Preface to the first edition

The drift of sea ice, forced by winds and ocean currents, is an essential element in the dynamics of the polar oceans, those essential and fragile components of the world's climate system. Because its structure is almost two-dimensional, the sea ice drift problem is fascinating for theoretical research in geophysical fluid dynamics. Apart from two-dimensionality, this medium is complicated by its granularity, compressibility, and non-linearity.

The drift transports sea ice over long distances, particularly to regions where ice is not formed by thermodynamic processes. The ice transports latent heat and fresh water, and the influence of ice melting on the salinity of the mixed layer is equivalent to a considerable amount of precipitation. The ice cover forms a particular air–sea interface, which is modified drastically by differential ice motion; consequently, sea ice dynamics is a key factor in air–sea interaction processes in the polar oceans. In particular, the opening and closing of leads (open water channels) have a major impact on air–sea heat exchange. Thus the drift of sea ice plays a very important role in high-latitude weather, polar oceanography, and global climate. This is of renewed interest owing to the increasingly growing concern about man-made global warming.

The waters in the region at the ice margin are known for their high biological productivity because of favourable light and hydrographical conditions; therefore, the location of ice margins – to some degree determined by the drift of ice – is of deep concern in marine ecology.

The drift of ice is also a major environmental factor. Pollutants accumulate in the ice sheet, originating from the water body, sea bottom, and atmospheric fallout, and they are transported within the ice over long distances. A particular pollutant question is oil spills. The drift and dispersion of oil in ice-covered seas has become a very important issue; it is a difficult problem, oil being partly transported with ice and partly dragged by ice. There are three major oil exploration areas in the seasonal sea ice zone: offshore Alaska, Barents Sea, and offshore Sakhalin Island in the Sea of Okhotsk.

Sea ice has always been a barrier to winter shipping. For the purpose of sea ice monitoring and forecasting, ice information services have been in operation for about 100 years. The drift of ice shifts the ice edge, opens and closes leads, and forms pressure zones, which are all key points in navigation through an ice-covered sea. Also hummocks and sea ice ridges result in local accumulation of ice volume and strength, causing major problems to marine operations and constructions. Because of ice dynamics, the ice situation may change rapidly; therefore, ice information services work in all ice-covered seas on a daily basis, updating their ice charts and producing ice forecasts. Expansion of the Northern Sea Routes requires ongoing development of sea ice mapping and forecasting services, where sea ice dynamics plays a key role.

This book presents the science of sea ice drift through its 100-year history to the present state of knowledge. Chapter 1 gives a brief historical overview and presents the sea ice drift problem and the subject matter of the book. The material includes geophysical theory, observations from field programmes, and mathematical models. Chapter 2 describes sea ice material and how it needs to be approached from the perspective of the research and modelling of ice drift. Chapter 3 presents methodologies, data analysis, and the outcome of sea ice kinematics measurements and techniques to construct the ice conservation law, a fundamental law in the dynamics of sea ice. The equation of motion is presented and analyzed in Chapters 4 and 5, including the rheology problem, derivation of two-dimensional equations, and magnitude estimation and scaling. In Chapters 6–8, solutions to the ice drift problem are presented, from simple analytical models to full numerical models. The free drift case results in an algebraic equation, while analytical solutions are easily obtained for channel and zonal flows, critically important tools to interpret the results of more complex models. Chapter 9 briefly discusses some applications of the knowledge of sea ice drift. The end matter contains a collection of study problems, the references, and the index.

The underlying idea behind the book has been to include the whole story of sea ice dynamics in a single volume, from material state through the laws of dynamics to mathematical models. There is a crying need for a synthesis of these research endeavours, as sea ice dynamics applications have been increasing and, apart from review papers, no comprehensive book exists on this topic in English.

The author has contributed to research into sea ice dynamics since 1974. In particular, his topics of interest have been (in chronological order): short-term sea ice forecasting, drift stations in the Baltic Sea, MIZEX (Marginal Ice Zone Experiment), sea ice ridging, sea ice remote sensing, seasonal modelling of Baltic Sea ice conditions, scaling problems, and finally sea ice in coastal zones. This book has grown from the author's lectures on sea ice drift, initially at the University of Helsinki, Finland and then at UNIS (Universitetsstudiene i Svalbard), Longyearbyen, Norway, and from visits to various universities, in particular the Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, USA and Hokkaido University, Mombetsu and Sapporo, Japan.

In the progress of his research the author has learned about sea ice drift from a large number of colleagues. Especially, he wants to thank Professors Erkki Palosuo and William D. Hibler III, as well as Professors Jan Askne, Robert V. Goldstein, Sylvain Joffre, Zygmunt Kowalik, Sveinung Løset, Anders Omstedt, Sergey N. Ovsienko, Kaj Riska, Hayley H. Shen, Kunio Shirasawa, Peter Wadhams, and Wu Huiding. He is also deeply thankful to his students in sea ice dynamics, in particular Professor Zhang Zhanhai, Dr Jari Haapala, Dr Paula Kankaanpää, and Mr Keguang Wang. His home institutes, the Finnish Institute of Marine Research (1974–1992) and the Department of Geophysics (1992; renamed in 2001 as the Division of Geophysics/Department of Physical Sciences) of the University of Helsinki, are deeply thanked for good working conditions and support. The scientists and technicians who have participated in the ice dynamics research programmes from these institutes and from several other organizations are gratefully acknowledged. Mr Keguang Wang is also thanked for a careful scientific review of the manuscript. Also, he and Ms Pirkko Numminen provided assistance with some of the graphics. Finally, the author wants to thank the Praxis team – Clive Horwood, Philippe Blondel, and Neil Shuttlewood –for professional guidance and help in getting this book completed, in particular to Dr Blondel for his very careful and excellent review of the whole book.

Matti Leppäranta
Helsinki, 18 June 2004

Preface to the second edition

This second edition has been prepared six years after the first one. There has been much progress in sea ice dynamics during this period, and consequently a revision is well motivated. This edition contains new sections on thermodynamics, ice–ocean dynamic interaction, frequency spectrum of ice drift, spatial structures of ice velocity, and oil spill models in ice-covered waters. In addition, based on comments from several readers and students of the first edition, modifications, restructuring, additions and technical improvements have been made in most sections.

The progress in the research of sea ice drift has been largely connected to the ice thickness problem, scaling issues, ice engineering and climate models. Mapping of sea ice thickness, in particular the dynamic-thermodynamic evolution of ice thickness, is the main problem to be solved before deeper revisions of sea ice dynamics theory and models are feasible. *Cryosat-1*, ESA's satellite designed for mapping the thickness of sea ice and glaciers, was destroyed shortly after launch in 2005, but in 2010 a new era in sea ice science started with *Cryosat-2*. Ice engineering needs for sea ice dynamics models have been largely increasing for oil-spill cleaning, ice forcing on ships and platforms, and operational strategy in oil and gas exploration in ice-covered waters. Also the navigation conditions have been changing in ice-covered seas in the northern hemisphere due to a decrease of ice thickness and extent.

As a whole, the role of cryosphere is coming more and more important in the Earth system science. The World Climate Research Programme (WCRP) established a core project Climate and Cryosphere (CLIC) in 1999, European Geophysical Union (EGU) established a division of Cryospheric Sciences (CR) in 2002, and the International Union of Geodesy and Geophysics (IUGG) established its eighth association, the International Association of Cryospheric Sciences (IACS), in 2007. In addition, International Polar Year (IPY) took place in 2007–2009 with a major cryosphere programme.

The author is grateful to his collaborators in the research of sea ice dynamics. Fruitful contacts have continued with the majority of the colleagues listed in the preface of the first edition. Especially he is thankful to organizers of two major IPY Sea Ice Summer Schools in 2007 for the invitation to give lectures, organized in Shanghai by Professors Zhang Zhanhai and Wu Huiding and in Longyearbyen, Svalbard by Dr Dirk Notz and Professor Frank Nilsen. A joint sea ice research and education programme was also started between the author and Professor Li Zhijun from the Dalian University of Technology in 2007. Others to thank are Professor Knut Høyland, Dr Tuomo Kärnä, Dr Yusuke Kawaguchi, Dr Tarmo Kõuts, Professor Aleksei Marchenko and Professor Achim Stössel. The list of PhD students in sea ice dynamics has increased by MSc Mika Mäkelä, MSc Ioanna Merkouriadi, MSc Annu Oikkonen and MSc Caixin Wang. The author also wants to thank Dr Juha Karvonen and Dr Simon Prinsenberg for help in the preparation of this book. Ms Salla Jokela has helped with the new graphics, and the Praxis team has been of great help as usual. Support to continue sea ice research has been available from the Academy of Finland and Maj and Tor Nessling Foundation, Finland.

Matti Leppäranta
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