SEA ICE
An Introduction to its
PHYSICS, CHEMISTRY, BIOLOGY AND GEOLOGY

Edited by
David N. Thomas & Gerhard S. Dieckmann
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David N. Thomas* and Gerhard S. Dieckmann†

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Science
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An Introduction to its Physics, Chemistry, Biology and Geology

Edited by
David N. Thomas* and Gerhard S. Dieckmann†

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Dedication

This book is dedicated to all the ships’ crews, air support teams, field station/base crews and the myriad of other people associated with the logistic support that makes sea ice research possible. Beyond their help, however, our families and friends have had to come to terms with us being at the ends of the earth, often for long periods of time. In most cases they never get to experience, first hand, the wonders we have seen. It is only right that this book is dedicated to them.

And now there came both mist and snow,
    And it grew wondrous cold:
And ice, mast-high, came floating by,
    As green as emerald.

And through the drifts the snowy clits
    Did send a dismal sheen:
Nor shapes of men nor beasts we ken,
    The ice was all between.

The ice was here, the ice was there,
    The ice was all around:
It cracked and growled, and roared and howled,
    Like noises in a swound!

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Foreword

G.E. (Tony) Fogg

Almost everything discussed in this book stems from the unique nature of water. Whereas comparable compounds are gases at what we regard as normal temperatures, water is a liquid, with a greater heat capacity than almost all other substances and which, on solidifying, unlike most other fluids, becomes a solid lighter than itself. Laboratory scientists have explained these peculiarities, but the all-pervading complexities to which they give rise in the natural environment are still insufficiently investigated and understood. These complexities are especially evident in sea ice and their study is becoming increasingly important. Sea ice covers some 7% of our planet and knowledge of its distribution and behaviour is needed for the purely practical purposes of navigation but, beyond that, as we now begin to realize, sea ice acts as an extremely powerful heat engine, controlling global temperatures at levels which make life sustainable.

Sea ice also provides a habitat for living organisms which, in spite of apparently extreme conditions, play an important part in the ecosystems of the polar seas. In studying these things tremendous difficulties have to be faced in making observations under natural conditions and progress has been slow. However, problems are being overcome and knowledge advances. In the past, seafarers, although not altogether unmindful of the beauties of form and colour in sea ice, generally looked on it as exasperatingly unpredictable – Captain William Parry wrote in 1819 of its ‘whimsicalities’ – formidable in its destructive power, but unproductive and uninteresting in itself. Only a few thought it worth studying. James Cook, on his voyage in Antarctic waters in 1772–75, discussed the origin of sea ice with his naturalist J.R. Forster but, obviously, could not make detailed observations (Hoare, 1982). The most comprehensive account from around this time was that of the whaler William Scoresby in his paper on Greenland ice (1815). This dealt with kinds of ice, the differences between those of fresh and salt waters, their formation, distribution, movement and seasonal changes. The effects of ice movements on bird behaviour were noted, as were the relationships between ice, sea and atmosphere, and particularly the capacity of the ice as ‘a powerful equaliser of temperature’. Scoresby entertained his crew by fashioning lenses from clear sea ice and using them to light pipes and ignite gun-powder. Robert Hooke in the early days of the Royal Society had already demonstrated the transparency of freshwater ice to radiant heat – an
important point – and Chinese conjurers had similarly used ice burning glasses some fourteen centuries before that (Needham, 1962).

However, of all people in Scoresby’s time, the Inuit had the deepest understanding of sea ice. Since they migrated into the Canadian Arctic and Greenland some four thousand years before, they had travelled much on the ice and the ‘little ice age’ (ca. 1600–1850 AD) forced them to resort to hunting seals in the winter at breathing holes and leads, devising sophisticated techniques for pursuing their quarry at different seasons and under varying conditions of ice surface (Aporta, 2002). Obviously, such experience would have been invaluable in the polar explorations carried out in the 19th century but, for example, the British Royal Navy would have none of it and even Scoresby, being a whaler rather than a naval man, was not allowed to play a part.

During these times some advances were being made on the small-scale, mainly biological, level. Some of the early explorers in Antarctic waters, Bellinghausen in 1820 for example (Debenham, 1945), had commented on the discoloration of sea ice and surmised that dust from the land or droppings of seabirds were responsible. James Clark Ross, on his voyage south in 1839–43, was initially inclined to such a view but his assistant surgeon, Joseph Hooker, collected some of the material and found it to consist of the remains of microscopic organisms which the eminent German protozoologist C.G. Ehrenberg later identified as diatoms (Ross, 1847). The existence of microscopic plants in the open sea was unrecognized at that time but Hooker realized the abundance and importance of diatoms in ocean waters and thus provided the basis for biological oceanography. The significance of their presence in ice as well as in the ambient water was passed by. Fridtjof Nansen (1897) seems to have been the first to make serious studies of micro-organisms in sea ice. The fact that the same species of diatoms, quite different from those elsewhere, were to be found in ice from the Bering Strait and from the east coast of Greenland was used by him in formulating his theory of Arctic Ocean currents. However, progress remained slow. An idea, now abandoned, that water molecule polymers concentrated around thawing ice are particularly favourable for living organisms was put forward to explain the abundance of algae in ice by V. Lebedev (1959). Identification of sea ice diatoms was carried out by various authors but in situ investigations of sea ice communities did not develop until the work of J.S. Bunt (1963), using scuba diving in the Antarctic, and R.A. Horner and V. Alexander (1972), investigating heterotrophy in sea ice communities in the Arctic.

The necessity of gaining a better knowledge of sea ice distribution and movements became acute, both for navigation and geographical purposes, at the beginning of the 20th century. Studies of the geophysics of sea ice had been initiated by Nansen in his crossing of the Arctic Ocean but advances were slow and uneven. With sea ice extending some 160° of longitude to the north of them and with the possibilities of a north-east passage, the Russians in particular were quick to employ recently developed ice-breaking ships for both survey and scientific purposes. A succession of research vessels being beset in Antarctic ice, culminating in the
crushing and sinking of Shackleton’s ship *Endurance* in 1915, emphasized the need for much more information about the physical characteristics of sea ice. Following World War II, increased use of ice-breakers, the introduction of helicopters to place scientists and their equipment on ice, and an amazing proliferation of remote-sensing techniques have made it possible to get some of the information required.

Chapter 1 in this book, by Gerhard Dieckmann and Hartmut Hellmer, adds detail to this historical sketch. The chapter outlines a framework on which a coherent picture, basic and still with large gaps, of sea ice science may ultimately be built. The relationships between sea ice, ocean and atmosphere are clearly dominant but complicated in the extreme. There are different ice classes, thermodynamics which must allow for multiple layering, viscous-plastic rheology, snow cover, seawater flooding and the formation of superimposed ice, brine pockets and the biological activity they harbour, all coupled to circulation patterns of different degrees of complexity in both atmosphere and ocean. Then there are surprising differences, as well as similarities, between the sea ices of the Arctic and the Antarctic. Present information about these usually comes from spot localities, and extrapolation to large-scale processes can be problematic.

Sea ice phenomena extend over wide ranges of scale in time and space, and the question arises as to whether those at the microscopic end of the scale are of interest only to specialists or are of significance in the global context. This question is considered by Hajo Eicken in Chapter 2. Putting aside the hypothetical butterfly flapping its wings to annoy meteorologists, one can easily think of more likely possibilities in this complex system. The chance establishment of algal growth may, for example, cause considerable alterations in albedo over extensive ice surfaces. Eicken discusses the links between microstructure and behaviour of ice on the large scale, covering the growth, decay and heat budget of ice, simple models of sea ice growth, the physical chemistry of sea ice, solute segregation and ice microstructure, salinity evolution, thermal properties, dielectric and optical properties, and macroscopic ice strength (including advice on walking on thin ice). It becomes evident that small-scale processes do affect large-scale behaviour to a considerable extent.

The growth of sea ice is not a matter of thermodynamics alone. There is a mechanical aspect arising when winds and currents break up the initial cover and build up the fragments into pressure ridges. It is necessary to have a measure of ice thickness or, better, volume, as well as horizontal distribution in order to determine the effects of climate change. This matter is dealt with by Christian Haas in Chapter 3. Model, field, and remote-sensing studies are all required but have been rather limited. The satellite CryoSat, which employs a synthetic interferometric aperture radar altimeter, if ground validation proves it satisfactory, should provide a main source of information for the improvement of sea ice models. Approaching the problem from below, the British Autosub project has had some success in the Antarctic.

Sea ice as an insulator limits flow of heat between ocean and atmosphere and its high albedo results in reflection of solar radiation back into the atmosphere. Given
the vast extent and seasonal two-fold expansion in the Arctic and the reciprocal change of five-fold in the Antarctic, the geophysical impacts are enormous and fluctuating. Added to this, the formation and melting of ice bring about vertical redistribution of salt, which is a potent factor in ocean circulation and productivity. Especially if we are to get an idea of the trend of global warming we need to have reliable data on the variations of sea ice. Josefino Comiso reviews the situation in Chapter 4. Satellite data obtained over two decades show large seasonal fluctuations in ice extent which are inversely correlated with those in sea temperature. Large-scale trends in ice cover point to decline in the Arctic but to increase over most of Antarctica. Results so far have some statistical uncertainty and cyclic patterns have to be taken into account.

Primary production in sea ice has been dismissed in the past as making only a negligible contribution to the global total. Recent research, as summarized by Kevin Arrigo (Chapter 5), is still hampered by logistic restraints and lack of adequate techniques for measuring primary production in situ, but such data as have been obtained point to it being greater per unit area than has been thought, and one must not forget that it is one of the most extensive ecosystems on earth. Microprobes capable of non-invasive sampling of the different microhabitats in sea ice are desirable and numerical models can perhaps be used to suggest where information is most lacking.

The smudges of colour noticed in sea ice by the early explorers and eventually recognized as responsible for this primary production have proved to be more than accidental and more varied, active and complicated in organization than could have been supposed. In Chapter 6 Michael Lizotte points out that sea ice microbiology is just one beneficiary of the tremendous advances made in aquatic microbiology generally in recent years. Biochemical analysis, isotopic tracers, specific metabolic inhibitors, genetic analysis, advanced microscopy and micromanipulation are employed as well as helicopters, drills, and diving equipment. Apart from the algae responsible for the photosynthesis there are small invertebrates, protozoa, fungi, bacteria, archaeabacteria and viruses. Besides having to tolerate low temperatures these organisms are often cut off from the ambient environment, which may involve nutrient deficiency, and subject to abrupt osmotic stress. They may live in a rich organic soup in which the webs of transfer of metabolites and energy must be intertwined in a most complicated way. There is everything to be learned about the development and functioning of ecological relationships in the ice.

Small animals use sea ice for feeding, refuge and breeding, either as permanent residents or temporary visitors. Biogeography comes to the fore here, the difference between the Arctic, where rotifers and nematodes are most abundant, and the Antarctic, where copepods, euphausiids, and turbellarians are most prominent, being at the phylum rather than the species level. This is discussed by Sigrid Schnack-Schiel in Chapter 7. The life cycles of these animals are largely determined by the seasonal fluctuation of the ice, the behaviour of the Antarctic krill being of particular interest in relation to the food web of the Southern Ocean.
Ecophysiological investigations have not progressed far except that the survival mechanisms used by fish frequenting pack ice have been found to involve glyco-proteins as antifreeze agents.

Large air-breathing animals, the epifauna, are not dependent directly on sea ice as a source of food but may use it as a solid platform on which they can live and breed, and from which they can launch foraging forays into the water. Others, which as David Ainley, Cynthia Tynan and Ian Stirling point out in Chapter 8 include the human species, find it merely a barrier to getting at food or, at another level, carrying out exploration. Seals in both polar regions have rather the same general behaviour habits on and under sea ice but differ in minor respects. Polar bears in the north and emperor penguins in the south have fascinating and completely different adaptations to the rigorous conditions on the upper surface of the ice. Seasonal changes in sea ice, both in bulk and distribution, have ecological consequences for both mammals and seabirds, maybe producing species-specific alterations in demography, range and population size. These must be studied not only for purposes of both economic exploitation and conservation but as potentially sensitive indicators of long-term changes in climate or marine pollution.

One might think that sea ice can play no great part in marine geochemistry. Indeed this was so until recently, but when it was realized that sea ice is the site of considerable microbiological activity the situation changed. However, as David Thomas and Stathis Papadimitriou emphasize in Chapter 9, it is necessary to have a background of the abiotic changes in chemistry which take place when sea water freezes, in order to assess the biological activities. This is no easy matter but the large-scale ice tank facilities, such as have become available in Hamburg, will help greatly. A comprehensive view of what is known and what might be known with the aid of new techniques of the chemistry of a wide variety of substances is given in this chapter. Among them the occurrence of dimethyl sulphide in sea ice is of particular interest since this product of marine algae is involved in the formation of aerosol particles, providing cloud condensation nuclei which become important factors in localized and global climate control.

Chapter 10, by Amy Leventer, deals with particulate flux, both living and non-living, from sea ice. Downward transport of solid material plays an integral part in the cycling of carbon and silica in the oceans besides providing food for benthic organisms and contributing to the sedimentary record. Long-term monitoring with sediment traps could provide much information on the interannual variability of ecosystems. The release of living material by melting ice not only provides a source of food for pelagic grazers but potential inoculum for the seasonal growth of plankton. What happens at this stage, of course, will have a considerable impact on higher trophic levels. Another aspect is that particles from the atmosphere may be intercepted by sea ice, and it is an interesting possibility that these may contain iron, an essential but scarce trace element in phytoplankton growth, and so contribute to blooms at the ice edge.

Finally, in Chapter 11, Leanne Armand and Amy Leventer discuss the past
distribution of sea ice, an important matter for reconstructing past oceanic and climatic conditions. The evidence comes from the records extending over the Quaternary period provided by microfossils and geochemical and sedimentary tracers, including ice-rafted debris. Dinoflagellate cysts have played an important part in Arctic studies whereas in the Antarctic dependence is mainly on diatom distributions. Such information has to be combined with modern physical interaction studies between ice, ocean and atmosphere, involving complex statistical treatments. Sea ice conditions can now be reasonably incorporated in general circulation models predicting future climates but palaeontologically determined conditions have not yet been used in models to simulate past climates.

The chapters in this book are of necessity specialized. At one extreme the physicist, concerned with the thermodynamics or hydrodynamics of the ice itself, regards living organisms as of marginal importance. At the other extreme the biologist may study organisms in isolation. Nevertheless, sea ice functions as an integrated system. The physicist should remember that there is always a remote but real chance that the most elegant of mathematical models of ice movement can be put awry by seemingly trivial biological activity. A walrus, for example, may take it into its head to bash through 20 cm of ice at a critical spot. The biologist is more consciously aware that he needs information about the physical and chemical processes going on in the environment in which his organisms live but may not be sufficiently well informed.

However, in this book we have the different aspects linked together into a coherent picture. The incentives attracting ‘pure’ scientists to study sea ice are strong. For the physicist there is the challenge of overcoming technical problems, such as reconciling remote-sensing data with ground data and having the excitement of getting out into the field in order to do it, then constructing numerical models which can account elegantly for the ‘whimsical’ behaviour of sea ice. The biologist has the thrill of exploring a unique ecosystem which ranks in novelty with the astonishing communities found around hydrothermal vents in the deep ocean and in porous sandstone in the dry valleys of Antarctica.

Sea ice research also has its practical applications. These include the everyday tasks of charting sea ice for navigation and the management of fisheries. At present, though, the matter of global warming draws most attention, sea ice being a major component of the earth’s heat engine, the understanding of which is a necessary part of predicting what may happen in the near future. Related to this is the tracing of variations in climate in the past. Studies of sea ice microbiology can be of help in counteracting the effects of oil spills in Arctic waters or in finding micro-organisms active at low temperatures which may be used to avoid the expense of providing elevated temperatures in industrial processes. In a wider field, investigation of sea ice microhabitats may indicate what is to be expected in looking for life elsewhere in the solar system and what techniques should be used in detecting it. ‘There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy’ (William Shakespeare, 1603, Hamlet).
References

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Chapter 1

The Importance of Sea Ice: An Overview

Gerhard S. Dieckmann and Hartmut H. Hellmer

1.1 Introduction

Following the initial freezing of sea water, sea ice is profoundly modified by the interaction of physical, biological and chemical processes to form an extremely heterogeneous semi-solid matrix. Oceanic, atmospheric and continental inputs all serve to influence the formation, consolidation and subsequent melt when the ice returns to water. Probably the most important property of sea ice is that, despite it being solid, it is less dense than sea water and therefore floats.

During the course of a year, tremendous areal expanses of sea water in the Arctic, the Southern Ocean, and also in the Baltic and other seas such as the Caspian and Okhotsk, undergo a cycle of freezing and melting. In winter, sea ice covers an area of up to 7% of the earth’s surface, and as such is clearly one of the largest biomes on earth (Comiso, Chapter 4).

With the exception of the Inuit, who over several thousand years adapted to a life closely associated with Arctic sea ice, until the turn of the last century sea ice was simply a hostile environment and an obstruction to the navigation of sea routes and the hunting of birds and mammals (Fogg, 1992; Weeks, 1998). It is only during the past 200 years, and mostly within the past 100 years, that adventurous expeditions have visited the polar oceans and our understanding of the significance of sea ice in a global context has begun to develop.

Today we know that the annual cycle of sea ice formation and degradation not only plays a pivotal role in governing the world’s climate, but also influences processes in the oceans down to the abyss. The life cycles of marine plants and animals ranging from micro-organisms to whales, and even man, are also influenced by the large-scale cycles of ice formation. Sea ice is recognized as a fundamental component of system earth, which cannot be ignored in the large-scale environmental discussions and the predictions of future climate conditions.

Recently, disturbing headlines from the high latitudes regarding the effects of ozone holes, collapsing ice sheets and rising temperatures seem to indicate that rapid climate change is underway. The seeming inevitability of shrinking ice on the
Arctic Ocean, for instance, would infer a threat to the indigenous way of life of local human communities, hard times ahead for Arctic birds and mammals including the polar bears, and an ice-free Northwest Passage (Kerr, 2002; Smith et al., 2002). In the Antarctic, significant changes in the extent and distribution of sea ice cover are attributed to global climate warming. These changes are closely related to obvious ecological changes in krill and whale feeding, and have severely affected local seabird populations (Croxall et al., 2002).

Sea ice research spans many modern scientific disciplines including, among others, geophysics, glaciology, geology, chemistry, biogeochemistry and numerous branches of biology. Sea ice research is important for climate researchers and oceanographers interested in processes pertinent for the localized polar regions and also for global-scale climate and ocean processes. Present-day sea ice research ranges from molecular studies into the composition and structure of the ice itself, to that of the elements and the microorganisms living within the ice, through to scales many orders of magnitude greater up to the monitoring of ice cover from space (Plate 1.1).

Modern ice-breakers, as well stations on the peripheries of Antarctica or the Arctic, greatly facilitate access to sea ice, even during seasons when in the past ice and weather conditions prohibited effective work. During the past 50 years these facilities have greatly enhanced the chances for regional meso-scale studies on the development and growth of sea ice and the dynamics of pack ice fields. These include investigations into the physicochemical interactions between the atmosphere, ice and underlying water, as well as into the fauna and flora living within or in close association with sea ice (Eicken, Chapter 2; Haas, Chapter 3; Schnack-Schiel, Chapter 7; Ainley et al., Chapter 8). Geologists use information gathered from sediment cores in areas beneath past and present sea ice cover, obtained by ice-breaker, to reconstruct the earth’s history, particularly that of the sea ice extent (Leventer, Chapter 10; Armand & Leventer, Chapter 11).

On an even larger scale, airborne equipment used from helicopters or light airplanes provides information on heat exchange, floe distribution and sea ice thickness as well as on the distribution of birds and animals. Submarines and remotely operated, or autonomous, vehicles are the latest tools to be used for obtaining insight into the underside topography of sea ice fields, ice thickness and the behaviour of animals under the ice (Brierley & Thomas, 2002; Brierley et al., 2002). New technologies have been harnessed to investigate the fluxes of organic matter from sea ice to benthic communities on the sea floor, as well as investigating the seasonal dynamics and growth of these communities (Haas, Chapter 3; Schnack-Schiel, Chapter 7; Leventer, Chapter 10).

Constantly improving remote-sensing technology and new satellites (Haas, Chapter 3; Comiso, Chapter 4) enable high-resolution, large-scale monitoring of the ice cover, surface roughness, dynamics and thickness on a seasonal and interannual basis. This information is being compiled to drive models that reconstruct and forecast the behaviour and role of sea ice with regard to past and present climate
change, as well as enabling assessment of its large-scale ecological significance (Comiso, Chapter 4; Arrigo, Chapter 5). Satellite and global positioning technologies allow the tracking of birds and animals, including seals and polar bears, and their seasonal migrations associated with sea ice (Ainley et al., Chapter 8). Sophisticated suites of information such as diving depths, water temperature and salinity, and foraging behaviour can be transmitted daily over many months allowing a far greater understanding of animal behaviour in sea ice covered regions than has ever been possible before (Bornemann et al., 2000; Plötz et al., 2001).

This chapter provides a brief overview of the importance of sea ice. It spans the historical development of sea ice research and the expansion in research interests through to the current state-of-the-art issues and new perspectives that are receiving increasing attention.

1.2 Historical aspects of sea ice exploration

For obvious reasons the historical development of sea ice research differs greatly between the northern and southern hemispheres. A detailed chronological account is beyond the scope of this chapter and is more fully covered by Fogg (1992), Martin (1998) and Weeks (1998). Excerpts have been extracted from these works to compile the brief summary that follows.

In both hemispheres it was probably the biology associated with sea ice that led to man’s interest, association and confrontation with this hostile environment. Around the Arctic, Baltic and Caspian Seas man has inhabited coastal areas for millennia, living off the animals closely associated with sea ice, and adapting their lifestyles and migrations to the seasonal fluctuations in sea ice cover. In the Antarctic it was the whalers and sealers of the 19th century who first encountered sea ice during the pursuit of their prey.

The first records of sea ice date back to reports in the Baltic, and near Greenland, when Irish monks crossed Mare Concretum during their voyages to Iceland. These journeys actually took place in approximately 795 AD (Weeks, 1998). In about 1070, Adam of Bremmen described both Iceland and Greenland as well as sea ice. Two hundred years later a book containing descriptions of sea ice was written by the priest Ivarr Bodde. There is a detailed report with a map showing the crossing of sea ice on the Baltic Sea prepared by Olaus Magnus Gothus in 1539, whilst expedition reports containing general descriptions of sea ice in the Arctic, such as those of Martin Frobisher, date back to 1576 (Weeks, 1998). Because of the general expansion of ocean trade routes during the later 18th century, interest increased in finding a route that offered faster passage between Europe and the Orient. One of the most notable expeditions during that time was the Great Northern Expedition started in 1733 under the command of Vitus Bering, who concluded in 1774 that the route was probably not navigable with the ships available at that time.

The 19th century began with a series of expeditions established mainly to clarify