

Ola M. Johannessen • Leonid P. Bobylev  
Elena V. Shalina • Stein Sandven  
Editors

# Sea Ice in the Arctic

Past, Present and Future

 Springer

*Editors*

Ola M. Johannessen  
Nansen Scientific Society  
Bergen, Norway

Leonid P. Bobylev  
Nansen International Environmental and  
Remote Sensing Centre (NIERSC)  
Saint Petersburg, Russia

Elena V. Shalina  
Nansen International Environmental and  
Remote Sensing Centre (NIERSC) and  
Saint Petersburg State University  
Saint Petersburg, Russia

Stein Sandven  
Nansen Environmental and Remote  
Sensing Center  
Bergen, Norway  
  
University Centre in Svalbard  
Longyearbyen, Svalbard, Norway

ISSN 2510-0475

Springer Polar Sciences

ISBN 978-3-030-21300-8

<https://doi.org/10.1007/978-3-030-21301-5>

ISSN 2510-0483 (electronic)

ISBN 978-3-030-21301-5 (eBook)

© Springer Nature Switzerland AG 2020

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG.  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Foreword

Sea ice is recognised to have a significant influence on global climate. It has an impact on the heat exchange between the ocean and atmosphere, a critical influence on the high-latitude atmosphere and freshwater balance, and an essential role in regulating the global thermohaline circulation. “What happens in the Arctic doesn’t stay in the Arctic” has become an important catch phrase.

The loss of sea ice is just one effect of the increasingly warmer Arctic, which is warming at a rate two to three times faster than the rest of the planet on average. The change in temperatures at the poles can have a major effect on all parts of the globe because of the interconnected nature of Earth’s climate system.

Against this backdrop, the book *Sea Ice in the Arctic: Past, Present and Future*, edited by Ola M. Johannessen and colleagues, provides essential information and assesses the current situation of Arctic sea ice. Sketching out the long-term perspective, the book treats a wide range of relevant topics. For example, it discusses the reconstruction of paleo-records (spanning a reference frame for the exceptional nature of today’s changes), highlights more recent observations and methods (including measurements from space), and touches upon future trends like the use of artificial intelligence in sea ice classification and corollary effects like the impact of climate change on the Arctic economy.

The European Space Agency (ESA) has been addressing Arctic sea ice through various projects like the Climate Change Initiative (CCI), which features sea ice as an Essential Climate Variable (ECV), and through sea ice monitoring data sets from CryoSat, SMOS, Sentinel-1, and Sentinel-3. They are fundamental to data assimilation into coupled models and for delivering operational services through the Copernicus Marine Environment Monitoring Service (CMEMS).

The ESA remains committed to continue its endeavours in this regard, as the need for sustained sea ice and ocean data sets in the Arctic is recognised by Copernicus users. Three relevant Copernicus Sentinel high-priority candidate missions are currently being studied: an imaging passive microwave mission (for ice concentration), a polar ice and snow topography mission (for sea ice thickness), and an L-band synthetic aperture radar (SAR) mission as a complement to Sentinel-1.

ESA's activities in the domain of Arctic sea ice are just one element of a wide-scale effort to monitor and protect our planet Earth for future generations – a global endeavour by nature – requiring a holistic societal approach. This book is an important element of this endeavour, raising awareness, informing public debate, and sketching a way forward to tackle the strategic topic of Arctic sea ice.

Director of Earth Observation Programmes  
European Space Agency  
Frascati, Italy

Josef Aschbacher

# Contents

<b>1</b>	<b>Introduction</b> . . . . .	<b>1</b>
	Ola M. Johannessen	
<b>2</b>	<b>Sea Ice in the Arctic Paleoenvironments</b> . . . . .	<b>9</b>
	Leonid P. Bobylev and Martin W. Miles	
<b>3</b>	<b>Marginal Ice Zone and Ice-Air-Ocean Interactions</b> . . . . .	<b>57</b>
	Ola M. Johannessen, Stein Sandven, Richard Davy, and Einar O. Olason	
<b>4</b>	<b>Changes in Arctic Sea Ice Cover in the Twentieth and Twenty-First Centuries</b> . . . . .	<b>93</b>
	Elena V. Shalina, Ola M. Johannessen, and Stein Sandven	
<b>5</b>	<b>Arctic Sea Ice Thickness and Volume Transformation</b> . . . . .	<b>167</b>
	Elena V. Shalina, Kirill Khvorostovsky, and Stein Sandven	
<b>6</b>	<b>SAR Sea Ice Type Classification and Drift Retrieval in the Arctic</b> . . . . .	<b>247</b>
	Natalia Y. Zakhvatkina, Denis Demchev, Stein Sandven, Vladimir A. Volkov, and Alexander S. Komarov	
<b>7</b>	<b>Sea Ice Drift in the Arctic</b> . . . . .	<b>301</b>
	Vladimir A. Volkov, Alexandra Mushta, and Denis Demchev	
<b>8</b>	<b>Sea Ice Modelling</b> . . . . .	<b>315</b>
	Matti Leppäranta, Valentin P. Meleshko, Petteri Uotila, and Tatiana Pavlova	
<b>9</b>	<b>Operational Forecasting of Sea Ice in the Arctic Using TOPAZ System</b> . . . . .	<b>389</b>
	Laurent Bertino and Jiping Xie	

**10 Current and Projected Sea Ice in the Arctic in the Twenty-First Century . . . . . 399**  
Valentin P. Meleshko, Tatiana Pavlova, Leonid P. Bobylev,  
and Pavel Golubkin

**11 Climate Change Impact on the Arctic Economy . . . . . 465**  
Lasse H. Pettersson, Anton G. Kjelaas, Dmitry V. Kovalevsky,  
and Klaus Hasselmann

**12 Annex: SAR Sea Ice Interpretation Guide . . . . . 507**  
Ola M. Johannessen

**Afterword . . . . . 575**  
Ola M. Johannessen

# Contributors

**Laurent Bertino** Nansen Environmental and Remote Sensing Center, Bergen, Norway

**Leonid P. Bobylev** Nansen International Environmental and Remote Sensing Centre (NIERSC), Saint Petersburg, Russia

**Richard Davy** Nansen Environmental and Remote Sensing Center, Bergen, Norway

**Denis Demchev** Arctic and Antarctic Research Institute, Saint Petersburg, Russia  
Nansen International Environmental and Remote Sensing Centre, Saint Petersburg, Russia

**Pavel Golubkin** Nansen International Environmental and Remote Sensing Centre, Saint Petersburg, Russia

**Klaus Hasselmann** Max Planck Institute for Meteorology, Hamburg, Germany

**Ola M. Johannessen** Nansen Scientific Society (NSS), Bergen, Norway

**Kirill Khvorostovsky** Russian State Hydrometeorological University, Saint Petersburg, Russia

**Anton G. Kjelaas** Norwegian Scientific Academy for Polar Research, Nesoddtangen, Norway

**Alexander S. Komarov** Environment and Climate Change Canada, Ottawa, ON, Canada

**Dmitry V. Kovalevsky** Climate Service Center Germany (GERICS), Helmholtz-Zentrum, Geesthacht, Germany

**Matti Leppäranta** Institute for Atmospheric and Earth System Research (INAR), University of Helsinki, Helsinki, Finland

**Valentin P. Meleshko** Voeikov Main Geophysical Observatory, Saint Petersburg, Russia

**Martin W. Miles** NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

Institute of Arctic and Alpine Research University of Colorado, Boulder, CO, USA

**Alexandra Mushta** Nansen International Environmental and Remote Sensing Centre, Saint Petersburg, Russia

**Einar O. Olason** Nansen Environmental and Remote Sensing Center, Bergen, Norway

**Tatiana Pavlova** Voeikov Main Geophysical Observatory, St. Petersburg, Russia

**Lasse H. Pettersson** Nansen Environmental and Remote Sensing Center, Bergen, Norway

**Stein Sandven** Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway

University Centre in Svalbard, Longyearbyen, Svalbard, Norway

**Elena V. Shalina** Nansen International Environmental and Remote Sensing Centre (NIERSC) and Saint Petersburg State University, Saint Petersburg, Russia

**Petteri Uotila** Institute for Atmospheric and Earth System Research (INAR), University of Helsinki, Helsinki, Finland

**Vladimir A. Volkov** Nansen International Environmental and Remote Sensing Centre, Saint Petersburg, Russia

**Jiping Xie** Nansen Environmental and Remote Sensing Center, Bergen, Norway

**Natalia Y. Zakhvatkina** Arctic and Antarctic Research Institute, Nansen International Environmental and Remote Sensing Centre, Saint Petersburg, Russia