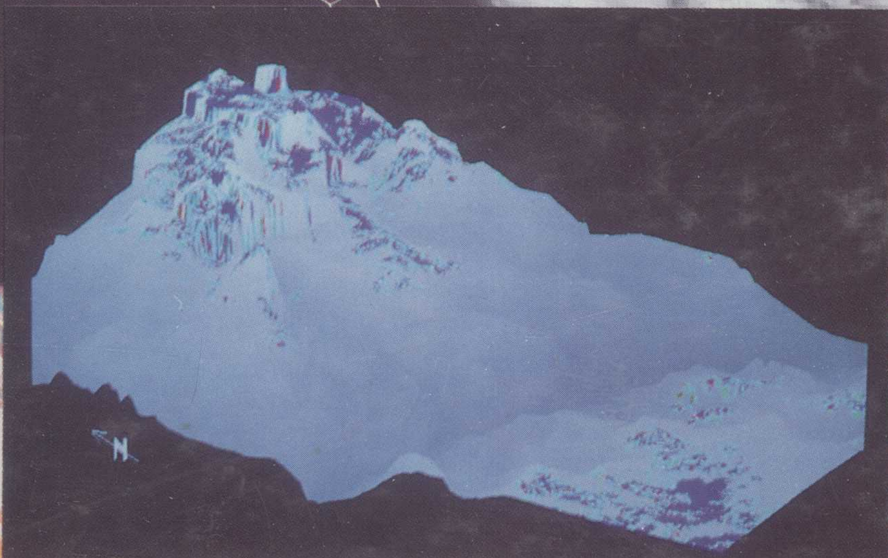
Cold Climate Hydrometeorology



D.S. UPADHYAY

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JOHN WILEY & SONS
NEW YORK • CHICHESTER • BRISBANE • TORONTO • SINGAPORE

First Published in 1995 by
NEW AGE INTERNATIONAL (P) LIMITED, PUBLISHERS
4835/24 Ansari Road, Daryaganj
New Delhi 110 002, India

Distributors:

Australia and New Zealand:
JACARANDA WILEY LIMITED
PO Box 1226, Milton Old 4064, Australia

Canada:
JOHN WILEY & SONS CANADA LIMITED
22 Worcester Road, Rexdale, Ontario, Canada

Europe and Africa:
JOHN WILEY & SONS LIMITED
Baffins Lane, Chichester, West Sussex, England

South East Asia:
JOHN WILEY & SONS (PTE) LIMITED
05-04, Block B, Union Industrial Building
37 Jalan Pemimpin, Singapore 2057

Africa and South Asia:
NEW AGE INTERNATIONAL (P) LIMITED, PUBLISHERS
4835/24 Ansari Road, Daryaganj
New Delhi 110 002, India

North and South America and rest of the World:
JOHN WILEY & SONS. INC.
605 Third Avenue, New York, NY 10158, USA

Library of Congress Cataloging-in-Publication Data

ISBN 0-470-21955-6 John Wiley & Sons
ISBN 81-224-0794-3 New Age International (P) Limited, Publishers

Printed in India at Taj Press, New Delhi

Preface

Hydrometeorology is a recent branch of earth sciences which started in the early 20th century after a systematic world wide observational network came into existence. To meet the ever-increasing demand for fresh water supply, serious attention has been drawn to the need for efficient water management. It has resulted in the fast growth of this science in the past few decades. Snow and glaciers, besides being the storage of locked in fresh water, also throw many challenges in understanding their continuously varying properties and their role in climate monitoring, weather modification and avalanche formation.

This subject has been introduced in many degree courses of civil and water resource engineering, Hydrology, Meteorology and atmospheric sciences, Geophysics and Geography etc., while a lot of research work, theoretical as well as applied, has been undertaken by academicians and operational scientists to develop the technology required to meet the challenges being faced. Under these circumstances, a scarcity of appropriate books and published literature, particularly in the Indian context is a long felt need. This volume aims at fulfilling this need to some extent. It will be useful to the university students and researchers in Hydrometeorology, climatology and related branches of water and atmospheric sciences. Working scientists and researchers in service organisations will also find it useful in their operations and applied research.

The introductory chapters touch upon the role of snow and ice, its nature and general scope of the book, weather elements and basic meteorological principles involved in atmospheric motion and weather formation. Chapter 3 describes in detail the evaporation and precipitation processes, the methods of measurement and analysis and potentials of precipitation as the producer of fresh water. Chapter 4 is fully devoted to climatology, various controls of climate, concepts of climate system and climate change. Discussions on Indian monsoons with special reference to the role of Himalayan snow and ice are also covered. Properties of seasonal snow pack and their variations particularly over western Himalayas have been highlighted in chapter 5.

Large quantity of fresh water (order 5000 km^3) is locked in Himalayan glaciers. Glaciers also play important role in climate monitoring, sediment transportation and maintaining environmental standards. These aspects are discussed in the 6th chapter on Glaciology. Chapter 7 covers Snow Hydrology, the various melt processes and consequent water yield. Efforts are made to present descriptions of various concepts and techniques practiced in Hydrometeorology. Illustrated flood and drought conditions in India are featured in chapter 8. A large part of this chapter is given to discussing frequency-intensity analysis of extreme rainfall series and physical approach to design storm evaluation. The specialised topics of remote sensing methods of rainfall estimation, network design, quantitative precipitation forecast and water balance techniques have also been introduced in this chapter. It was felt necessary to focus on avalanches in chapter 9, bringing out conditions of their formation over Himalayan slopes, forecasting techniques and other control measures, keeping in view that so far very little published material is available on this subject with reference to the Himalayas.

I express my gratitude to Dr. N. Sen Roy, the Director General, India Meteorological Department for granting permission to publish this book. I am also grateful to the Department of Science and Technology (DST) for providing valuable support in completing the task. For illustration purposes, I have used some published data and maps of the India Meteorological Department, Central Water Commission, Snow and Avalanche Study Establishment and a few other agencies for which I am deeply indebted to them. On most occasions sources have been acknowledged within the text. Grateful thanks are also due to Sri Asanga Machwe for his encouragement and keen interest in brining out this volume. I have also to thank my five-year old grand daughter 'Chuk Chuk' who hated my long sittings on manuscript cutting her play time; but liked to see her name in print.

August 1995
New Delhi

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Contents

CHAPTER 1

INTRODUCTION

1.1 SNOW–AN ENIGMA

A snow crystal is made of ice, air, water and impurities; ice forming the framework of crystal and others filling up the void. A *snow cover* or pack is regarded as a network of such crystals randomly arranged. Moisture flows continuously through the pores of the pack under various metamorphic processes. Consequently, the texture and properties of snow pack undergo non-stop change till it exists on ground. Thus snow becomes one of the most complex, dynamic and enigmatic materials in the regime of earth sciences.

Impact of snow is both positive and negative. It is a valuable resource for enhancing water and power supply; it also disrupts water and power supply. It is a beauty and delight as sports and recreation; it is a terror in the form of blizzard, slide and avalanche. It supports movement by skiing and snow vehicles; it restricts movement by disrupting traffic and blocking pathways. It controls flood by freezing flow; it contributes to floods by melting. It helps food production by increasing soil moisture and irrigation; it harms crops by exposing them to low temperature and cutting down the growing period. It protects life beneath the pack and supports wild life; it restricts life particularly the insects and small animals. It maintains environmental standard; it modifies environment, plant life and changes meterological conditions by producing airmass, and altering energy regime of surroundings. It creates problems by way of diseases, slowing down of human activities, damage to properties and increase in cost of living due to additional energy requirement and snow clearance from roof and road; if managed efficiently it can provide many community facilities and even serve as building material in snow bound areas.

1.2 NATURE OF SNOW AND ICE SCIENCE

As a branch of earth sciences, it is essentially *multi-disciplinary* and primarily *data based.*

1.2.1 A Multi-Disciplinary Science

Mechanism of snowfall is dealt in *Cloud Physics* and Meteorology. It includes processes like (i) *nucleation* (formation of ice particles) in cloud masses reaching above freezing level (ii) *riming* – growth of crystal (graupel) by formation and adhering of droplets to ice surface. (iii) *sublimation* — formation of crystal by sublimation of vapour; this usually occurs in symmetrical manner. If deposition is along one axis snow needles or columns are formed; if along one plane, plate type crystals and if along 3-dimensional space, star like crystals are formed. (iv) *Aggregation* of crystal to form flakes. These processes are physically controlled by temperature and humidity conditions inside the cloud mass.

Snow cover is formed due to successive accumulation of precipitated snow on the ground and its redistribution by wind drift, slides and avalanches. Steepness and orientation of slopes alongwith vegetation and forest cover are important factors influencing the development of snow cover. Orography and sciences of flora and forestry deal with these aspects.

Metamorphic processes of snow are governed by the laws of heat and mass transfer through the porous materials. Consequent changes in properties and strength of snow cover fall within the purview of Mechanics and Physics. Snow behaves as an elastic as well as a plastic material. This property helps us to understand the development of stress and strain in various parts of the pack, creep and glide movements and failure of snow layers which trigger off avalanches. Principles of material sciences explain this behaviour of snow.

Snowcover serves as a water reservoir which contributes to river flow; it generates avalanches and modifies weather and atmospheric circulations at various temporal and spatial scales. Hence there is ample scope for applying principles of Hydrology, Avalanche mechanics and Meteorology in snow studies.

Glaciers are formed due to successive accumulation of snow, over a long period of time on a comparatively level ground. They act as water regulators and indicators of climatic change. They also influence biotic diversity and survival strategies of organism living in that region. Furthermore impact of glaciers and polar ice on local and global environment is significant in many ways such as reconstruction of paleoclimate, monitoring pollution and large scale melting due to green house warming. Thus Glaciology, Paleoclimatology, Biology, Chemistry of pollution and ozonosphere and Ecology have important part to play in understanding glacier processes and effects.

Besides high attitude sickness, dryness and high Blood Pressure problems, snow cover poses many additional health hazards such as frost bite, snow burn and blindness and avalanche hazards like injury, hypothermia (excessive cooling), asphyxia (suffocation). We are aware of the weakening of atmospheric ozone layer and consequent increase in solar ultra violet rays reaching earth's surface. Skin cancer and crop damage are the two main dangers associated with this. The problem is rather serious in snow bound regions due to high reflectivity of ultraviolet rays from snow surface. Therefore, medical sciences have sufficient scope in this area.

Excessive snow deposition renders the agricultural land unutilised for one part of the year, reduces growing period and exposes crops to low temperature.

On the other hand it nourishes soil moisture, adds to the water storage in lakes and ponds and enhances irrigation facilities. These effects demand specialised agricultural study and planning in these areas. Other related climate, topographic and soil conditions also have to be considered simultaneously.

Branches of Engineering also have an important role when it comes to the problems of roof failure due to snow loading, construction of hydraulic structures for power generation and water storage, use of snow and ice as building material and construction of avalanche control structures like diversion walls, road galleries, snow bridges and nets.

Snow cover and forest canopy influence each other. Forest cover affects deposition of snow and its melt rate. Snow cover determines type of forest. Creeping and gliding motion of snow tends to deform the trees at lower part of stem. Forest also reduces floods, retards avalanches and controls blizzards. Hence it is important to study snow cover in relation to forest and vegetation.

Recreation and winter sports on snow are added attractions for tourists. Town planning is also related to development of tourism in snow bound area. The management and socioeconomic sciences, thus have a good scope of application.

Among other prominent effects of snow and glaciers are weathering and carving of mountain peaks, and snow melt contribution in evaluating design storm value of a snow bound catchment. Hence Geology and Hydormeterology have some role to play in the study of snow sciences.

1.2.2 A Data-Based Science

The processes of moisture transportation aloft, cloud formation, nucleation of vapour or droplets on ice surfaces, growth of snow crystals as a consequence of riming, sublimation or aggregation and their eventual release as snow fall are far too complex to be governed by exact laws or models. Concentration of ice nuclei in a cloud mass varies tremendously in time and space. It may vary by 1 or 2 orders in a few minutes or a few hundred metres. The types of crystals formed are innumerable depending on the manner in which cloud droplets are deposited around a nucleus. Bentley, an American scientist photographed about 6000 different types of crystals during his life time and yet felt that the list was incomplete.

Likewise, the variabilities involved in properties of snow pack do not follow completely and exactly the known laws of earth sciences. Further more, all the factors responsible for these variabilities are not yet fully understood. The same thing can be said about various interactive processes of snow and other factors mentioned in section 1.2.1.

Long term data collected from a dense network are required to be analysed and studied to understand the nature of variabilities in various factors and phenomena. Most of the relationships, laws and inferences deduced in snow hydrology and meteorology are empirical in nature. Parameterisation of physical factors and mathematical modelling of processes like global and regional circulations of atmosphere, glacial behaviour, snow melt, snow-air interactions, watershed management, flood forecasting, etc are conceptual and need input of observed data and ground truth for their operational utilisation. With the availability of larger and newer data sets, the empirical relations and models are subjected to continuous revision and refinement.

In fact, systematic growth of snow and ice sciences began during the later part of the 19th and early 20th century when planned observational networks were set up in many countries. Development of science was significantly accelerated with the coming of radars, weather satellites (1960), earth resource satellites (1972) and other improved observational devices. Introduction of modern computer systems further enhanced the data-base management system and capacity to solve more sophisticated atmospheric and hydrologic models.

1.3 OUR WATER RESOURCES AND GLACIERS

The total water resource of our planet is 1386×10^6 km^3. Of this only 35×10^6 km^3 is freshwater; 24×10^6 km^3 in the form of snow and ice and remaining in ground, rivers, marsh, lakes, soil and atmosphere. Global distribution of the entire hydrosphere is given in Table 1.1.

Table 1.1 Global distribution of hydrosphere

S. No.	*Residence*	*Volume (10^6 km^3)*	*Volume (per cent)*	*Residence time (years)*	*In terms of water depth (m)*
1.	Ocean	1338.0	93.93	4000	2620
2.	Ground	23.4	4.12	A few weeks to 10,000 yrs	46
3.	Soil	0.0165	0.005	One week of to one year	0.03
4.	Glacier & ice	24.0641	1.65	10-1000	47
5.	Lakes	0.1764	0.016	10	0.35
6.	Marsh & swamps	0.01147	0.001	1-10	0.02
7	Rivers	0.00212	0.0001	few weeks	0.004
8.	Biological	0.00112	0.00005	a few days	0.002
9.	Atmosphere	0.0129	0.001	10 days	0.025
	Total	1385.98461			

All living being need water for survival. 65% of our body is water and even 10-12% reduction will cause death. In a way, water is the life blood of the environmental system. There is no clearcut evidence or proof as to when and how water was formed on this planet. It is largely believed that it was formed around in the very beginning about 4500 million years ago when the earth was formed. Since then the quantity of water is constant. It is always in motion in an endless hydrologic cycle; from ocean to atmosphere by evaporation, dropped as precipitation on the surface and then to the ground by infiltration and back to the ocean by surface and underground flows.

1.3.1 Deserts and Glaciers

Hydrologic cycle may undergo changes. Its long term variations result in formation of deserts and glaciers. Regional and short term variations cause floods and droughts. Deserts are generated in areas where precipitation falls much short of evapotranspiration while glaciers are produced where precipitation (solid form) exceeds evaporation and melting. Deserts and glaciers are very sensitive ecosystems and could be used as indicators of climatic change. These extreme climatic conditions create hostile environment for all forms of life and bioproductivity of these systems is very low.

The existing surface area occupied by desert is 24.45 million km^2; 7.99 million km^2 extreme deserts and 16.46 million km^2 the region with extremely high degree of desertification hazards. Glaciers on earth occupy 16.23 million km^2 area.

1.3.2 Hydrologic Cycle, Freshwater and Snow

In a hydrologic cycle, about 453 thousand km^3 of water evaporates from oceans and 72 thousand km^3 from land surfaces every year. Of this 412 units directly fall on to oceans and seas and 113 on land by precipitation. 72 units of land precipitation replenishes soil moisture and the remaining flows back to sea.

The hydrologic cycle is an efficient producer of fresh water; but it is a very poor distributor. Distribution of precipitation is erratic in space and time, resulting into floods and droughts. Also a large quantity of fresh water flows back to oceans as surface run off.

In this respect snow and glaciers play a very positive role by storing water during winter and releasing them in summer. Snow is a significant part of fresh water resource which establishes stream flows.

1.4 AVERAGE GLOBAL DISTRIBUTION OF SNOW AND ICE

Snowcover is formed when snow is sufficient to persist on the ground till the next spell of snowfall. If the cover appearing during winter ablates by the end of summer, it is termed as *seasonal snow cover.* Ablation occurs as a consequence of melting, evaporation, wind drift and avalanche. The other farms of snow and ice cover are (i) firn — the snowpack which survives at least one summer. This is old snow with small areal extent, resting in the depression zones of mountains or in forested areas. (ii) glacier — formed due to successive accumulation of snow over a long span of time.

Areal distribution of snow and glaciers can be considered at three scales:

(i) *Macro* (10^6 km^2). At this scale, the distribution depends on large scale orography and airmass controlling temperature regime of the area.

(ii) *Meso* (10^2 – 10^3 km^2). It is redistributed snow caused by wind, avalanche, vegetation, forest, etc.

(iii) *Micro* (10 – 10^2 km^2). It depends on surface roughness, depressions and mechanism of snow transportation.

1.4.1 Permanent Ice and Glacier

These are found at almost all latitudes. In polar region ice and glaciers begin at sea level itself. But their attitude rises to about 3000 m in mid latitudes and 5000-6000 m in tropical and equatorial regions. The altitude of permanent snow line is highly correlated with the freezing level (0°C) altitude of free atmosphere.

Average global distribution of permanent snow and ice is given in Table 1.2.

Table 1.2. Global distribution of permanent snow and ice

S.No.	*Region*	*Volume (10^3 km^3)*	*Surface area (10^3 km^2)*
1.	Antarctica	21600	13980
2.	Greenland	2340	1802.4
3.	Arctic islands	83.5	226.09
4.	Asia	15.63	118.935
5.	Europe	4.09	21.415
6.	North America	14.062	67.522
7.	South America	6.750	19.0
8.	Africa	0.003	0.022
9.	New Zealand	0.10	1.0
10.	New Guinea	0.007	0.0145
	Total	24064.1	16235.5

Table 1.3. Distribution of permanent snow and ice in Asia and Europe

	Volume km^3	*Surface area km^2*
Asia		
(i) Pamir Alai	1725	11255
(ii) Tienshan	735	7115
(iii) Sajam Alatau	140	1635
(iv) Eastern Siberia	30	400
(v) Kamchataka	80	1510
(vi) Hindu Kush	930	6200
(vii) Karakoram	2180	15670
(viii) Himalayas	5000	43000
(ix) Tibet	4820	32150
Europe		
(i) Iceland	3000	11785
(ii) Scandinavia	645	5000
(iii) Alps	350	3200
(iv) Caucasus	95	1430

1.4.2 Snow and Glacier over Himalayas

The Himalayas, regarded as abode of snow and ice, cover an area of 4.6 million km^2 above an attitude of 1500 m. 0.56 million km^2 lies above 5400 m and 3.20 above 3000 m. According to the first generation inventory prepared by the Geological Survey of India, the Himalayas contain about 5000 glaciers spreading over 43000 km^2. These glaciers mostly belong to the Indus and Ganga river basins. Their sizes vary from less than a km^2 to as large as the Siachen Glacier which is 72 km long. Average depth and speed of the Himalayan glaciers are less than the global mean depth and speed.

Snow charts derived from satellite (TIROS-N, GOES) imageries indicate that the spread of seasonal snow cover over the Himalayas may be 10 times or even more as compared to the permanent snow and glacier area. Building of cover begins during the period, October to December, develops during January to March and starts ablating from April onward reaching a minimum in September. For instance, in 1979 snow pack was formed in the second week of December whereas in 1981 it was formed in the first week of October. Some Satellite estimates of snow cover area are given in Table 1.4.

Table 1.4. Satellite estimates of snow cover

Maximum Coverage		*Minimum Coverage*	
Months	*Area (10^6 km^2)*	*Months*	*Area (10^6 km^2)*
Jan 80	2.11	Sep 79	0.93
Mar 81	3.67	Sep 80	0.74
Jan 82	2.44	Sep 81	0.55

1.4.3 Eurasian Snow Cover

The Eurasian snow cover areas as monitored by NOAA satellite visible sensors (1966-86) have been used to work out the mean and coefficient of variation (*cv*) for each month. These are given in Table 1.5.

Table 1.5. Mean snow cover and its coefficient of variation

Month	*Mean Snow Cover Area (10^6 km^2)*	*Coefficient of Variation (%)*
Jan	28.9	8.0
Feb	29.7	9.1
Mar	25.7	7.0
Apr	18.4	10.3
May	11.6	14.0
Jun	5.5	25.6
Jul	1.4	48.8
Aug	0.8	75.0
Sep	1.6	62.5
Oct	10.0	47.0
Nov	20.0	8.5
Dec	25.9	7.7

Monthwise variation in the extent of snow cover indicates large spread of seasonal snow cover over the continental high lands.

1.5 ROLE OF SNOW AND ICE

(i) Melt Water Supply

Five percent of the total global water is fresh. Of the available fresh water one-third comes from snow and ice and remaining by other channels like ground, rivers, lakes, etc. The supply from snow is rather more important as it is released during dry summer.

Besides meeting the local needs of water for domestic, industrial and agricultural purposes and generation of hydroelectric power, they also contribute to and establish river runoff.

(ii) Avalanche

Snow avalanches are generated due to the structural failure of snow cover resting on slopes. Failure may occur as a consequence of (a) *external stresses* caused by intense snowfall, movement of human beings or animals and sound waves. (b) *metamorphic activities* resulting in weak layers inside snow cover. (c) *excessive melting* of upper layers. Meltwater percolates underneath and lubricates the surface to produce slab avalanche during spring months.

On all snow bound slopes with elevation above 10 degrees, avalanches occur and cause destruction of life and property of the local dwellers and winter tourists every year all over the world.

(iii) Modification of local Weather and Climate

Among the short term (days to weeks) influence of snow cover on weather is: (a) the formation of cold airmass at lower levels due to high albedo and emissivity of snow (b) the generation of baroclinicity at the boundary of snow and bare land due to sharp temperature contrast. As a long term (month to season) effect, snow cover can change the surface albedo and consequently influence energy regime of the boundary layer.

Some researchers have found out negative correlation between winter snow cover over Himalayas and rainfall over northwest India during subsequent summer monsoon. A correlation ranging from -0.3 to -0.4 is reported by various authors.

(iv) Glaciers are Indicators of Climate and Climatic change

The polar glaciers and ice cover a large area (over 10% of earth's land surface) forming ice caps on both the poles. The thickness of northern ice-cap varies between 800 and 3000 m and that of the Antarctica ice between 2000 and 4800 m. These ice caps are one of the major controllers of climate. In turn, climate also influences the areal extent of these ice-caps. The Antarctica ice occupies minimum area during summer end (Feb-Mar). By the end of winter (Sep-Oct) the cap expands to its maximum area.

Polar ice provides ideal conditions for the formation of cold and dry airmass resulting in anticyclonic circulation. It tends to affect the climate of temperate and tropical region also. One example is the intrusion of north easterly cold wind over northwest India as an outflow of the Siberian anticyclone.

Sharp temperature contrast over snow and bare land near the snow line is also symptomatic of ice functioning as cooling agent. The region covered by seasonal snow experiences abrupt rise and fall in temperature at the time of ablation and formation of cover.

Satellite observations of snow coverage in the northern hemisphere show almost parallel variation in coverage area with low tropospheric air temperature. It happens because the formation and melting of snow are closely related to the heat balance. High reflectivity, poor conductivity and low melting point are the properties of snow cover which result into lowering the air temperature.

For the same reasons glaciers are also sensitive to climate change and therefore, provide valuable information about paleo climate. The following periods of cold and warm climate during the past 10,000 years were associated with expansion and contraction of polar ice caps.

Cold period (little ice age)	*Warm period*
900-300 BC	7000-5000 BC
1430-1850 AD	1000-1200 AD

A glacier consists of stratified layers of successive deposition of snow over a long period of lime. Inside its numerous strata, sediments and various life form like seed, bacteria, pollens' etc are burried. Hence ice-core studies provide information not only about past climate, but also about other terrestrial activities.

The position of equilibrium line of the continental glaciers is an important link for deciphering past fluctuations of warm and cold period of the region.

(v) Ice cores are useful for monitoring level of pollutants

Ice-core data recorded at the Russian observatory 'Vostok' in Antarctica gave some information about CO_2 concentration during past 1,60,000 years. Variation of CO_2 level appears to be highly related with glacial oscillations. About 30-40 thousand years ago concentration of CO_2 in the atmosphere was very low (0.02% by volume) as compared to present level of 0.035%.

1.6 HISTORICAL BACKGROUND

Snow and ice attracted our attention since ages because of their various interactive phenomena like melt, flood, blizzard, avalanche and glaciation. But their scientific study started very recently at the end of 19th or the beginning of 20th century, when systematic observational networks were set up.