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ENCYCLOPEDIA OF EARTH SCIENCES SERIES

# ENCYCLOPEDIA *of* SNOW, ICE AND GLACIERS

*edited by*

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## Preface

Snow, ice and glaciers (SIG) are the components constituting what is called cryosphere. They exist at all latitudes and contain the majority of the earth's fresh water. Due to their dominant prevalence, they influence weather, climate, ecosystems, vegetation, and life and human activities in a variety of ways. Indeed they shape human civilization. Owing to looming climate change and global warming, temperature changes now seem inevitable and are changing the landscape of snow, ice and glaciers, or even the existence thereof. In fact, the changes occurring in SIG can be construed as major indicators of climate change. The nature of cryosphere is highly interdisciplinary and calls for an updated interdisciplinary account of its dynamics. Recent decades have witnessed increasing attention to SIG and scientific communities have started working collectively to develop the basic foundation upon which the broad understanding of cryosphere rests. However, there is still a long way to go.

Discussions on climate change and global warming now seem to be occupying the center stage in public debates, professional forums, news media, and political dialog. As a result, the general public has become much more aware of what is happening to our climate. Since both climate change and climate variability have been found to be closely linked with the cryosphere, it is important for scientists and professionals in the field of earth, environmental, oceanic and atmospheric sciences to develop a better understanding of this sphere from conceptual, theoretical, technical and applied viewpoints. This is especially important for snow, ice and glacier covered areas, since they are rarely stable and are continuously changing in their thickness, areal extent, and flow speeds. Recent advances in field-based studies and quantitative and numerical modeling have provided answers to several key questions but have also highlighted the urgent need for cryospheric studies in many areas, for example, contribution of snow, ice and glacier melt to the sea level rise; importance of snow and glacier to water resources; and so on.

The objective of this Encyclopedia is to present the current state of scientific understanding of various aspects of earth's cryosphere – snow, glaciers, ice caps, ice sheets, ice shelves, sea ice, river and lake ice, and permafrost – and their related interdisciplinary connections under one umbrella. Therefore, every effort has been made to provide a comprehensive coverage of cryosphere by including a broad array of topics, such as the atmospheric processes responsible for snow formation; snowfall observations; snow cover and snow surveys; transformation of snow to ice and changes in their properties; classification of ice and glaciers and their worldwide distribution; glaciation and ice ages; glacier dynamics; glacier surface and subsurface characteristics; geomorphic processes and landscape formation; hydrology and sedimentary systems; hydrochemical and isotopic properties; permafrost modeling; hazards caused by cryospheric changes; trends of glacier retreat on a global scale along with the impact of climate change; and many more quantitative estimates of various glacier parameters, such as degree-day, mass balance, extent and volume, and downwasting. Also included are articles on GPS application, and satellite image application in glaciology; GPR analysis; and sea level rise.

For purposes of the Encyclopedia 463 articles were selected. Literature on snow, ice and glaciers has grown too large to be fully treated in a single volume; therefore, the selection of articles included some subjectivity but was reviewed by many experts who have long been at the forefront of research in the field of cryosphere. We truly understand that given the scope of this subject it is almost impossible to include each and every topic in this type of reference book, but we have tried our best to avoid any glaring omissions or miss something which could significantly hamper the quality of the Encyclopedia. Therefore, we have made the contents of the Encyclopedia exhaustive, but we understand that we might have missed certain topics. We are also aware of some partial omissions. As it frequently happens, willing contributors

cannot unfortunately be always found for all the suggested topics. It may be noted that if the reader does not see an entry for the particular topic that interests him or her, then he or she should look in the index because that topic may have been covered under a different heading and perhaps in more than one article. In making the list exhaustive, it is possible that there might be a little bit of repetition here and there, but we do not want readers to read two articles to understand one.

The material presented in the articles consists of established information on a particular topic and represents easily accessible digested knowledge. The level of material is such that a graduate student can benefit from the presentation which is not necessarily from his or her area of expertise. An effort has been made such that each article stands on its own, without an assumption that a reader will be seeing any other portion of the Encyclopedia. Although entries are presented in alphabetical order, they have been organized under major compilation headings which should become particularly obvious when the reader uses the cross-references with each entry. This is not an exhaustive list but hopefully it gives a structure to the Encyclopedia's contents. Of equal value are the many references given with the entries.

This *Encyclopedia of Snow, Ice and Glaciers* is supposed to provide clear explanations of current topics, and is not structured as a student textbook, but it is rather for quick access to particular terms and concepts in self-contained entries. We hope that this volume will also tempt the casual reader to browse through and become curious about the different facets and foci of cryosphere.

The contributors represent varying backgrounds and many of them represent WHO'S WHO in the cryosphere. It is hoped that the Encyclopedia will serve as a reference to scholars and students. The Encyclopedia will also be a valuable resource for geologists, geographers, climatologists, hydrologists, and water resources engineers; as well as to those who are engaged in the practice of agricultural and civil engineering, earth sciences, environmental sciences and engineering, ecosystems management, and other relevant fields.

The encyclopedia is comprised of articles under three categories: A, B, and C. Tables 1, 2 and 3 provide a list of major headings of articles included in the encyclopedia for a quick reference (see List of Articles, pages 1233–1237). 64 articles in category A represent major divisions and review topics. These also serve to coordinate the widely scattered entries of categories B and C. 182 Category B articles constitute building block items, inspired by textbook subheads, but also the cookbook items. 217 articles in category C are mini-entries dealing with materials, fancy terms, or outdated concepts. All these categorical entries on different topics are compiled in an alphabetical order, with their length being related to their relative importance.

March 2011

Vijay P. Singh  
Pratap Singh  
Umesh K. Haritashya  
(Editors-in-Chief)

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## Guide to the Reader

For the beginners, it is good to start with a general article, then track the list of cross-references provided at the end of the article to locate similar or relevant articles. For example, if one wants to learn about hydrological aspects of snow and glaciers, then one should go to Glacier Hydrology and Snow Hydrology, then Melt Runoff Modeling, then Impacts of Snow and Glaciers on Runoff, then Hydrochemical Characteristics of Snow, Ice and Glaciers, then Hydropower: Hydroelectric Power Generation from Alpine Glacier Melt, or several other specific Snow or Glacier Hydrology related articles. The list of cross-references provided at the end of the article is not exhaustive, otherwise it would lead to a long listing, rather it is a guide for the reader to find other relevant articles, which are further cross-referenced.

Experts or other readers with background in cryosphere may directly search for specific topics. For example, Ice Age Cycles: Data, Models, and Uncertainties, or Basal Sediment Evacuation by Subglacial Drainage Systems. If one does not find the topic one is looking for, it is possible that it may have been covered under a different heading. Therefore, one should go to the index that would lead to the articles that may cover the topic of interest. If a reader is looking for more explanation than what is already described under any particular topic, then most articles provide important and landmark bibliographic references that relate to both general and research articles. Some articles provide older references which allow readers to find the historical aspect of the topic.

As depth increases, firn porosity decreases and air mixing becomes more restricted (Schwander et al., 1997; Bender et al., 1997). Seasonal layering can also affect the rate of air movement through firn (Albert, 1996) and may produce impermeable layers in the non-diffusive zone. These prevent air from equilibrating with that in the diffusive zone (Sowers et al., 1992; Schwander et al., 1997). While air may mix locally, within the summer layer for example, impermeable winter layers impede its vertical diffusion (Fain et al., 2008).

### Firn measurements

Borehole logging is used to measure firn properties in situ. These include temperature, density, and vertical strain. Unlike snow, which must be sampled at depth by digging a large snow pit and sampling from the sides, firn has enough cohesion (Cohesion) to permit the extraction of intact cores that are used to measure density, porosity and permeability, grain size, and anisotropy.

Because firn is compressible, seasonal layers thin with depth. It is also porous and subject to the migration of chemical species deposited with the snow (Chemical Composition of Snow, Ice, and Glaciers). Both of these aspects can complicate age-depth calculations. Where annual layers cannot be distinguished optically or from the geochemical record, a density profile produced from a borehole log of vertical strain or measurements of mass, length, and diameter of core sections can reveal seasonal layering.

### Summary

A transitional state between fallen snow and meteoric ice, firn is a complex material where vast morphological and chemical changes are taking place.

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### Cross-references

- [Antarctica](#)
- [Chemical and Microbe Records in Snow and Ice](#)
- [Chemical Composition of Snow, Ice, and Glaciers](#)
- [Cohesion](#)
- [Geochemistry of Snow and Ice](#)
- [Glacier](#)
- [Ice](#)
- [Isotopic Characteristics of Ice, Snow, and Glaciers](#)
- [Layering of Snow](#)
- [Overburden Pressure](#)
- [Snow Grains](#)
- [Stratigraphy of Snowpacks](#)
- [Temperate Glaciers](#)

### FJORDS

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### Synonyms

Fiord

### Definition

Fjords are long, narrow, and over-deepened features with steep sides and are carved into bedrock by the glacial activity and flooded by melting water (Figure 1).





**Fjords, Figure 1** Fjord as seen in Milford Sound, New Zealand. Photo courtesy Dr. Luke Copland.

Fjords are erosional landforms that represent the movement of a glacier within a confined channel along the valley bottom. The movement of a glacier and formation of fjords is entirely controlled by topography. They are common in the polar regions, but can also be found in subpolar and temperate regions (Table 1). Fjords have existed for millions of years and they range from a few kilometers to several tens of kilometers wide and several kilometers long. Because of their location and relationship with the sea level on one side and tectonically active high mountains on the other side, they are an important feature. They also possess unique characteristics of oceanic processes and ice-ocean interface (Straneo et al., 2010), and therefore, they are appropriately termed as one of the complex and dynamic landsystems that provide information about glacial, fluvial, and oceanographic features.

Most fjords are a Palimpsest feature which makes them an extremely important feature, because they can provide information about the successive glaciations through floor sediments. However, these sediments need to be carefully analyzed, since they may have been buried by younger glacial marine sediments. Fjords act as natural sediment traps and typically have high sediment accumulation rates, providing the potential for high-resolution palaeoclimatic and palaeoenvironmental studies on decadal to centennial timescales and presenting a unique opportunity to study land–ocean interactions. Cowan et al. (2010) used the fjord sediment to identify two prominent glacial erosion surfaces associated with Last Glacial Maximum advance and Little Ice Age advance. Fjords comprise several rock basins, but many of them are deepest at the beginning and become gradually shallower toward the sea. This could be related to the erosive power

of glaciers, which becomes lesser and lesser toward the end of the feature.

Sediment deposition in fjords can be related to retreating glaciers by depositional zones moving in the upward direction and hiatuses in retreat by push moraines or morainal banks. Powell and Molnia (1989) has shown various depositional system models associated with retreating glaciers, and he (Powell, 2003) has discussed such models in various types of environment from polar to temperate. Sediment deposition can also be related to advancing glaciers in the form of increasing till thickness from head of a fjord toward the sea limit.

Fjords also provide critical information about marine limits and relate to with the isostatic uplift of deglaciated outer coasts.

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### Cross-references

[Sediment Core and Glacial Environment Reconstruction](#)

**Fjords, Table 1** Some of the major local controls on modern fjord landsystems (Adopted from Powell, 2003)

Climatic zone	Glacial flow velocity	Internal ice condition	Bed condition	Subglacial water free	Glacier terminus	Sediment contribution						Modern examples				
						Glacial		Glacifluvial		Marine			Terrestrial			
						Sub-	En-/ supra	Sub-	En-/ supra	icebergs	Sea ice		biogenic	Fluvial	Mass flow	
Temperate	Fast	Temperate	Deforming till, local	Conduit flow	Tidewater cliff	2	2	5	1	2	1	3	3	1	Alaska, British Columbia, Chile	
Subpolar	Fast	Slightly cold	Deforming till	Conduit flow	Tidewater cliff	3	1	3	1	1	2	1	3	1	Svalbard, Canadian and Russian Arctic	
	Moderate	Cold	Mostly frozen, local till	None to minor conduit flow	Short floating tongue or tidewater cliff	2		2		1	2	1	1	1	Antarctic Peninsula	
Polar	Fast	Cold	Deforming till	Local conduit thin film	Floating tongue	3	1	3		3	1	1	2	1	Greenland, Ellesmere Island, Baffin Island	
	Moderate	Very cold	Deforming till	None	Floating tongue	3	1	1	1	1	1	1	1	1	3	Antarctica (Mackay)
	Slow	Very cold	Mostly frozen, some till	None	Floating tongue or tidewater cliff	1	1	1	1	1	1	1	1	1	3	Antarctica (Ferrar and Blue)