Remote Sensing of Sea Ice in the Northern Sea Route

Studies and Applications

Ola M. Johannessen, Vitaly Yu. Alexandrov,
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Yevgeny U. Mironov and Nikolay G. Babich

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Professor Ola M. Johannessen
Founding Director
Nansen Environmental and Remote Sensing Center
Mohn-Sverdrup Center for Global Ocean Studies
and Operational Oceanography
Geophysical Institute, University of Bergen,
Bergen, Norway

Professor Stein Sandven
Nansen Environmental and Remote Sensing Center
Bergen, Norway
University Courses on Svalbard—UNIS,
Longyearbyen, Norway

Mr. Lasse H. Pettersson
Mr. Kjell Kloster
Nansen Environmental and Remote Sensing Center
Bergen, Norway

Dr. Vitaly Yu. Alexandrov
Nansen International Environmental and Remote
Sensing Center
St. Petersburg, Russia

Dr. Leonid P. Bobylev
Nansen International Environmental and Remote
Sensing Center
St. Petersburg, Russia
Nansen Environmental and Remote Sensing Center
Bergen, Norway

Professor Ivan Ye. Frolov
Dr. Vladimir G. Smirnov
Dr. Yevgeny U. Mironov
Arctic and Antarctic Research Institute (AARI)
St. Petersburg, Russia

Mr. Nikolay G. Babich
Murmansk Shipping Company
Murmansk, Russia

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Preface

The Northern Sea Route (NSR) consists of the sailing routes in the Russian Arctic between the Barents Sea in the west and the Bering Strait in the east (Figure 1). It is the shortest sailing route linking northwestern Europe and northeastern Asia. The distance between Yokohama and Hamburg is almost half of that through the Suez Canal and 10–14 days in sailing time can be saved using the northern route. However, the presence of sea ice significantly hampers navigation. In winter the sailing routes are covered with ice, and even in summer some parts are ice-covered, especially in the Laptev and East Siberian Seas. Therefore, a fleet of conventional and nuclear Russian icebreakers supports safe and cost-effective ship transportation during the different seasons.

Hydrometeorological information, including sea ice data, is accordingly an essential and integral part of navigation safety. Therefore, the Northern Sea Route Administration, founded in 1932, established a service of hydrometeorological support for the region.

From the start of this service, polar aviation began ice reconnaissance to support all shipping transport in the Arctic. By 1935, all foreign aircraft—except *Dornier Wal* seaplanes which were used for ice reconnaissance until 1945—were replaced by aircraft manufactured in Russia. In the 1950s, visual airborne ice reconnaissance continued to be the main tool for sea ice monitoring and hydrometeorological services for Arctic navigation. Annually, 30–40 Russian aircraft carried out 500–700 ice reconnaissance flights. In 1964, the scientific and manufacturing association NPO Leninets began developing SLAR specifically for ice reconnaissance. In summer of 1966 AARI obtained the first TV images from *ESSA-2* and *Meteor-1*. In 1975 the first satellite of the Russian *Meteor-2* series was launched and used for sea ice monitoring. In September of 1983 the first satellite of the Russian *Okean-01* series with SLR (side-looking radar) was launched and, as a result, almost immediately shipping support became more efficient.

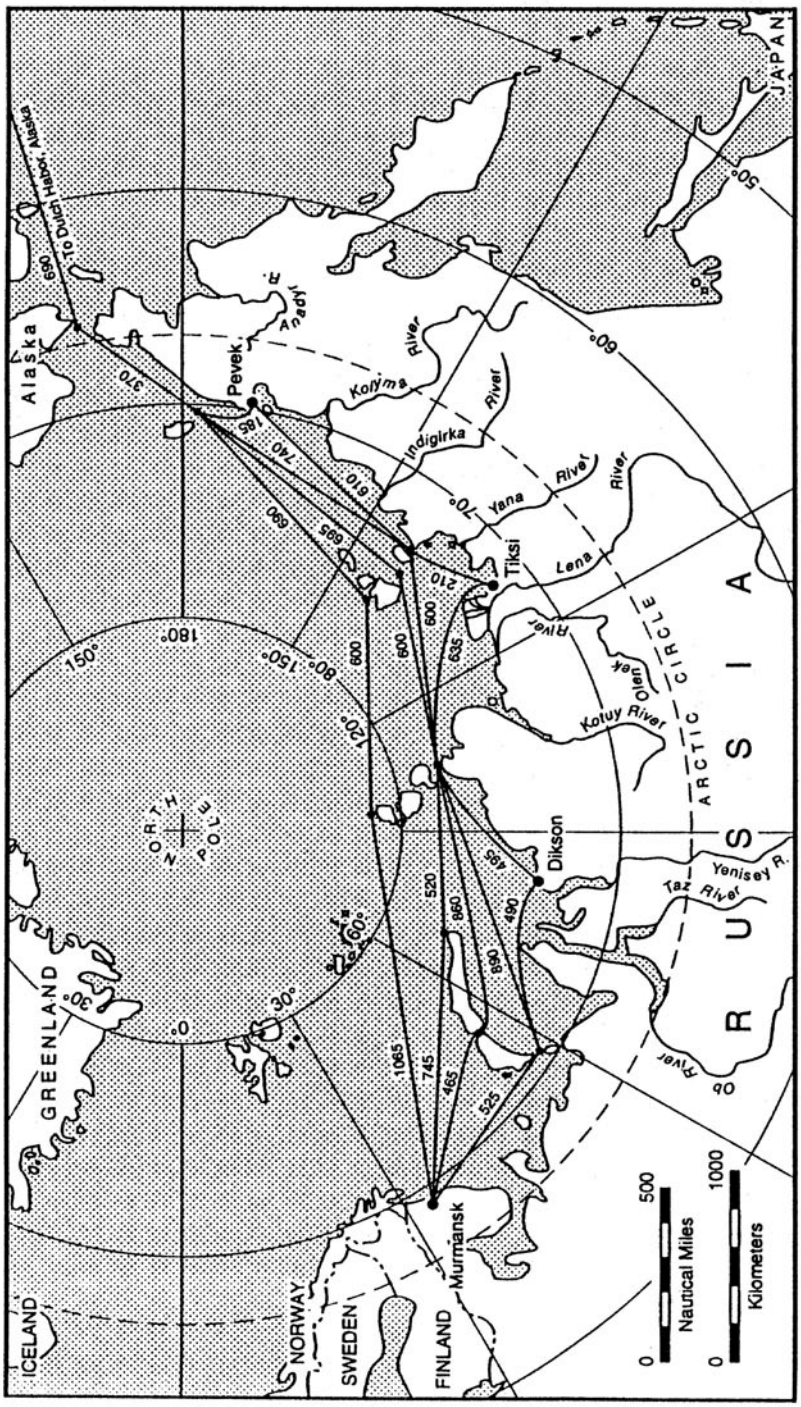

Figure 1. The major sailing routes along the NSR and distances between different sections in nautical miles.

Routine sea ice monitoring today is primarily based on satellite remote-sensing data in the optical and infrared range. However, weather- and light-independent satellite remote-sensing data in the microwave range significantly improved the availability of sea ice information. This began in the NSR in August 1991, just 2 weeks after the launch of the European Space Agency (ESA) *ERS-1* satellite, when real time synthetic aperture radar (SAR) images were transmitted to the French vessel *L'Astrolabe* to assist her navigation through the NSR from Europe to Japan. The *L'Astrolabe* expedition, headed by Pierre Sauvadet, included an *ERS-1* SAR project between ESA, with Guy Duchossois as *ERS-1* mission manager and the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, with Ola M. Johannessen as the project leader.

After the success of using SAR to route *L'Astrolabe* through the ice, the Nansen Centers in Bergen and St. Petersburg, and the Murmansk Shipping Company (MSC), conducted a number of campaigns to demonstrate the use of SAR for supporting the operations of the nuclear icebreakers of the MSC and their convoys. The principal project demonstrating the use of SAR in the NSR was "Icewatch" or, to give it its full title, "Real-Time Sea Ice Monitoring of the Northern Sea Route Using Satellite Radar Technology" that ran from 1994 to 1996. This was the first joint earth observation project between ESA and the Russian Space Agency (RKA). Partners in the "Icewatch Project"—in addition to ESA and RKA—were the Nansen Center in Bergen, the scientific and manufacturing association NPO Planeta and, later, the Scientific Research Centre for Exploration of Natural Resources (NITs IPR) in Moscow, the Arctic and Antarctic Research Institute (AARI) of Rosshydromet in St. Petersburg, the Scientific Foundation Nansen International Environmental and Remote Sensing Center in St. Petersburg and the Murmansk Shipping Company (MSC). Project leaders were Ola M. Johannessen of the Nansen Center and Alexey M. Volkov of the Scientific Research Center for Exploration of Natural Resources (NITs IPR) under RKA, with Guy Duchossois and Günther Kohlhammer of ESA and Georgy M. Polishuck of RKA as space agency representatives.[1] Based on the "Icewatch Project" two *ERS-1* and *-2* SAR receiving stations were installed in the Russian Federation—one in Moscow and the other in Khantymansiisk in western Siberia.

Following on from the "Icewatch Project", SAR data from *ERS-1* and *-2*, the Canadian *Radarsat* and the ESA *Envisat* started to be used semi-operationally in the NSR jointly with ice monitoring from AARI. This is the basis for this book, which is jointly written by authors from NERSC, AARI, NIERSC and MSC. Half of the writing of this book was funded by ESA through José Achache when he was Director of Earth Observation in ESA and Joseph Aschbacher, Programme Coordinator at ESA, while the remaining half was financed by institutional funding.

This book was also a component of the EU/INTAS Climate and Environmental Change in the Arctic (CECA) project, which was led by Prof. Ola M. Johannessen,

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[1] Mr. Alain Fournier-Sicre, Head of the ESA Permanent Mission in the Russian Federation, Moscow, was instrumental in facilitating the cooperation between the two space agencies.

NERSC, with Dr. Leonid Bobylev, NIERSC, and Prof. Lennart Bengtsson, Max-Planck Institute for Meteorology, as partners. The CECA Project was awarded the Laureate of the EU transnational research Descartes Prize in Earth Science for 2005.

Ola M. Johannessen	*Leonid Bobylev*	*Ivan Frolov*
Director NERSC	Director NIERSC	Director AARI
Nina Novikova	*Volker Liebig*	*Anatoly Eu. Shilov*
NTsOMZ	Director of EO, ESA	Head of Department, RKA

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This book is based primarily on the joint research and demonstration projects carried out between 1991 and 2005. The first was the European Space Agency's (ESA) project "*ERS-1* SAR Ice Routing of the *L'Astrolabe*" which supported the French vessel in her voyage through the Northern Sea Route in 1991. Subsequent projects were: the ESA–Norwegian Space Center's "*ERS-1* Pilot Demonstration Project—Real-time Sea Ice Monitoring of the Northern Sea Route Using *ERS-1* Satellite Radar Images" (1992–1995); the Nansen Center in Bergen's "SAR Strategy Program" (1994–1996) funded by the Research Council of Norway; ice routing of the Japanese project "*Kandalaksha '95* Voyage" through the Northern Sea Route; the ESA–Russian Space Agency's (RKA) "Real-time Sea Ice Monitoring of the Northern Sea Route Using Satellite Radar Technology—Icewatch Project" (1994–1996); the three EU projects "Ice Routes" (1997–1998), "Arctic Demonstration and Exploratory Voyage—ARCDEV" (1998–1999) and the "Integrated Use of New Microwave Satellite Data for Improved Sea Ice Observations—IMSI" project (1997–1999); as well as the ESA GMES project "SAR Ice Monitoring for Climate Research—ICEMON" (2003–2005).

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Studies with objectives of determining ice conditions in Arctic seas and developing methods for satellite information processing and analysis were carried out within the framework of these projects with the financial support of the Federal Service for Hydrometeorology and Environmental Monitoring and the Ministry of Education and Science of the Russian Federation. The authors are especially thankful to Professor A.V. Bushuyev, lead scientist in methods of sea ice remote sensing and Professor Z.M. Gudkovich, lead scientist in ice regime research at the Arctic and Antarctic Research Institute.

The Authors

Figures

Tables

Abbreviations

AARI	Arctic and Antarctic Research Institute
ACIA	Arctic Climate Impact Assessment
AFC	Aerial photo camera
AIISA	Automated Ice Information System for the Arctic
AIJEX	Arctic Ice Joint Experiment Study
AIRP	Automated Information Receiving Point
AMSR	Advanced Microwave Scanning Radiometer
ANSR	Administration of the Northern Sea Route
AO	Arctic Oscillation
AP	Alternating Polarization
APT	Automatic Picture Transmission
ARCDEV	ARCtic Demonstration and Exploratory Voyage
ARGOS	Satellite-based location and environmental data collection system
ARI	Arctic Research Institute
ARKTOS	Advanced system for classification of sea ice types in satellite radar images
ARO	Arctic Research Observatory
ASAR	Advanced SAR
ASF	Alaska SAR Facility
AVHRR	129, 149–150
BMP	Windows BitMaM
CCG	Canadian Coast Guard
CIHMI	Center for Ice and Hydrometeorological Information
CIM	Composite Ice Map
CIS	Canadian Ice Service
CNSR	Committee of the Northern Sea Route
DARMS	Drifting Automatic Radio Meteorological Stations

DMI	Danish Meteorological Institute
DMSP	Defense Meteorological Satellite Program
DN	Digital Number
ECDIS	Electronic Chart Display and Information System
ECHAM-4	Max-Planck Institute for Meteorology in Hamburg, Germany
ECNIS	Electronic Cartographic Navigation Information System
EEA	Exclusive Economic Area
EM	ElectroMagnetic
EO	Earth Observation
EOS	Earth Observation System
ERS	European Remote Sensing satellite
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer
ESTEC	European Space Research and TEChnology Centre of ESA
ETSI	Expert Team on Sea Ice
EU	European Union
EUMETSAT	EUropean organization for the exploration of METeorological SATellites
FNMOC	Fleet Numerical Meteorological and Oceanographic Center
FRI	Full-Resolution Image
FTP	File Transfer Protocol
FYI	First-Year Ice
GHG	GreenHouse Gas
GIF	Graphic Interchange Format
GIS	Geographical Information System
GLCM	Gray Level Co-occurrence Matrix
GLONAS	A global positioning system
GMES	Global Monitoring for Environment and Security
GMT	Greenwich Mean Time
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HadCM3	Hadley Centre at the UK Met Office
HDF	Hierarchical Data Format
HF	High Frequency (radar)
HH	Horizontal polarization
HMS	HydroMeteorological Service
HRPT	High-Resolution Picture Transmission
HV	Transmission is made in one polarization and receiving in another
IABP	International Arctic Buoy Program
ICG	Icelandic Coast Guard
ID	IDentifier
IFREMER	French Research Institute for Exploitation of the Sea
IICWG	International Ice Charting Working Group

IIP	International Ice Patrol
IMO	Icelandic Meteorological Office
IPCC	Intergovernmental Panel on Climate Change
IR imager	InfraRed radiometer
IR	InfraRed
JPEG	Joint Photographic Expert Group (file format)
KSAT	Kongsberg SATellite Services, Tromsø, Norway
LDA	Linear Discriminant Analysis
LFO	Low-Frequency Oscillation
LKF	Linear Kinematic Feature
LNG	Liquefied Natural Gas
LRI	Low-Resolution Image
MANSR	Main Administration of the Northern Sea Route
MCC	Multiple Cross Correlation
met.no	Norwegian Meteorological Institute
MIZ	Marginal Ice Zone
MLP	Multi-Layer Perceptron
MMF	Ministry of Marine Fleet
MODIS	MODerate-resolution Imaging Spectroradiometer
MOH	Marine Operations Headquarters
MOS	Japanese Marine Observation Satellite
MSC	Meteorological Service of Canada
MSC	Murmansk Shipping Company
MYI	Multi-Year Ice
NAO	North Atlantic Oscillation
NASA	National Aeronautical and Space Administration
NAVICECEN	Naval Ice Center
NAVOCEANO	Naval Oceanographic Office
NCEP	National Center for Environmental Prediction
NERSC	Nansen Environmental and Remote Sensing Center
NESDIS	National Environmental Satellite Data Information Service
NIB	Nuclear IceBreaker
NIC	National Ice Center
NIERSC	Nansen International Environmental and Remote Sensing Centre
NOAA	National Oceanographic and Atmospheric Administration
NORSEX	NOrwegian Remote Sensing EXperiment
NPI	Norwegian Polar Institute
NRT	Near-Real Time
NSIDC	National Snow and Ice Data Center
NSRA	NSR Administration
NZN	Novozemelsky northern ice massif
NZS	Novozemelsky southern ice massif
OY	Ob'–Yenisey
PAF	Processing and Archiving Facility (ESA)

PALSAR	Phased Array L-band Synthetic Aperture Radar
PDF	Probability Density Function
RAR	Real Aperture Radar
RGPS	*Radarsat* Geophysical Processor System
RICAE	Riga Institute of Civil Aviation Engineers
RKA	Russian Space Agency
RMS	Root Mean Square
RRMC	Regional Radio-Meteorological Center
RT	Real Time
SAR	Synthetic Aperture Radar
SAT	Surface Atmospheric Temperature
SLAR	Side-Looking Airborne Radar
SLP	Sea Level Pressure
SLR	Side-Looking Radar
SMMR	Scanning Multi-channel Microwave Radiometer
SRES	Special Report on Emission Scenarios
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SWK	SouthWestern Kara Sea (SWK)
SZE	Severozemelsky eastern ice massif
SZW	Severozemelsky western ice massif
TIFF	Tagged Image File Format
TM	Thematic Mapper
TSS	Tromsø Satellite Station (now KSAT)
UGMS	Yakutian Administration of the Hydrometeorological Service
UL, ULA	Classes of ice-strengthened ships
ULS	Upward-Looking Sonar
URL	Uniform Resource Locator
VH	Transmission is made in one polarization and receiving in another
VH	Vertical polarization
VPI	Russian system for broadcasting of information
WMF	Windows Meta File
WMO	World Meteorological Organization
WS	Wide-Swath
WSM	Wide-Swath radar Mode on *Envisat*
WWW	World Wide Web
YY	Yamalo–Yugorsky

Authors

Prof. Ola M. Johannessen
Nansen Environmental and Remote Sensing Center,
Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography and
Geophysical Institute, University of Bergen, Bergen, Norway
Ola.Johannessen@nersc.no

Dr. Vitaly Yu. Alexandrov
Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia
Vitali.Alexandrov@niersc.spb.ru

Prof. Ivan Ye. Frolov
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Frolov@aari.nw.ru

Prof. Stein Sandven
Nansen Environmental and Remote Sensing Center, Bergen, Norway and
University Courses on Svalbard—UNIS, Longyearbyen, Svalbard, Norway
Stein.Sandven@nersc.no

Mr. Lasse H. Pettersson
Nansen Environmental and Remote Sensing Center, Bergen, Norway
lasse.pettersson@nersc.no

Dr. Leonid P. Bobylev
Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia and
Nansen Environmental and Remote Sensing Center, Bergen, Norway
Leonid.Bobylev@niersc.spb.ru

Mr. Kjell Kloster
Nansen Environmental and Remote Sensing Center, Bergen, Norway
Kjell.Kloster@nersc.no

Dr. Vladimir G. Smirnov
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Vgs@aari.nw.ru

Dr. Yevgeny U. Mironov
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Mir@aari.nw.ru

Mr. Nikolay G. Babich
Murmansk Shipping Company, Murmansk, Russia
Deyneka@msco.ru

Contributing authors

Alexandrov, Vitaly Yu.
Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia
Vitali.Alexandrov@niersc.spb.ru

Babich, Nikolay G.
Murmansk Shipping Company, Murmansk, Russia
Deyneka@msco.ru

Babiker, Mohamed
Nansen Environmental and Remote Sensing Center, Bergen, Norway
Mohamed.Babiker@nersc.no

Bobylev, Leonid P.
Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia and
Nansen Environmental and Remote Sensing Center, Bergen, Norway
Leonid.Bobylev@niersc.spb.ru

Bogdanov, Andrey V.
Ruhr-Universitaet, Institut fuer Neuroinformatik, Bochum, Germany
Andrey.Bogdanov@neuroinformatik.ruhr-uni-bochum.de

Borodachev, Viktor Ye.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Aaricoop@aari.nw.ru

Bushuev, Andrey V.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Aaricoop@aari.nw.ru

Frolov, Ivan Ye.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Frolov@aari.nw.ru

Gorbunov, Yury A.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Gua@aari.nw.ru

Gudkovich, Zalman M.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Aaricoop@aari.nw.ru

Johannessen, Ola M.
Nansen Environmental and Remote Sensing Center, Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography and Geophysical Institute, University of Bergen, Bergen, Norway
Ola.Johannessen@nersc.no

Karelin, Igor D.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Aaricoop@aari.nw.ru

Karklin, Valery P.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Karklin@aari.nw.ru

Kloster, Kjell
Nansen Environmental and Remote Sensing Center, Bergen, Norway
Kjell.Kloster@nersc.no

Losev, Stanislav M.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Aaricoop@aari.nw.ru

Loshchilov, Viktor S.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Lvs@aari.nw.ru

Lundhaug, Maria
Nansen Environmental and Remote Sensing Center, Bergen, Norway
Maria.Lundhaug@vesta.no (current affiliation)

Melentyev, Vladimir V.
Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia
Vladimir.Melentyev@niersc.spb.ru

Miles, Martin
Bjerknes Centre for Climate Research, Bergen, Norway and
University of Bergen, Bergen, Norway
Martin.Miles@geo.uib.no

Mironov, Yevgeny U.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Mir@aari.nw.ru

Myrmehl, Cathrine
Nansen Environmental and Remote Sensing Center, and
Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography, Bergen, Norway
Cathrine.Myrmehl@nersc.no

Paramonov, Alexandr I.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Paramonov@aari.nw.ru

Pettersson, Lasse H.
Nansen Environmental and Remote Sensing Center, Bergen, Norway
lasse.pettersson@nersc.no

Sandven, Stein
Nansen Environmental and Remote Sensing Center, Bergen, Norway and
University Courses on Svalbard—UNIS, Longyearbyen, Svalbard, Norway
Stein.Sandven@nersc.no

Shcherbakov, Yuriy A.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Jas@aari.nw.ru

Smirnov, Vladimir G.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Vgs@aari.nw.ru

Spichkin, Vladimir I.
Arctic and Antarctic Research Institute, St. Petersburg, Russia
Aaricoop@aari.nw.ru

Zaitsev, Lev V.
Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia
Lev.Zaitsev@niersc.spb.ru

Introduction

This book covers a range of topics related to the monitoring of sea ice conditions in support of navigation in the Northern Sea Route (NSR). It includes the history of exploration of the Northern Sea Route, organization of sea ice monitoring, analysis of sea ice conditions, methodologies of satellite remote sensing of sea ice for supporting navigation and climatic variability of sea ice conditions in the Arctic Ocean and the Northern Sea Route. Use of the most advanced microwave techniques of sea ice monitoring—such as SAR data provided by the European *ERS-1*, *ERS-2*, *Envisat* and the Canadian *Radarsat* satellites—is specifically addressed.

Chapter 1 presents a brief history of Northern Sea Route exploration, the present period and future prospects for its use. During the 17th century the Russian Pomors and Cossacks sailed along the western and eastern parts of the Northeast Passage and discovered the Bering Strait. In the early 18th century the Great Northern Expedition mapped almost the entire coast of the Arctic Ocean. Many renowned expeditions were accomplished in the 19th century. Thus, Nordenskjöld onboard *Vega* passed for the first time through the entire NSR. De-Long attempted to reach the North Pole onboard *Jeannette*. Fridtjof Nansen's *Fram* sailed eastward through the Kara and Laptev Seas, where her transarctic drift started. Also, from the second half of the 19th century, trade shipping was developed in the Kara Sea for exporting Siberian mineral resources and importing industrial goods. By the beginning of the 20th century the whole Arctic coast had been discovered and studied, and navigation maps of Eurasian Arctic seas produced.

Studies and exploration of the Northern Sea Route continued during the Soviet period using icebreakers, aircraft, research vessels and a network of hydrometeorological stations. In 1932 the Northern Sea Route Administration was given the task of finally laying out the sea route from the White Sea to the Bering Strait, equipping and maintaining it in good state and ensuring safe navigation along it. Accordingly, a service of hydrometeorological support including sea ice monitoring for navigation was organized. In 1933 the *Sibiryakov* completed her voyage all along the NSR during

one navigation summer season. Since 1935, shipping operations—servicing the extensive industrial development in the Eurasian coastal Arctic area—were conducted according to the Soviet plan for cargo operations. Transport of goods in the Northern Sea Route continuously increased and during the late 1980s more than 6 million tons per year were shipped.

From July 1991 the NSR was officially declared open for non-Russian merchant vessels, and the French vessel *L'Astrolabe* was the first to pass through from west to east. However, after the Soviet period, much of the industrial production in the northern regions decreased and cargo turnover through the NSR was only 1.5–2.0 million tons after 1996.

However, the recent increase in oil and gas exploration and production and the associated increase in industrial activities in the areas of the far north of Russia will cause a further increase in transport in the NSR in the years to come, since the shelf area of the Arctic Ocean has 20–25% of the world's remaining oil and gas reserves. Therefore, safe operation in ice-infested waters in the NSR requires real time hydrometeorological and sea ice information of high quality and reliability.

Chapter 2 is devoted to sea ice conditions for the whole Arctic Ocean and in Eurasian Arctic Shelf seas. Significant seasonal changes in ice area in the Arctic Ocean occur in the marginal seas, with the seasonal maximum and minimum of ice extent in March–April and in September, respectively. Two major features of ice drift in the Arctic Ocean are the anticyclonic Beaufort Gyre and the transarctic ice flow between the North Pole and the northern margins of Eurasian Shelf seas, towards the Greenland Sea and Fram Strait.

Knowledge of sea ice conditions in Eurasian Arctic seas is essential for navigation in the Northern Sea Route and the offshore industry. Analysis of 50 years of observations from Russian polar stations and visual ice reconnaissance data allowed studying of ice formation and ice thickness growth, ice exchange between Eurasian Arctic seas and the Arctic Basin, distribution of fast ice, flaw polynyas and drifting ice. First-year ice prevails in Arctic Shelf seas; however, multi-year ice is often observed in the East Siberian Sea and in the northern parts of the Laptev and Kara Seas. On average, before the annual onset of ice formation, 80% of the eastern Laptev Sea and 85% of the southwestern Chukchi Sea are ice-free while the Barents Sea and the southwestern Kara Sea are almost ice-free. The northeastern Kara Sea and the western areas of the Laptev Sea and the East Siberian Sea become approximately 50% ice-free.

Chapter 3 addresses various aspects of sea ice monitoring and services in the NSR and in other Arctic countries. Soviet sea ice reconnaissance flights were made part of the hydrometeorological service for navigation at the beginning of the 1930s, and later on ice reconnaissance flights were made every 10 days more or less regularly during the entire navigation period. In the last decades of the 20th century various airborne remote-sensing techniques—such as side-looking airborne radars, radar video-impulse sea ice thickness meter, optical and radar satellite images—were implemented and widely used for operational support of shipping and compilation of weekly composite ice charts for the entire NSR. The first stage of an automated ice information system for the Arctic was accepted for commercial operation in 1989.

The Center for Ice and Hydrometeorological Information at the Arctic and Antarctic Research Institute (AARI) provides ice information to users in near-real time. They regularly issue ice charts and ice forecasts. With the end of regular airborne ice reconnaissance in the early 1990s, satellites became the main tool for acquisition of sea ice information.

To ensure safe operations in ice-covered seas operational monitoring of sea ice and icebergs has been developed in Arctic countries over several decades. The major ice services in the northern hemisphere are the U.S. National Ice Service, the Canadian Ice Service, the Danish Ice Service for Greenland waters, the Icelandic Ice Service and the Norwegian Ice Service, all of which are briefly described.

A study of users' requirements for sea ice information was done as part of the "Icewatch Project". The major user of sea ice information for navigation in the NSR is the Murmansk Shipping Company, being responsible for provision of icebreaker escort of merchant ice class cargo vessels and tankers. Depending on the purpose, tasks and objectives, ice information is divided into three main categories: strategic, operational and tactical. Analysis of different remote-sensing data concludes that *Envisat* and *Radarsat* SAR radar images, which can cover the entire area of the NSR in a 48-hour period, to a large extent satisfy users' requirements for support of navigation in sea ice, and therefore need to be routinely implemented in AARI's operational systems.

Chapter 4 deals with methodologies of satellite remote sensing of sea ice. Currently, Russian sea ice monitoring of the Northern Sea Route is based primarily on the optical and infrared images from *NOAA* and *Terra* satellites. Classification of sea ice parameters from these images is done, and derivation of ice thickness using IR images is also possible in the absence of clouds and for sea ice up to 120 cm thick.

The major principles of synthetic aperture radar (SAR) are described. Analysis of backscatter (σ^0) from sea ice shows that, at the C-band, surface scattering is predominant for young and first-year ice, as well as summer ice, while volume scattering is typical of old ice in winter conditions. Typical changes in radar backscatter from sea ice during winter are: low backscatter from grease and new ice and nilas; increase for pancake and gray ice; decrease in first-year ice; and, finally, increase for multi-year ice. Significant differences between the backscatter of the same ice types was found between sea ice at the ice edge and within the pack ice, but this was due to different roughness.

Signatures of the principal sea ice types and their expressions in *ERS*, *Radarsat* and *Envisat* SAR images have been specified and verified based on a series of subsatellite field experiments. The main sea ice parameters—including stages of ice development, forms of fast ice and pack ice, ice edge location, polynyas, ice surface features and icebergs—have been derived from radar images. Some ambiguities in their interpretation are caused by the similarity of signatures between different sea ice types and features. Techniques currently used for automatic classification of SAR images are presented. Furthermore, description of the methodology of ice chart compilation from satellite images and principles of sea ice mapping and generation of digital ice chart data are described. Examples of ice charts compiled from

different satellite sensor systems are presented including the use of Geographical Information System (GIS) tools.

Chapter 5 is devoted to studies of sea ice conditions in western and eastern parts of Eurasian Arctic seas. Regular use of satellite images for monitoring the Barents and Kara Seas began in the early 1970s, and after 1991 composite ice charts have been based on the optical and infrared range as well as side-looking radar (SLR) satellite imagery from the Russian *Okean* satellite. In spite of relatively coarse resolution they allow detection of ice edge, boundaries of landfast ice and polynyas and zones of different concentration and age with sufficient accuracy, including seasonal changes.

Satellite SAR data are used semi-operationally for studies of sea ice conditions in the NSR, and some results of these studies are described. The fast ice boundary in the western part of the Eurasian Russian Arctic and around Franz Josef Land was determined from *Radarsat* ScanSAR images for selected years. Furthermore, using *ERS* SAR and *Radarsat* ScanSAR images, the mean and standard deviations of polynya widths have been determined in the western Eurasian Arctic. Short-term, medium-term and long-term ice drift estimates were derived from successive satellite images for the Laptev Sea. The SAR imagery represents a unique capability for mapping ice drift in straits and near the coasts where other data sources provide limited information because of limited spatial resolution and cloudiness.

Chapter 6 deals with semi-operational use of SAR data for supporting ice navigation. Since 1991 the Nansen Centers in Bergen and St. Petersburg together with Murmansk Shipping Company have demonstrated the use of SAR data for planning and selection of the navigation route in sea ice. Ten expeditions are described. In these expeditions *ERS-1/2*, *Radarsat* and *Envisat* SAR images were transmitted to icebreakers in near-real time to help them navigate in sea ice. This experience proves that high-resolution light- and weather-independent SAR images can be effectively used for both strategic and tactical support of icebreaker operations in sea ice. In 2004–2005 *Envisat* ASAR images for the western part of the NSR were routinely transmitted every 3 days to the MOH at the Murmansk Shipping Company, which selected and transmitted sailing routes to the nuclear icebreakers. Even in relatively easy sea ice conditions during winter–spring 2005 the average speed of ships in ice increased by about 30–40% as a result of using SAR data for ice routing.

The methodology of using SAR data onboard icebreakers for their tactical navigation in sea ice was also tested in many of the expeditions. It includes processing SAR raw data to make images, transmission of the images to icebreakers in the Northern Sea Route and their use by captains for ship routing. Experience of using satellite imagery in the optical and infrared band onboard the icebreakers is also described. Here, particular attention is drawn to the present technique of *NOAA* and *Meteor* imagery presentation onboard icebreakers in the Electronic Chart Display and Information System (ECDIS) of ship navigation.

The future of sea ice monitoring in the NSR should combine use of remote-sensing data in different spectral ranges, including routine use of SAR data, implementation of new information products for ice services and efficient distribution to users. Any future system of satellite monitoring for the purpose of ice navigation

should primarily be based on satellite data with a spatial resolution of at least 50–100 m and subject to daily coverage.

Chapter 7 is devoted to the climatic variability of sea ice in the Arctic with the emphasis on the NSR. Long, continuous, observational data sets are necessary in order to investigate the long-term climatic fluctuations of sea ice. AARI data are the most comprehensive record for the Northern Sea Route and the greater Eurasian Arctic.

Overall, the interannual fluctuations of ice area in Eurasian Arctic seas during the 20th century indicate a gradual decrease through the century. However, interannual to multi-decadal variability in the ice cover area of the Arctic Ocean and its seas can also be characterized as having a quasi-periodic behavior on multiple time scales. AARI data analysis found these variations to be characterized by cyclic fluctuations with periods of 2–3, 5–7, 8–12 years and about 20 and 50–60 years, respectively.

Sea ice data sets derived from passive microwave data are among the longest continuous satellite-derived geophysical records, extending over the last quarter century. Analyses of merged SMMR–SSM/I data establish the decrease in Arctic sea ice area and extent (1978–2005) to be about ~3% per decade. Sea ice decrease in recent decades has been larger during summer, and September 2005 was the absolute minimum extent observed. A relatively large (~7% per decade) reduction in the multi-year ice area was found for the same period.

Knowledge of the long-term variability of ice cover in the Arctic Ocean and its marginal seas is of crucial scientific importance for climate study development, but also of strategic importance for planning shipping and other types of economic activities—such as gas and oil production in the Arctic, particularly in the Northern Sea Route.

The AARI authors of this book present sea ice scenarios for the 21st century using statistical models based on observed climatic variability of sea ice cover in the 20th century and predict that the ice extent will vary with a dominant period of 50–60 years reaching maximums around 2030–2040 and 2090–2095, respectively, and minimums in-between.

On the other hand, the Norwegian group of authors (Johannessen *et al.*, 2004) predict—by use of two coupled global climate models—that a reduction in the ice extent of 80% will occur during the summer as a result a doubling of CO_2 in the atmosphere and 20% during wintertime. These predictions are also strongly supported by the ACIA (2004). However, internal variability of the climate system—as observed with the strong warming event that peaked around 1940 and caused a major reduction in sea ice extent—can upset these predictions (Johannessen *et al.*, 2004). Finally, an assessment is made on how future climate will affect ice conditions in the Northern Sea Route.

The **Afterword** discusses present and future situations regarding gas and oil production and reviews other industrial activities, including the future use of the Northern Sea Route.