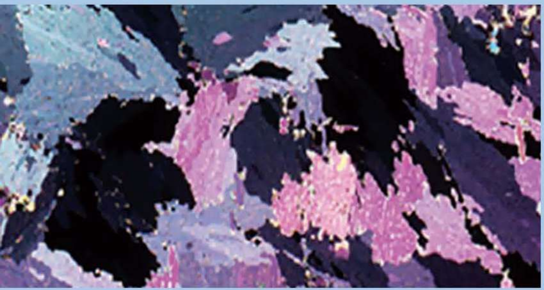
SEA ICE

PHYSICS AND REMOTE SENSING



MOHAMMED SHOKR AND NIRMAL K. SINHA

SECOND EDITION

WILEY

Sea Ice

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Physics and Remote Sensing

Second Edition

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Front cover images: the main central photo shows the Canadian icebreaker Pierre Radisson, operated by the Canadian Coast Guard, in the north water polynya (Sarvarjuaq to Inuit in Canada) north of the Baffin Bay. A few scientists were exploring a possible sampling site on the apparent thin sea ice in late April 1998. The photo was taken by M. Shokr while joining the expedition. The bottom left image is a photograph of a thin section of young ice in a calm bay in the Labrador Sea, eastern Canada, showing the crystallographic structure of the ice. The photo was taken by M. Shokr in March 1996. More details are given in section (5.3.3.4) The center bottom image is an artistic view of a European radar satellite orbiting the earth. The bottom right image, showing the letters "ICE", illustrates the principle of interference colors for optical retardation, which articulates the "anatomy" of sea ice (i.e., the crystalline structure). The word ICE has been cut from vertical thick sections of directionally solidified columnar-crystal ice, frozen from distilled water. More information is presented in section (4.2.5). The image was prepared and photographed by N.K. Sinha.

Back cover image: this was also taken by N.K. Sinha and it shows the images of the two co-authors of this book reflected off the dark glasses of a fellow engineer during a field expedition in the Canadian Arctic in May 1993 (M. Shokr at the left side and N.K. Sinha at the right side).

To the two most caring women in my life, my Late mother and my wife; my three sons who taught me more than I have ever taught them; and to all those who inspired me to finish this book knowing that they will not read it.

Mohammed Shokr

If I was successful as a scientist, it was only because of the unconditional support I received from my wife, Supti Sinha, and my three daughters, Priya, Roona, and Shoma, who often helped me in my cold laboratory. Shoma was born while I was camping on an old ice floe near the North Pole during my long, long absence from home.

Nirmal K. Sinha

CONTENTS

PREFACE

During the winter months, sea ice plays the most important role in the daily life of coastal communities of the cold regions of the earth. As for the Arctic regions, especially Canada and Russia, the recent trend of sea ice retreat under global warming is leading to new opportunities for the extension of navigational season and exploitation of natural resources. Growing interest in sea ice for socioeconomic purposes has also increased awareness of its role in affecting the global environment, the climate system, and most importantly the human aspects. The advent of remote sensing techniques from Earth-observing satellites, as the major tool for obtaining global record of sea ice, is making it necessary to re-examine sea ice as a material with updated knowledge and approaches.

In the customary description of snow, fresh-, and sea-ice, often the basic sciences and measurement techniques used are assumed to be known yet not covered or explained in details. These are mostly related to a few physical aspects: (1) the thermodynamic high-temperature state (being close to the melting point) of these materials, (2) physics of solidification governing the development of microstructural features especially in sea ice, (3) the impact of mobility and ageing of sea ice on its geometrical and physical properties, and (4) the birefringent properties of ice crystals that are used extensively for revealing internal substructures. By the same token, the customary description of the applications of remote sensing usually leaves out details of the electromagnetic wave interaction with ice and its snow cover, particularly the impact of the snow on the measured reflection, radiation, and radar scattering. This book is written with the hope of filling these gaps and to making a bridge between the physics and the remote sensing communities. This is spot-on whether the readers are working on sea ice in the two primary polar cryosphere or on snow/ice of the secondary cryosphere of the Himalayas and other mountain ranges.

The advent of satellite remote sensing and its applications to sea ice, in the 1970s, fulfilled a wish by some of the pioneers of ice research in the 1950s. That was to develop instruments suited for recording the evolution and dynamics of sea ice in the polar environment. Space-borne sensors operating in the visible, infrared, and passive microwave emerged but it wasn't until the introduction of the Synthetic Aperture Radar (SAR), in 1978, onboard Seasat when the sea ice community realized how revolutionary this tool would be for ice reconnaissance and parameter retrieval at fine resolutions. Work started in the 1980s to study the feasibility of developing space-borne imaging radar systems. The work bore fruits in the 1990s, when the European the Europe Remote Sensing Satellite (ERS) and the Canadian RADARSAT-1 were completed. Data from those satellites and a bunch of earlier satellite-borne visible, thermal infrared, and passive microwave sensors opened many opportunities for individuals from different disciplines to join the interesting field of remote sensing of sea ice. Individuals from the ice physics and mechanics disciplines also came forward to link their knowledge to remote sensing observations.

The first author of this book considers himself lucky when opportunities emerged for him in Environment Canada, starting in 1988, to get involved in many projects to demonstrate applications of imaging radar data in support of the Canadian sea ice monitoring program. Later he expanded his experience by developing applications using microwave (active and passive) and other remote sensing data categories. Opportunities also emerged for him to participate in field expeditions in the Arctic and the eastern seas of Canada and be in direct touch with the fascinating world of sea ice. The second author has spent long career in scientific research of high temperature material, of which ice has been at the core of his research. He has contributed to development of advanced knowledge on crystallographic structure of natural ice. He also considers himself lucky when opportunities emerged for him to get involved in many Arctic R&D activities after he joined the National Research Council of Canada in January, 1975. Both authors combined their experience in sea ice physics and remote sensing to produce this book. The idea of the book started in 2010 when the authors felt the importance of combining knowledge in these two fields in a single publication. They were also keen to present their unpublished data collected and analyses conducted over many years of collaborative work.

In many ways this is an entirely new book on natural floating ice in oceans with an emphasis on sea ice. The goal is to describe and explain the principles of physics and chemistry of sea ice and its space-borne observation using a suite of remote sensing imaging systems. The reader needs only to flip through the pages to note that the general appearance related to the format and illustrations are different from any technical book. The subjects are treated with a multidisciplinary and, to some extent, transdisciplinary approach. Underlining assumptions are that the reader/user will come with wide ranging engineering backgrounds—civil, mechanical, environmental, electrical/electronic, etc. or sciences—physics, chemistry, geography, oceanography, climatology, and even social sciences and anthropology related to human settlements. The style used, therefore, is to describe complex subjects in an understandable way so that the reader will not only gain a working knowledge of basic science related to the area of study, but also applications of ice information retrievals using remote sensing tools. It is also expected that the reader will cultivate an appreciation of the human aspects required to carry out the investigations and, of course, the real-life operational issues encountered in shipping, fishing, etc.

This book is intended to summarize experiences acquired by international researchers and operational sea ice communities. Focus is placed on experiences gained in Canada, of which its northern sea water is covered by about one million square kilometers of sea ice in winter on an average. The book is also intended to reach out to a variety of sea ice audiences interested in different aspects of ice physics, mechanics, remote sensing, operational monitoring, climatic impacts, etc. Information covers sea ice processes operating at a range of spatial scales from micro- and macro-scales (such as brine entrapment in sea ice within high energy paths of crystallographic structure) all the way to the synoptic scale of ice motion across the Arctic-wide domain.

The first edition of this book was published in June 2015. It contained ten chapters in addition to the Introduction: five on ice physics, four on remote sensing of sea ice, and one providing a historical account of the national ice monitoring service in Canada. In this new edition some of the content and layout has remained the same, while significant changes have also been made. Chapters are not free-standing. Instead, links are established as much as possible between information about the different themes of the chapters. More melding of physics and remote sensing has been included.

In this edition, the chapter on the Canadian ice monitoring is removed while three new chapters have been added. After the Introduction (Chapter 1), Chapters 2 to 6 constitute the ice physics part of the book. They present key physical properties and processes suitable to anyone with a background in physics and mathematics. However, some topics may be considered advanced. Chapter 4 on laboratory techniques for revealing the polycrystalline structure of ice has been rewritten with inclusions of more microphotographs to reveal fine features of ice microstructure. Chapter 6 on major field expeditions has been expanded to include information on international expeditions rather than focusing on Canadian field programs. In some sections of the ice physics part the presentation has been made more detailed and coherent to clarify new concepts. This includes entrapment of inclusions at subgrain boundaries and the etching and replica techniques that reveal microdetails of sea ice crystallographic structure.

Chapters 7 to 11 constitute the remote sensing part of the book. They are devoted to remote sensing basic principles, platforms, and most importantly retrieval of ice and snow parameters from active and passive imaging sensors, with emphasis on microwave systems. New material is introduced in this part to capture advancements in new satellite sensor technologies and analysis methods. Chapter 8 is a new chapter that covers the suite of satellite sensors most useful for sea ice and snow monitoring. Chapter 12 is another new chapter (written by Rasmus Tonboe), which covers radiative transfer approaches in modeling microwave emission and scattering from snow-covered sea ice. Chapter 13 (the third new chapter) addresses key differences between the responses of sea ice to climate change in the two polar regions, with links to their different geographic and environmental factors.

Mohammed Shokr and Nirmal K. Sinha
22 December 2022

ACKNOWLEDGMENTS AND RECOGNITIONS

When the first author started his collaboration with the Canadian Ice Service (CIS) in 1988 as a scientist employed by then Environment Canada (now Environment and Climate Change Canada), the staff was very supportive and welcoming of his input in processing the remote sensing images of sea ice. More importantly, they granted him opportunities to learn about the operational ice monitoring program. Part of the learning process was participation in a "round robin" reconnaissance flight, which was an annual series of flights to generate single span shots of ice conditions across the eastern section of the Arctic. That was the author's first observation of sea ice, though from some 10,000 feet above the surface. Shortly after, the author was involved for many years in field work on the Arctic and Labrador Sea ice to sample and measure ice and snow properties and crystalline structure. He would like to express his deepest appreciation to members of the CIS team who supported his efforts to develop knowledge about sea ice operational aspects: John Falkingham, Bruce Ramsay, Terry Mullane, Mike Manore, Dean Flett, Matt Arkett, and Dr. Roger De Abreu. Ken Asmus offered great help in field and laboratory experiments. The author would also like to express his sincere thanks to the team of scientists and support staff who supported his work during several field expeditions. The generous support of many individuals led the author to develop not only knowledge but passion for sea ice and the cold region environment. For that, he would like to acknowledge the support of the Late Dr. David Barber of the University of Manitoba, and extend thanks to Dr. Simon Prinsenberg of the Department of Fisheries and Ocean Canada, Drs. Garry Timco and Michelle Johnston of the National Research Council of Canada and all members of the field expeditions with whom he shared work and experience during the decade of the 1990s. Dr. Venkata Neralla and Mr. Roop Lalbeharry of Environment Canada inspired the first author to complete this book. Dr. Shawn Turner of Environment Canada reviewed parts of the remote sensing material and Dr. Walter Meier of the National Snow and Ice Data Center (NSIDC, USA) kindly reviewed Chapter 13 of this edition.

The second author would like to convey his sincere appreciation to innumerable persons who helped him in the field and to recognize the financial, technical, and strategic supports provided by several Canadian and International organizations since 1975. George Hobson, Director of Polar Continental Shelf Project (PCSP) in Canada from 1972 until 1988, provided moral, financial and strategic support to the author for almost ten years (1977–1986). This allowed him to train an Inuit Team on carrying out the year-round investigations on growth, structure, and engineering properties of sea ice at Eclipse Sound near Pond Inlet in Baffin Island. Special thanks are due to Mr. M. Komangapik, Mr. S. Koonark, and Mr. S. Koonoo for their efforts in collecting scientific data in the harsh climatic conditions of the Arctic and to Ms. D. Komangapic, Ms. S. Akoomalik, and Ms. J. Arnakallak for performing tedious measurements in the Pond Inlet field laboratory and tabulating the results, and to Ms. I. Kilukishak and Mr. M. Komangapik for laboratory assistance in Mould Bay. The author also wishes to express his sincere thanks to Mr. Hermann A.R. Steltnar and his wife Mrs. Sophie Steltnar of Arctic Research Establishment (ARE) at Pond Inlet, for organizing and managing the field activities of the Inuit team and compiling the field data.

For studies related to multi-year (MY) sea-ice rubble field at the "Hobson's Choice" Ice Island, the author is obligated to Mike Schmidt, the PCSP camp manager for providing all the logistical support and to Drs. Ed Stander and Paul Barrette, respectively, for their assistances in conducting the microstructural analysis of MY sea ice and Ward Hunt shelf ice. Drs. Lorne Gold, Robert (Bob) Frederking, Robert Gagnon, Garry Timco, Mohammed Sayed, and Mary Williams of NRC provided encouragements, guidance, and useful critical comments for more than three decades. In fact, Bob Frederking introduced the author to the world of sea-ice engineering. He led the author, literally by hand, to his first field experience at Strathcona Sound, Baffin Island during the extremely cold polar environmental conditions of 24-hours dark "polar nights" of November–December, 1975. Due to the unavailability of any remotely sensed images, the only view of sea ice the author had during this mission was whatever was visible under the illumination of headlights of trucks positioned on the newly constructed dock. The truck had to be turned to get different points of view. Ice cores were taken by suitably pointing the headlights to the spot for sampling.

Very special regards go to Dave Wright of the Institute for Research in Construction of NRC who actually taught the author the refined techniques of "hot-plate melting" for making near-perfect thin sections of "fresh-water ice", fabricating a small field polariscope with built-in light source and working with him during the first few, but crucial field trips in the High Arctic in 1976–1977. Ron Jerome of the same institute provided technical assistance in almost all phases of laboratory and field investigations. This included the design of the large-field polariscope, 100-mm-diameter "feather-weight" fiber-glass ice-core auger, the NRC borehole indentor (BHI) and the portable cold laboratory used at Pond Inlet, Resolute and on board of icebreakers. The author is indebted to Donald Martin and the staff of the National Capital Commission (NCC) of Ottawa for securing the entire Dow's Lake and providing technical assistance during the days of testing for the evaluation (and modifications) of these tools over several years, before they were taken to the Arctic.

During the Mould Bay experiments of 1981–1985, the following persons were involved and provided assistance to the author: Dr. Rene' O. Ramseier, Ken W. Asmus, Larry B. Solar, Doug Hagen, and David M., Susan Digby and Dr. Chuck Livingstone of CCRS, EMR; David Lap and Catherine Bjerkelund; Drs. Tom Grenfell and Dr. Donald K. Perovich, and Arne Hanson. The author is also grateful to Drs. Michelle Johnston and Caizhao Zhan for their undivided attentions as PhD candidates during the many years of field experiments.

On the subject of extending the double microtoming technique, originally developed for sea ice to investigate the microstructural aspects of snow morphology, the author is thankful to Dr. Pramod Satyawali and Maj. Gen. Satya Sharma of Snow and Avalanche Study Establishment (SASE), India. He is also indebted to Dr. Alex Klein-Paste of the Norwegian University of Science and Technology (NTNU), Trondheim and Mr. Armann Norheim of the Norwegian Civil Aviation (AVNR), Oslo for refining the methods and applying to snow on runways.

Vance Garbowski and Howard Massecar, helicopter pilot of Vancouver-based Quasar provided field supports in Mould Bay and Baffin Bay. The author is indebted to Howard for rescuing and saving his life, on 22 June 1984, in northern Baffin Bay during a tsunami storm that shattered the 1.5-m-thick sea ice sheet and forced the author, David Lapp, and an Inuit polar-bear watcher to take shelter on a bergy bit. Otherwise, the tales of this author with respects to the human aspects of Arctic research would not have been told in this book.

Mohammed Shokr
Nirmal K. Sinha
December 2022

1

Introduction

1.1. BACKGROUND

Our world is divided into five regions according to the position of the sun throughout the year: a tropical region around the equator, two temperate regions, and two polar regions. On two equinoxes, 21 March and 23 September, the sun is directly over the equator and the sun's rays reach both the North and South poles. On 21 June (the Summer Solstice), the sun is directly over the Tropic of Cancer (about 23.5° N) in the northern temperate region, and on 22 December (the Winter Solstice) it is positioned directly over the Tropic of Capricorn (about 23.5° S) in the southern temperate region. In the two polar regions, mostly relevant to the material in this book, the sun never sets in their summer and never rises in their winter. The Arctic region (or zone) containing the North polar region (with latitudes greater than "about" 66.5° N) and the Antarctic region (or zone) containing the South polar region (having latitudes greater than "about" 66.5° S) are the primary cryospheric regions of the world. The 66.5° angle comes from the tilt of the earth's rotation axis (23.5°), such that 90° – 23.5° = 66.5°. Recall that cryosphere comprises all regions where water exists in solid form.

Although the latitudes of the Arctic and Antarctic circles depend on the earth's axial tilt, which fluctuates slightly with time (about 2° over a 40,000-year period), the variations in the boundaries of the polar region are very small and negligible. The secondary cryospheric regions include the Alps, Andes, Himalayas, Rockies, etc. Among the secondary cryospheric regions, the Himalayan belt covers and affects the largest effective area of human habitation.

Climate change has been affecting all the cryospheric regions of the world, and the effects can be directly observed and quantified using airborne and space-borne remote sensing as well as land-based instruments. Remotely sensed images of the land- and ocean-based snow and ice information are paramount in understanding the state of health of the earth for sustainability of life. Other methods such as ice core analysis of ice caps and ice shelves, composed mainly of snow in different phases, are also used. After all, snow is the messenger of the sky, and ice is the answer to the cold climate.

Sea ice covers most of the oceanic surface of the primary cryospheric area of the global surface. While not noticeable by the majority of the population of our planet, sea ice observations provide a powerful tool for quantifying climate change and the health of our only home. The world of sea ice encompasses the polar region, particularly the Arctic basin and a belt around the continent of Antarctica. Out of the 71% of the earth's surface that is covered by ocean, about 7%–15% is covered by sea ice at certain times

Sea Ice: Physics and Remote Sensing, Second Edition. Mohammed Shokr and Nirmal K. Sinha.

(more in the winter and less in the summer). That is equivalent to 5%–10% of the earth's surface. About 37% of the total oceanic surface is covered by sea ice at one time or another. Sea ice area in the Arctic varies between a minimum of about 4 million km^2 in September to a maximum of about 15 km^2 in March. The corresponding figures for the Antarctic are 3 million and 18 million km^2 in February and September, respectively. However, the maximum volume of the sea ice cover in the Arctic (about 0.05 million km^3) is nearly twice the maximum volume in the Antarctic. This is because the mean thickness of sea ice is 3 m and 1.5 m in the Arctic and Antarctic, respectively.

Sea ice can develop very smooth or very rough surfaces. It can be soft or hard, a bare-surface or snow-covered, stagnant (fastened to the shoreline) or mobile pack ice, stiff and silent or crushing with loud noise. It exhibits seasonal variations to which life in the polar regions is closely adapted. In the Arctic region, sea ice starts its growth in September/October and reaches its maximum in February/March, when it covers the entire Arctic basin. This trend is reversed during the summer, and the ice extent reaches its minimum in September. In the Antarctic, the annual fluctuations range between a minimum in February to a maximum in August/September, when ice extends to latitudes between 55°–65° South.

For a limited time during the summer months, certain areas of the polar waters in the Arctic zone are used extensively by ships (ice-strengthened or escorted by icebreakers) where the floating bodies of new and old sea ice and icebergs can prove hazardous. The expected reduction of sea ice extent, the reduction of the navigationally hazardous old ice, and the increase in the duration of summer melting season will certainly increase marine activities in these areas. No doubt, the Arctic waters, particularly the legendary Northwest Passage (NWP) that passes through the Canadian Arctic Archipelago (CAA) and the Beaufort Sea, will be used more in the future for shipping goods between Asia, North America, and Europe.

Sea ice extent in both the Arctic and Antarctic averages the same, about 15 million km^2, during winter. However, because the mean thickness of sea ice in the Arctic is larger, the maximum volume of sea ice cover in the Arctic (about 0.045 million km^3) is nearly twice that of the Antarctic. In summer, ice extent shrinks significantly to about 50% of the winter coverage in the Arctic. Nearly 90% of the sea ice coverage disappears by the end of the summer in the Antarctic. Ice that melts completely during the summer is called "seasonal ice" or "annual ice." If the ice melts only partially, then the part that survives until the next winter and growth season is called "perennial ice." This can be second-year ice (SYI) or multi-year ice (MYI), depending on how many summers the ice has survived.

As a major component of the cryosphere, sea ice influences the global ocean and atmosphere in a profound manner. Its continuous interaction with the underlying oceans and the overlaying atmosphere leaves major impacts on weather, climate, and ocean current systems. Moreover, ice in one form or the other plays a significant role in the daily life of communities inhabiting the cold regions of the earth. Sea ice in particular influences the coastal areas in most of the circumpolar nations of the Northern Hemisphere. It affects, to a lesser extent, a few countries in the Southern Hemisphere. Of all the countries of the world, Canada has the longest coastline as well as the largest reservoir of fresh-water lakes and rivers with floating ice in them annually at least for half of the year. Except for Alaska, practically all the areas north of the 49° N in North America belong to Canada. While sea ice plays a major role in areas above 60° (north or south), it does not affect areas below that latitude except in the Hudson Bay, Labrador Sea, and the Gulf of St. Lawrence in Canada, and relatively speaking, to a lesser extent in the Baltic Sea, Gulfs of Bothnia and Fin in Europe, the Sea of Okhotsk, north of Japan, and Bohai Bay in China. Above about 35° N in Eurasia and North America, most of the streams, rivers, and lakes (e.g., Black Sea, Sea of Azo, Caspian Sea in Eurasia, and the Great Lakes in North America, to name a few among thousands) have some ice cover each winter. In fact, severity of winters in North America is often measured in terms of ice coverage of the five Great Lakes (Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario).

In spite of the fact that sea ice covers vast areas of sea surface of the earth, most of the people of the primary cryospheric regions of the world have not seen it or are even aware of it. That is because most people, even within the cold regions of the earth, live far from the areas affected by sea ice. Other than a few thousand multinational scientific observers and a few annual visitors, nobody lives in the South Polar Zone (beyond the Antarctic Circle). Only a few small communities of the Falkland Islands and Argentina consider the Antarctic region their home. On the other hand, beyond the Arctic Circle in circumpolar areas of Alaska, Canada, Norway, and Russia, perhaps a few million people live. This is incomparable to the nearly 3200 million people living in Afghanistan, Bangladesh, China, India, Nepal, Pakistan, and Tibet, who are indirectly affected by the Himalayan cryosphere, but sea ice does not exist in those regions.

It is not uncommon for people who live away from the circumpolar boundaries to be confused between sea ice and icebergs. Yet, general awareness about sea ice has been growing as public information about the decline of sea ice in the Arctic with its positive economic impacts and negative environmental impacts is spreading. This book, though not oriented to serve as a popular science document, provides scientific information with explanations that may hopefully expand the domain of interest in sea ice and attract a number of young scientists to pursue studies about its physical aspects as well as its detection using space-borne remote sensing technologies.

The Arctic Basin consists of primarily the Canadian and the Eurasian subbasins (for details on these two basins, see Chapter 3 in *Weeks*, 2010). It is extremely difficult to obtain extensive sea ice data in these areas because of the remote locations and extreme climatic conditions in which ice exists. Until the beginning of the twentieth century information about sea ice was mainly gathered and used by the local people who lived in the subarctic regions. Later, increasing information was obtained from ship sighting and harbor icing records, but the purpose remained to assist the very limited number of marine operations. However, since the end of World War II in 1945 and the beginning of the Cold War, there had been a significant increase in human activity in both the polar regions, and in particular the Arctic. Numerous weather stations equipped to gather scientific information and military bases with airports and radar lines were constructed in Canada, Alaska, and Greenland. Although some of the supplies for the construction and maintenance of these bases were transported by aircraft, ice-strengthened ships escorted by icebreakers were extensively used during the summer melt seasons. Submarines and buoys have also been used to gather data for sea ice in the Arctic Ocean.

Russia has a longer history of record on measurements of sea ice, dating back to several centuries. Russia (actually the Soviet Union) played an important role in increasing the awareness of the Arctic outside its boundaries. Scientific interest in Arctic sea ice grew fast during the Cold War era as nuclear submarines of the United States and Soviet Union used the Arctic Ocean basin as a prime area to launch ballistic missiles. Funds were made available by the United States for scientists to launch field studies in the Arctic for the first time in the 1950s. In fact, many US-based scientists together with their Canadian counterparts carried out their investigations on sea ice using facilities available in Canada. It is appropriate to mention here that the first English language book on physics of ice that covers significant sections on sea ice was written in Montreal, Canada by *Pounder* [1965] and incidentally, the first comprehensive English language book on the physics of glaciers, the source of icebergs, was also written in Ottawa, Canada by *Paterson* [1969].

The number of field studies dedicated to sea ice measurements in the Arctic peaked in the 1980s and 1990s. The work was motivated by the use of the space-borne remote sensing, particularly radar sensors. There was a need for on-sight field observations and measurements of sea ice characteristics to validate interpretations of satellite images and support information retrieval from the images. The scope of field programs has broadened later as knowledge accumulated and more scientific questions have risen. Today, major scientific field campaigns in the Arctic are highly multidisciplinary, and a few campaigns used icebreaker platform frozen in the ice for a few months or full year to study the ice and snow seasonal cycle. This has become a more efficient way to collect a wide range of data and link physical, biological, and meteorological aspects of the ocean-ice-atmosphere system.

It should be noted that field campaigns have produced wealth of information on now-covered sea ice but when the ice is thick enough to walk on safely. Ice thinner than 15 cm is not safe to sample while walking on, although this ice is probably the most important for weather and climate studies. It instigates the strongest interaction between the warm ocean and cold atmosphere in winter. The photograph in Figure 1.1 shows the procedure of cutting a sample of thin ice (about 50 mm thick) using a gangway descending from an icebreaker while the operator is attached to a harness. The ice surface appears to be covered with frost flowers. Obviously, information was lost during this sampling process due to brine drainage from the sample. Only crystallographic information could be preserved. Usually, thin ice can be studied in

Figure 1.1 Sampling of 0.05 m thick sea ice in the Baffin Bay in May 1998 by the author (Shokr) using a gangway lowered from an icebreaker (photo by K. Asmus, Canadian Ice Service).

facilities of outdoor laboratories, such as the one at the Cold Region Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, USA, or University of Manitoba, Winnipeg, Canada.

By mid-1990s (after the end of the Cold War), interest in Arctic sea ice shifted from being military-, security-, or offshore-industry-driven to being environmentally-driven. New concerns for the region are now comprised of issues such as environmental conservation, including nuclear waste and other pollution issues, protecting the livelihood of the Arctic's inhabitants and species, and most importantly identifying sea ice as an indicator and result of climate change. As a result of Arctic sea ice being a strong indicator of climate change, its monitoring has triggered an increase in funds by many countries to conduct more research. The Arctic basin connects the Atlantic and Pacific oceans. Therefore, if the ice diminishes or is replaced by thinner (navigable) ice, marine navigation routes (Northwest or Northeast passage) may open. This potential scenario will have a great positive economic impact on Canada, Russia and all countries that will use these navigation routes.

Antarctica is the land of glaciers and ice shelves from which icebergs calve and float within the surrounding sea ice. In fact, sea ice around Antarctica is home for numerous icebergs. Antarctic sea ice has not responded to the recent episode of climate change as much as the Arctic ice has. Nevertheless, the region has received attention lately because of the impact of climate change on glaciers and ice shelves. This impact has been manifested in the increasing number of icebergs calving from ice shelves. While numerous small icebergs have calved (and will continue to calve in the future), the number of major icebergs has also increased. The largest iceberg had recently calved from the Ross Ice Shelf in 2000. It was 295 km long and 37 km wide, larger than many small countries of the world. Mutual interaction between icebergs and the surrounding sea ice is the most important impact of climate change on Antarctic sea ice (section 13.4.2.3).

Snow cover plays an important role in the thermodynamic evolution of sea ice. Although it accounts roughly for only 10% of snow/ice volume, its properties differ sharply from their equivalent properties of sea ice. Two familiar examples are the albedo and thermal conductivity. The albedo of dry snow is above 0.9, which is much higher than the albedo of bare first-year sea ice surface (about 0.52). Increased albedo allows less sunlight to penetrate the surface. Therefore, snow-covered ice and the underlying seawater receive less sunlight. Equally important, the thermal conductivity of the snow is one order of magnitude less than that of sea ice. This means that snow can thermally insulate sea ice and slow down its growth. The above two factors cause a delay of sea icer melting in the spring in spite of the increase in air temperature.

Sea ice-related information is rather scattered over vast areas of interdisciplinary study fields (e.g., physics, chemistry, materials science, remote sensing, climate, oceanography, cryosphere, marine structure and operation, marine biology, and, not the least, civil, mechanical, and naval engineering, related to coastal and offshore engineering). Publications related to the physics and remote sensing are also scattered and not limited to the English language. When written in languages other than English, they obviously become not readily available. Some of the familiar books that address physics and geophysics related to sea ice are *Pounder* [1965], *Paterson* [1969], *Untersteiner* [1986], *Wettlaufer, Fasj and Untersteiner* [1999], *Petrich and Eicken* [2009], and *Thomas* [2017]. A comprehensive description of sea ice physics in addition to a historical background of the Arctic and Antarctic regions explorations is presented in *Weeks* [2010]. Books that cover remote sensing of sea ice with some coverage on sea ice physics include *Hall and Martinec* [1985], *Haykin et al.* [1994], *Carsey* [1998], *Jefferies* [1998], *Jackson and Apel* [2004], *Sandven and Johannessen* [2006], *Reese* [2006], *Johannessen et al.* [2007], *Comiso* [2010], and *Johannessen et al.* [2020]. A few notable review papers on remote sensing of sea ice include *Sandven* [2008], *Breivik et al.* [2010], *Kwok* [2010], *Meier et al.* [2011], and *Heygster et al.* [2012].

1.2. CANADA AND THE ARCTIC: HISTORICAL AND COMMUNITY SYNOPSIS

Except for small areas of persistent ice-free conditions, called polynyas, virtually all the northern oceanic areas of the second largest country in the world, Canada, freeze each winter. Historically, however, Canadian north is divided loosely to High Arctic and Low Arctic regions. The definition is based on various environmental and biological characteristics. Tundra is most common in the Low Arctic while polar barrens dominate the High Arctic. In Canada, the High Arctic is marked approximately by a circle parallel to the latitude of about 72°N and spans between the longitudes of 75°W and 125°W, and consists of numerous islands within the CAA. These islands are separated from those of the Low Arctic by a few connected sea waterways: Lancaster Sound, Barrow Strait, Melville Sound, and McClure Strait (Figure 1.2). These are hostile waterways for human activities because of the mobile pack ice in many areas. In general, the High Arctic used to be the "no-man's territory" until about 1958; but its vast area was traveled by explorers from Europe, particularly Norway, only during the late nineteenth and early twentieth century.

Naturally, the Inuit communities of the polar region of Canada concentrated their movements in the Low

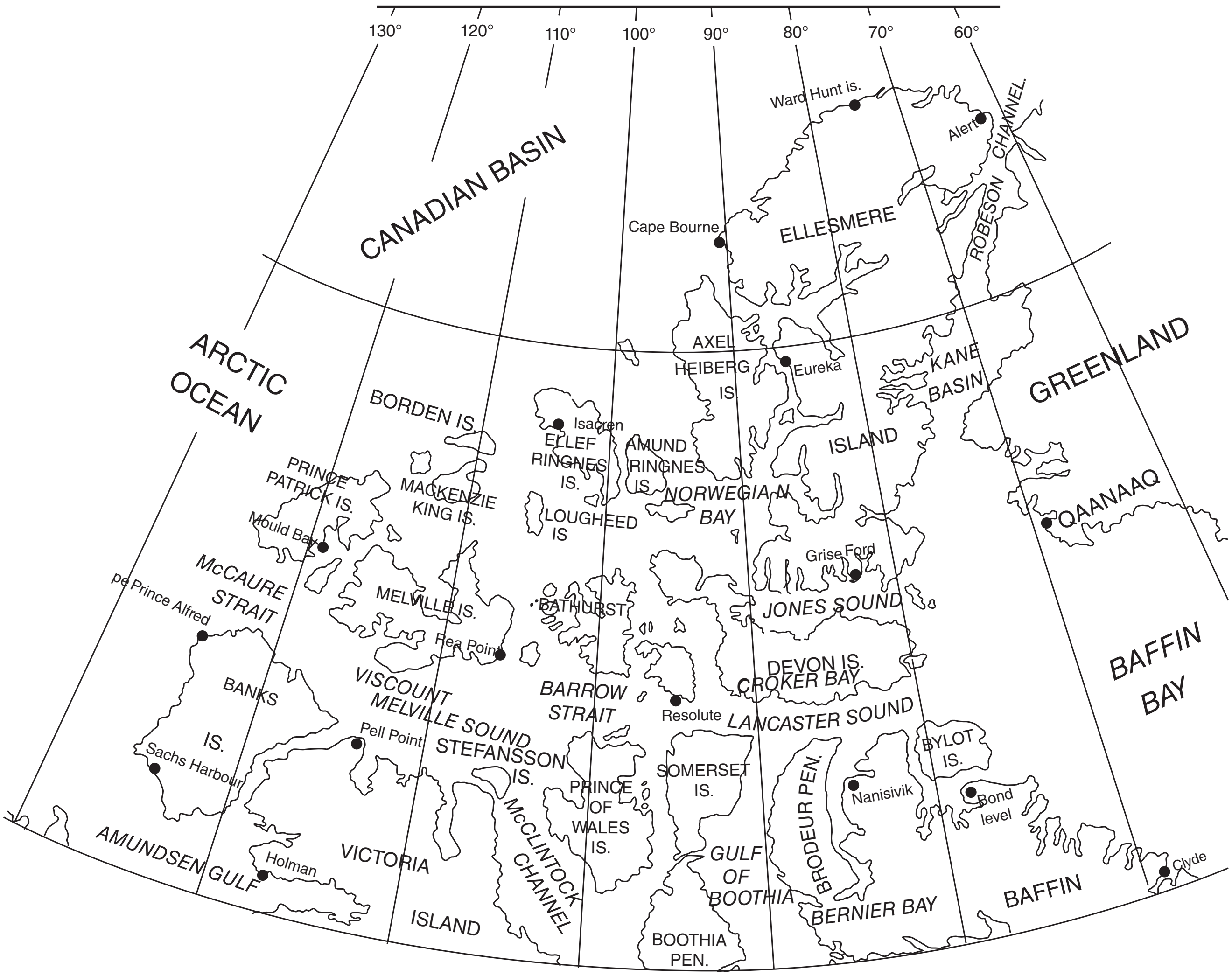

Figure 1.2 Map of the Canadian Arctic Archipelago showing locations of major islands and the weather stations (operational and decommissioned) operated by Environment and Climate Change, Canada.

Arctic region, particularly the Lancaster Sound and southern areas. The present-day settlements of Resolute Bay (74.72°N, 94.97°W) and Grise Fiord (76.42°N, 82.90°W), shown in Figure 1.2, were established by the federal government of Canada in late 1950s to move Inuit communities to live in the High Arctic, but did not succeed as planned. Even today, the Inuit communities of the newly formed territory of Nunavut prefer to live primarily in the Low Arctic. Nunavut was created to join the 10 provinces and two other territories of Canada on 1 April 1999. Before that it was part of the Northwest Territories.

Historically speaking, the islands of the High Arctic remained isolated from human activities, except for the explorers and the adventurers, until the unrest in Europe spilled over to the north Atlantic. World War II changed the situation significantly. Interest in the Arctic as a strategic and possible economic region was boosted, but even then, the climatological observations from the Canadian Arctic were scanty and inadequate for any meaningful analysis. Some geophysical and meteorological data were collected by the explorers and some useful data could be extracted from records kept by expeditions that attempted to find the NWP. These observations were, however, inadequate for accurate climatological studies because information was collected on an opportunity basis over short periods. The records rarely extended over a period longer than a year. Moreover, the observations made at different localities often were made in different years. The results were not comparable because of the absence of continuity in the mode of data collection.

The advent of the Cold War shortly after the end of World War II, led to the creation of strong interests in Canada and particularly in the United States for the establishment of a network of Arctic Stations. There was a general recognition that the weather in both Canada and the United States is dominated to a large extent by the Arctic air masses. Accurate forecasting in these two countries requires detailed knowledge of the weather pattern of the polar region. Consequently, it was realized that observations from the Canadian Arctic would increase knowledge of the circulation of the earth's atmosphere and permit an extension of the period of reliability of weather forecasts. It was emphasized that year-round observation stations have to be established for carrying out regular observational programs directly linked with the investigation of Arctic meteorological problems.

On 12 February 1946, the United States Congress approved the Arctic Project and eventually a suitable basis of cooperation between the governments of Canada and the United States was developed for the Canadian High Arctic. These two countries reached a working agreement on 27 February 1947, for the establishment and operation of five weather stations in the Canadian High Arctic. This agreement was originally made for a period of five years. Consequently, five strategically placed permanent weather stations were built on islands within the Canadian Archipelago. These stations included Alert and Eureka on Ellesmere Island, Isachsen on Ellef Rignes Island, Mould Bay on Prince Patrick Island, and Resolute on Cornwallis Island (see locations in Figure 1.2). Following the first five years of project, subsequent agreements affirmed that these five stations should continue to be operated jointly by Canada and the United States in accordance with the specifications agreed to at the Joint Arctic Weather Stations Conference, which was held annually. According to this agreement the Atmospheric Environment Services (AES) of Canada (now Meteorological Service of Canada–MSC), part of Environment and Climate Change Canada (ECCC), provided all permanent installations and approximately half the staff, including an officer in charge who was responsible for the overall operation of the station.

The advancements in rocketry led to the dawn of the space race and made the world smaller and more easily accessible. A sudden thrust in the space race was imposed by the successful launching of the Soviet Union's satellite "Sputnik" in October, 1957 and directly forced and indirectly enhanced interests in the north polar zone. The launching of the first man-made satellite suddenly proved the world to be small and the polar regions within reach, but more importantly, levied a need for obtaining an in-depth knowledge of the terrain in the north beyond the Arctic Circle—the High Arctic and the Canadian Basin. In 1958, the United States lost the race for launching the first man-made satellite, but succeeded in completing the much-publicized first underwater crossing of the Arctic Ocean using the submarine *Nautilus*. Although the Soviet Union (USSR) was prying the oceans with their fleet of nuclear submarines, no claim was made about any under-ice activities around the geographic North Pole by the USSR.

In a very direct manner, the under-ice activities and the space race forced Canada to increase the awareness of the Canadian Arctic Island and implement new measures to strengthen the Canadian sovereignty in all these islands of the High Arctic. This led to the establishment of two permanent human (Inuit) settlements, as mentioned earlier, Resolute at 74.72°N and Grise Fiord at 76.42°N. The United Nations Conference in 1958 on the Law of the Sea, which extended the resource and exploration rights of maritime nations on their continental shelves to a depth of 200 m, acted as the catalyst for Canada for undertaking multidisciplinary scientific exploration of the north. Consequently, the Canadian Government established the Polar Continental Shelf Project (PCSP) under the ministry of Energy Mines and Resources or EMR (recently renamed as Natural Resources Canada or NRCan) in 1958. The most important aspects were the geophysical mapping of the High Arctic—areas of the land and the ocean (Figure 1.2) stretching from Alaska to Greenland and from the Arctic Circle to the North Pole. The important field of investigations included recording the magnetic and gravitational data required for the space program.

Nonetheless, the Canadian Government decided not to invest heavily in building up its armed forces for the purpose of maintaining Canadian presence all over the Canadian High Arctic. Instead of sending armed forces personnel to the High Arctic, Canada always used a pool of scientists and experienced field workers. Since then, the Canadian sovereignty of the High Arctic is essentially maintained by the labor of love of Canadian scientists (as well as their scientific collaborators from other countries). The birth of the new territory of Nunavut in 1999, ranging from mountains and fiords on the eastern shores of Baffin and Ellesmere islands, through the lakes and tundra of the Barrens on the mainland, to the plateaus and cliffs of the Arctic coast, is changing the course of history of the Canadian Arctic.

Since 1959, the PCSP (Polar Shelf for short) with permanent base camps (shelters or shacks with rudimentary facilities) at Resolute on Cornwallis Island and Tuktoyaktuk in the Mackenzie Delta provided logistic support services to the scientists. This organization provides room and board (actually excellent nourishing food for the body and the soul) at the base camps, supplies land vehicles designed for all types of terrain, special field equipment, and responds to the Arctic fieldworker's greatest expense and concern: safe, efficient air transport (helicopters and aircrafts), and an excellent radio communications

Table 1.1 Weather stations in the Canadian Arctic region (currently operational or decommissioned).

Weather station	Latitude °N	Longitude °W	Start	End	Territory
Alert	82.522	62.285	1913	Cont.	Nunavut
Eureka	79.983	85.933	1947	Cont.	Nunavut
Isachsen	78.783	103.533	1948	1978	Nunavut
Grise Fiord	74.417	82.950	1973	1977	Nunavut
Mould Bay	76.233	119.333	1948	1997	NWT
Resolute	74.717	94.970	1947	Cont.	Nunavut
Nanisivik	72.983	−84.617	1976	2011	Nunavut
Pond Inlet	72.682	−77.969	1975	Cont.	Nunavut
Sachs Harbour	72.000	−125.267	1955	Cont.	NWT
Holman	70.733	−117.783	1941	1969	NWT
Clyde	70.486	−68.517	1933	Cont.	Nunavut

network. Civilian research scientists and engineers of Canada, of wide-ranging disciplines, played and keep playing the most significant roles in advancing polar science and crucial roles in flying the nation's flag in the High Arctic, the Canadian Basin. and the Arctic Ocean since 1959.

The weather stations in the Arctic region (most of them are in the High Arctic) are listed in Table 1.1. These stations were established by the Canadian Government and some were operated jointly with the US military. Only six stations are currently operational (out of about 900 stations operated by the MSC across Canada): Eureka, Alert, Resolute Bay, Pond Inlet, Sachs Harbour, and Clyde. The locations of all stations are marked in Figure 1.2. When all stations were operational, they formed a network for providing weather services which was considerably significant by the Arctic standards. A detailed historical account of development and expansion of meteorological facilities in the Arctic is given by *Smith* [2009].

Sea ice, in one form or the other plays a significant role in the daily life of communities inhabiting the cold regions of the world. The presence of ice in the seas is a welcoming sight for the people of the northern Canada, the Inuit. Those are indigenous people with common culture and language inhibiting the Arctic and subarctic regions of Canada, Greenland as well as Alaska. Actually, the people from the Baffin Island migrated and settled in Greenland, and share the same cultural aspects of the northern communities in Canada. The town of Qaanaaq (77.49°N, 69.38°W), also known as Thule or New Thule, is the northernmost permanent human settlement in the world, located in northwestern Greenland. For its population of nearly 650, like the other communities of the Low Arctic of Canada, the sea ice is home. Inuit communities have developed many stories, myths, and profound knowledge about sea ice.

Prior to the onset of outside pressures in 1960, life in the north continued both on land and the ice depending on the season. Inuit used to have temporary villages of igloos on the ice. Children were born on the ice. People would live and travel on the ice, albeit slowly, without the fast-moving snowmobiles introduced in the 1970s. Consequently, the Inuit had developed some "age-based" terminologies for sea ice types (some are introduced in the next section). In short, the frozen seas have always been a very welcome feature and still are, as can be felt from Figure 1.3. A child in Qaanaaq showed the co-author of this book (Sinha) a symbolic gesture of working together (Figure 1.4).

Figure 1.3 Using discarded sea ice samples from N.K. Sinha (after bending strength tests), the children of Qaanaaq, Greenland, posed proudly to show off one of their creations—an Inuit sculpture or "inukshuk" (photo of N.K. Sinha, from National Research Council Canada, Publication, *Sphere*, No. 4, 1994).

Hunting has been at the core of activities of the Inuit communities for generations. They hunt seals, caribou, musk-ox, and polar bears among other animals. Polar bear hunting used to be a major economic activity before it was regulated to save this species. It is still practiced though under strict regulations (quota proportional to the local bear population). In fact, the Canadian Arctic

Figure 1.4 Qaanaaq child proudly proving practical use of a core-hole and a sense of sharing (photographed by N.K. Sinha, March 1994).

Figure 1.5 Drying polar bear skin in the village of Resolute Bay in the Canadian Arctic. The picture was taken in May 1995 (photo by M. Shokr).

is one of the most successful areas for bear hunting. Inuit use polar bear meat as a source of protein, vitamin A, and iron; and bear skin to make warm clothes and blankets. Bear hunting involves scanning a wide expanse of ice on a dog sled and once a polar bear is spotted, the hunter releases the dogs to corner the bear, and then kill it with a harpoon. Figure 1.5 shows a polar bear skin drying in the sun in Resolute Village, Canadian Arctic.

In spite of the significant changes in the life of the Inuit communities in the last fifty years, day-to-day life is still intertwined with sea ice. However, with the advent of microwave communications systems, television signals reached the people of the north during the middle of the seventies. Saturdays became the days of the "Hockey-night of Canada" popularized by the Canadian Broadcasting Corporation (CBC). In early days of his research, based at Pond Inlet, the co-author (Sinha) found it impossible to get anybody to assist him on the ice during the days of hockey-nights. In fact, they would invite him to spend the time with them, share their food, hear their stories, and learn the intricacies of handling pucks on the ice. It is extremely important, therefore, for sea ice scientists and engineers, to work together with the local people of the north and share information and experience.

The Government of Canada allocates millions of dollars through programs to support and develop the indigenous communities in the Arctic region. Projects include tasks to mitigate impacts of climate change, maintain clean air and water, and warrant healthy environment. The government acknowledged the people of the north by issuing a series of stamps on the Arctic, of which a sample is shown in Figure 1.6. In Canada, those communities are called First Nations and now they have more say in their affairs.

1.3. THE FASCINATING NATURE OF SEA ICE

Most people living in cold countries, where snow and ice are part of the most familiar of natural phenomena, do not think much of scientific importance of these natural materials. We never realize that the solid state of water, in all of its forms, is actually a unique and the most fascinating natural crystalline material. Floating sea ice, in particular, is a very complex material. It features four readily noticeable and interesting characteristics. First, it is a composite material that encompasses three phases of matter: solid, liquid, and gaseous, depending upon temperature. Second, it exists in nature at temperatures very close to its melting point. In fact, the ice–water interface at the bottom of floating ice covers is always at the melting point. Third, it floats simply because it has lower density than the density of its melt (i.e., the liquid from which it solidifies). Moreover, snow deposits on floating ice sheets add to the complexities of the ice regime. Fourth and certainly the most important aspect of floating ice covers (both freshwater and sea ice) is the fact that they act like blankets and protect marine life in lakes, rivers, and oceans.

Figure 1.6 First-day cover issued by Canada Post in 1995 featuring a series of stamps on the Arctic and a photograph by N.K. Sinha (National Archive Canada No. C-24520) of NRC borehole indenter system (measuring ice strength) on sea ice in Resolute Bay ("Canada 95," The Collection of 1995 Stamps, published by Canada Post Corporation, pp. 40–41).

The first two characteristics make floating ice highly responsive to changes in atmospheric temperature, especially when it is thin. Its physical and radiometric properties, as well as the properties of a possible overlaid snow cover, change in order to maintain a state of thermal equilibrium between the ice and the atmosphere. The third characteristic is responsible for the flotation of ice on its melt and therefore moving in response to wind and oceanic current unless it is shore fast (called "landfast") or becomes grounded in relatively shallow waters. When landfast ice is subjected to tidal actions, it produces cracks, "ice hinges" and rubbles parallel to the shorelines. Sea ice is considered to be the fastest global-scale solid material moving upon the earth's surface. Given the complex nature of sea ice composition, its thermal state, and mobility, it is important to understand the processes involved in its formation, growth, desalination and deformation as well as its decay. This should help to demystify the descriptions found in literature about ice, and sea ice in particular, as apparently peculiar, bewildering, confusing, puzzling, baffling, etc.

The heterogeneous and multiphase composition of sea ice arises because the salts and gases that dissolve in seawater cannot be incorporated into the lattice (polycrystalline) structure of sea ice. This structure is made up of pure ice crystals, leaving salts to be included within the interstices of the solid ice matrix in the form of liquid brine. Gases are also included in the form of gaseous bubbles. Other impurities such as microalgae, non-organic deposits, and trace elements may also exist. A characteristic process that follows from this multiphase composition is the brine drainage (which takes other impurities with it) into the underlying ocean water. This process takes place at a rate that depends on the ice permeability and temperature. It continues throughout the lifetime of the ice cover causing the bulk properties of the ice to be continuously changing.

Since ice exists in nature at temperatures of only a small fraction below its melting temperature. Therefore, from the geophysical and materials science point of view, it is considered to be a high-temperature material. High thermal state of ice in nature and related implications are