) observed the variation in $\delta$-D was in the range of -4‰ to 2‰ per 100m rise in elevation for rain in Central Europe. Pack snow on the otherhand showed an increase in deuterium content with rise in elevation which came to be 5‰ + 3‰ per 100m rise in elevation. Similar variations have been observed by other investigators [ Bahadur (1976) ].

vii) Evaporation and melting also affect the concentrations of radioisotopes in the air. The distribution of isotopes derived by the original precipitation near the surface undergoes substantial changes due to uneven accumulation, may be because of drift, in Deuterium and Oxygen-18 contents. This can badly affect the studies conducted for altitude effect. There are chances that the whole thing may even reverse and lead to absurd results [Moser et al. (1975) and Friedman et al. (1972)].

The seasonal variations of the isotope contents in discharges from the glaciarise basins can be used to determine ablation periods, mean shares of meltwater from different areas, identification of the mean altitudes of seperate drainage basins, and resident times of water under different storage conditions [Ambach et al.(1976)]. In this Carbon-14, Tritium, Lead-210, Chlorine-36, Berilium-10, Argon-39 and Silicon-32, are considered for isotopic studies. It is apperent that the snow and glacier meltwaters are heavily depleted in heavy isotopic content and can be used to distinguish the origin of these waters from that of rainfall at lower altitude or due to grounawter contributions to the river inflows.

## 5. WORK CARRIED OUT IN INDIA

In India, studies on snow and glacier were probably carried out during as early period as Mug-hal period or earlier, but, systematic studies started with snow surveys by Dr. Church in 1947 [Bahadur et al.(1989)]. During 1969, the Indian National Committee in International Hydrological Programme appointed high level Committee on snow, Ice and Glaciers. Some studies like glacier mass balance, thermal profiling of ice body, hydrometeorological body observations, glacier dynamics, artificial melting of snow and ice, geomorphological and also the isotopic investigations were conducted and reports, papers, technical notes etc. on physical description, approach to the glacier, geological and geomorphological information, monitoring of meteorological parameters and advancement, recession of snout of the glaciers along with the mass balance and ice movement conducted by the conventional methods started coming up by a number of organisations like Geological Survey of India (GSI) and Department of Science and Technology (DST) etc.

At present, a number of organisations, departments and academic institutions like India Meteorological Department (IMD), Snow and Avalanche Study Establishment (SASE), Mineral Development and Exploration Division of Geological Survey of India (GSI), Survey of India (SOI), Department of Science & Technology (DST), Central Water Commission (CWC), National Remote Sensing Agency (NRSA), Physical Research Laboratory (PRL), and National Institute of Hydrology, Bhabha Atomic Research Centre (BARC) are involved in snow cover mapping and snow pack studies for determination and modelling of the water equivalent, runoff due to snow melt and impact of changing behaviour of the glaciers on runoff processes.

Indian contribution have been mostly around the Himalaya, which contains nearly trillion cubic metre of water in its glaciers comparable to the total ground water resource of the country. Nijampurkar et al.(1977) dated the glaciers with environmental isotopes. The possibility of study the receding behaviour by isotopic technique was suggested. A review of the isotopic technique for snow and glacier hydrology has been made by Bahadur (1985) and Jain et al. (1983), Nijampurkar (1983) has also reported the investigations of Himalayan glaciers using radioactive and stable isotopes. It was reported that study of radioactive tracers can provide quantitative estimates in understanding the behaviour of glaciers in the past. Nijampurkar and Rao (1988) carried out the studies pertaining the dynamics of the glacier ice, past accumulation rate of ice, climatic variations and chemical pollution using stable isotopes, natural and artificial isotopes and chemical tracers. Nijampurkar et al.(1989) reviewed the glaciological studies in Himalayan using radioisotopes.

The works carried out in India , by use of the radio-isotopes include dating of ice samples to obtain glacier flow rates, monitoring of beta-activity and measurement of Lead-210, Silicon-32.

## 6. REMARKS

None of the methods can solve the technical problems of measurement parameters of snow cover independently, while water equivalent of a large representative area is considered. Isotopic technique is a new technique as compared to the conventional techniques for the measurement of water equivalent of snow, ice and glacier. The snowmelt-runoff studies ,in India, started a decade before. But, they are limited to develop satisfactory forecasting models. Combination of two or more techniques: airborne gamma technique and automatic reporting type snow gauges (as ground devices) using the gamma or cosmic radiation absorption technique ,will help to provide better solution. Fully automatic system on snow cover and water equivalent is the necessity of the time for monitoring the temporal changes of these parameters of a particular course/catchment or representative basin. Efforts made to incorporate the nuclear isotopic techniques in last few years, are just the beginning, and, would need coordinated efforts of the organisations working in this field to develop and apply such forecasting and mass balance models to Indian snow fed catchments ,which may bring them to an operational level.

## ACKNOWLEDGEMENT

Authors are grateful to Dr. Satish Chandra, Director, National Institute of Hydrology, Roorkee for his invaluable encouragement and permission to publish the paper and Sri K. S. Ramasastri for taking pains to provide some useful information on the topic . Assistant provided by Sri N.K. Saini, R.A. is also acknowledged.

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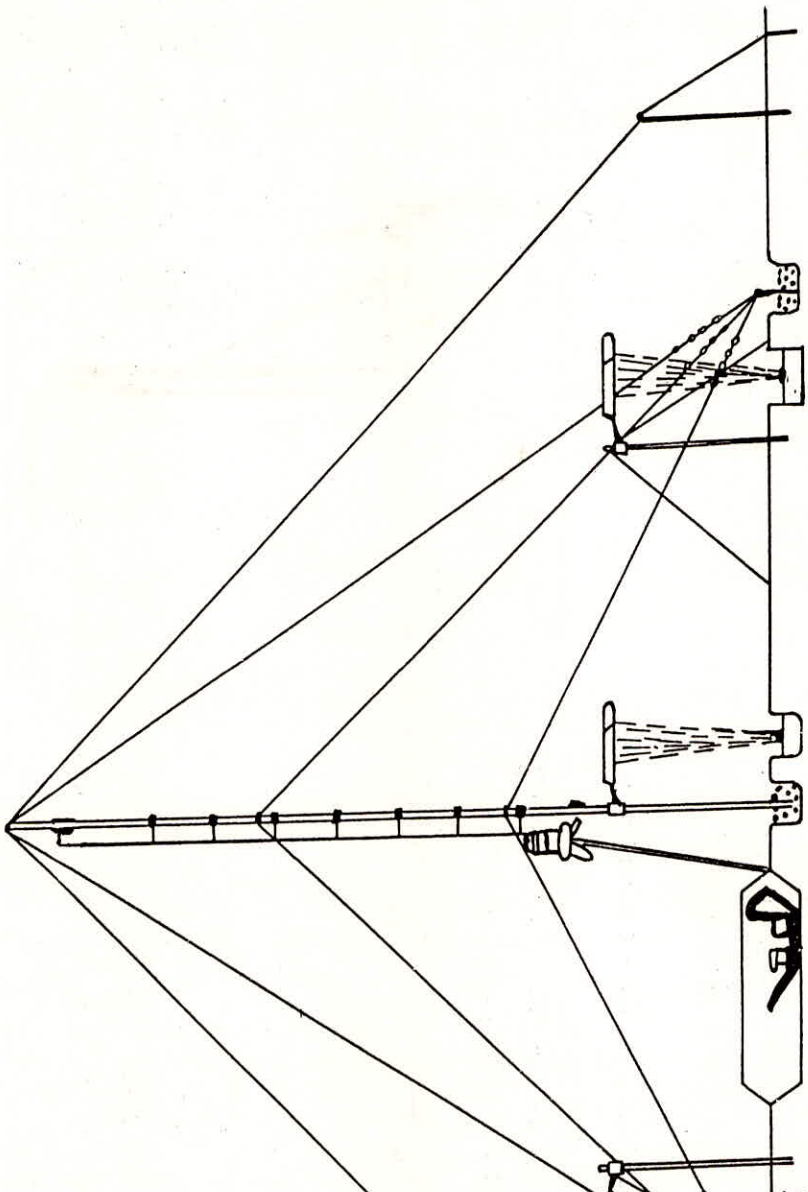

FIG. 1 SET UP FOR STATIONARY GAMMA SNOW GAUGE

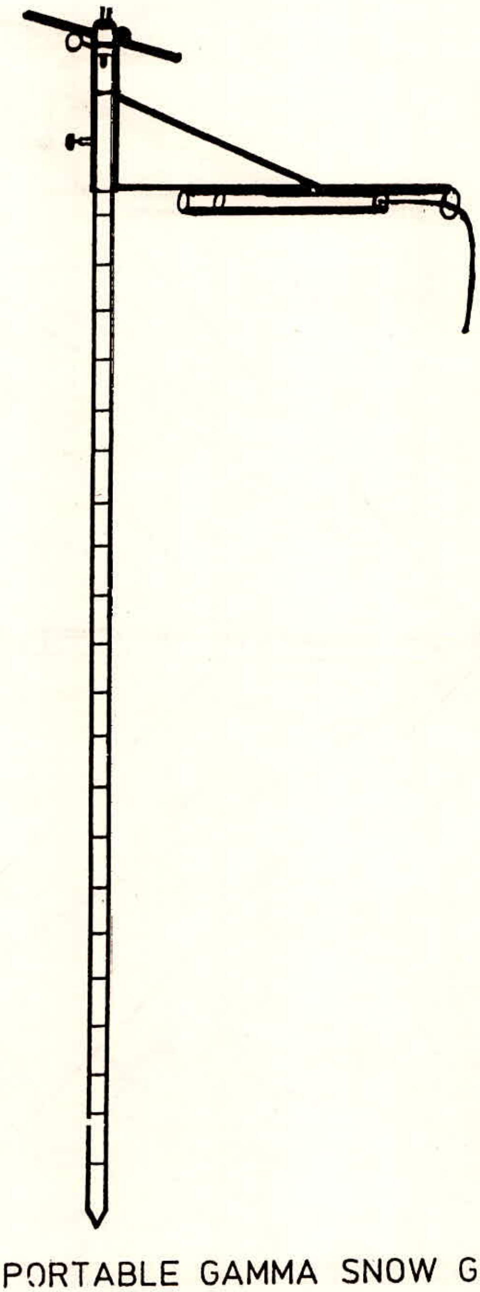

FIG. 2 SET UP FOR PORTABLE GAMMA SNOW GAUGE

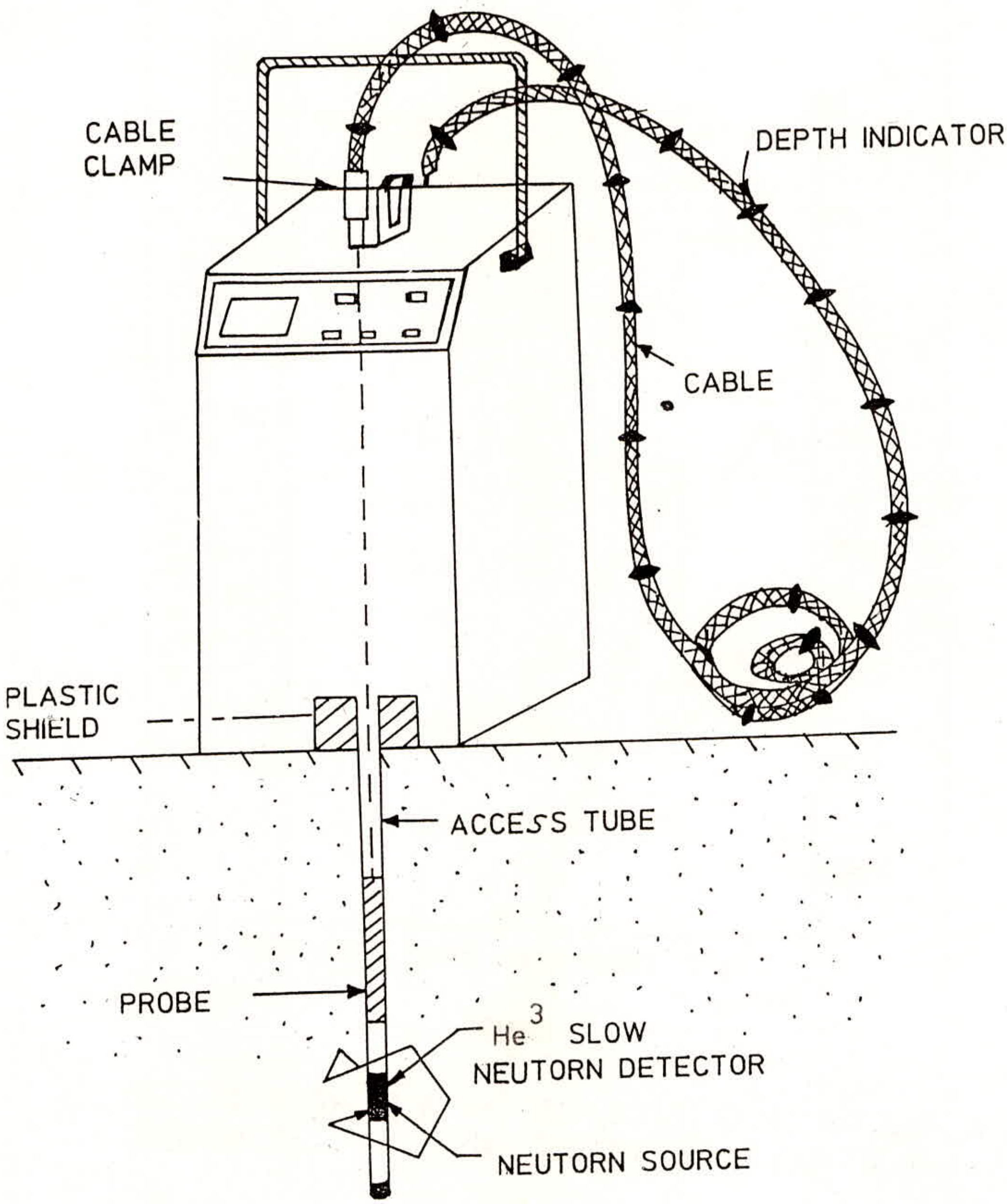


FIG. 3. NEUTORN PROBE

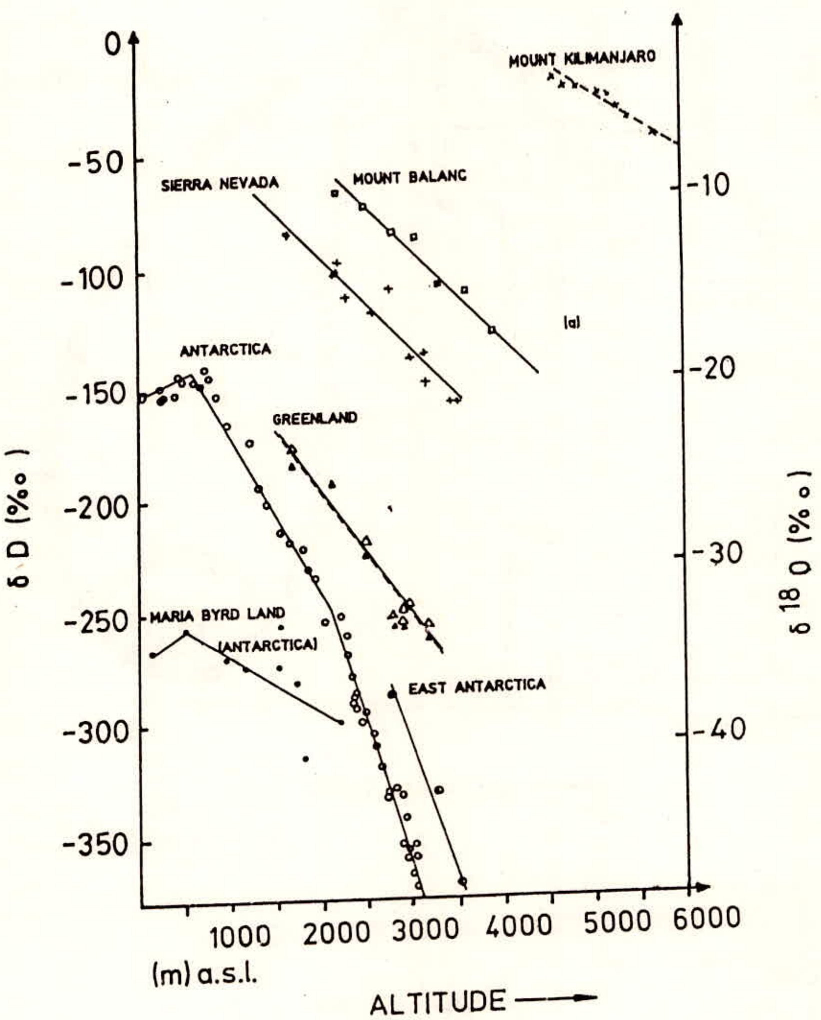


FIG. 4 DELTA VALUE FLUCTUATION WITH RESPECT TO ALTITUDE IN DIFFERENT PARTS OF THE WORLD

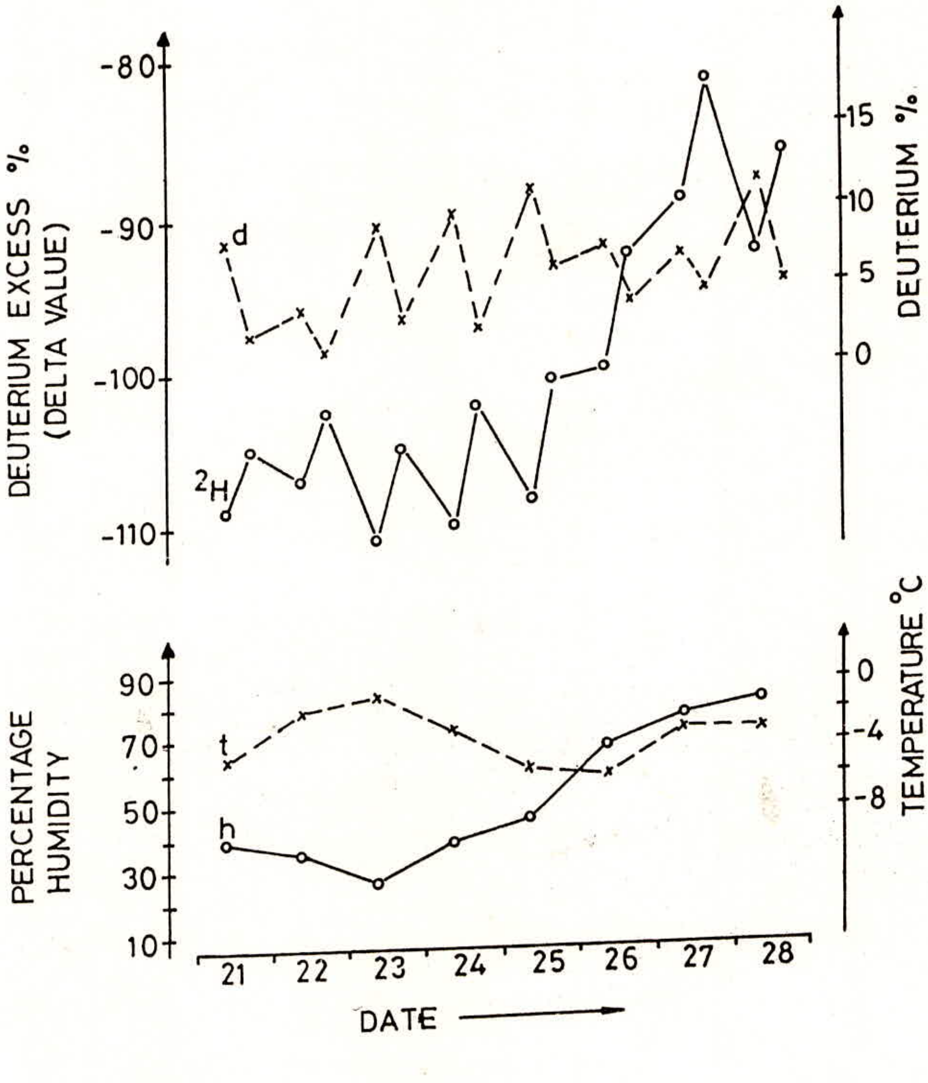


FIG. 5 INCREASE IN DEUTERIUM EXCESS AND VARIATION OF HUMIDITY AND TEMPERATURE