White Sea

Its Marine Environment and Ecosystem Dynamics Influenced by Global Change

Nikolai Filatov, Dmitry Pozdnyakov,
Ola M. Johannessen, Lasse H. Pettersson and
Leonid P. Bobylev

White Sea

Its Marine Environment and Ecosystem Dynamics Influenced by Global Change

Published in association with
Praxis Publishing
Chichester, UK

Professor Nikolai Filatov
Northern Water Problems Institute (NWPI)
Karelian Research Centre
Russian Academy of Science
Petrozavodsk
Karelia
Russia

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 Dmitry Pozdnyakov
Dr Leonid P. Bobylev
Director
Nansen International Environmental and and Remote Sensing Centre
St. Petersburg
Russia

Mr. Lasse Pettersson
Nansen Environmental and Remote Sensing Center
Bergen
Norway

SPRINGER–PRAXIS BOOKS IN GEOPHYSICAL SCIENCES
SUBJECT *ADVISORY EDITOR*: Dr Philippe Blondel, C.Geol., F.G.S., Ph.D., M.Sc., Senior Scientist, Department of Physics, University of Bath, Bath, UK
Published in association with the Nansen Group: NIERSC, St. Petersburg and NERSC, Bergen, Norway

---

ISBN 3-540-20541-1 Springer-Verlag Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springeronline.com)
Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available from the Internet at http://dnb.ddb.de

Library of Congress Control Number: 2005923493

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publishers.

© Praxis Publishing Ltd, Chichester, UK, 2005
Printed in Germany

The use of general descriptive names, registered names, trademarks, 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.

Cover design: Jim Wilkie
Project management: Originator Publishing Services, Gt Yarmouth, Norfolk, UK

Printed on acid-free paper

Contents

Preface xi

List of Contributors xv

Acknowledgements xix

List of figures xxi

List of tables xxxi

Abbreviations xxxv

Introduction xxxix

1 Geography of the White Sea and its watershed ***(A.V. Litvinenko, N.N. Filatov, and V.A. Volkov)*** 1
- 1.1 Main features of the White Sea 1
- 1.2 Bottom topography 2
- 1.3 Physical geography of the watershed 4
- 1.4 Physical geography of the administrative units 5
  - 1.4.1 Arkhangelsk Oblast 7
  - 1.4.2 The Murmansk Oblast 9
  - 1.4.3 Republic of Karelia 11

2 White Sea watershed hydrology and anthropogenic impact ***(V.V. Ivanov and V.A. Brizgalo)*** 15
- 2.1 Hydrological features and anthropogenic influence on the catchment 15
- 2.2 Water balance elements and water resources 22
- 2.3 Variability in the hydrological and chemical regimes of river systems 28

2.4 Main features of pollutant transport via river runoff 31
  2.4.1 Mineral forms of nitrogen and phosphorus 31
  2.4.2 Pollutants 36
2.5 Anthropogenic impacts on estuaries 47

3 Climate of the White Sea catchment and scenarios of climate and river runoff changes ***(N.N. Filatov, L.E. Nazarova, Ju A. Salo, and A.V. Tolstikov)*** 53
3.1 Climate 53
3.2 Climatic scenarios and estimation of river runoff changes 67
  3.2.1 Climatic scenarios 67
  3.2.2 Estimation of change in river runoff to the White Sea . . 70

4 Oceanographic regime ***(N.N. Filatov, D.V. Pozdnyakov, Ju.I. Ingebeikin, R.E. Zdorovenov, V.V. Melentyev, A.V. Tolstikov, and L.H. Pettersson)*** 73
4.1 Transparency and optical characteristics. 73
4.2 Circulation patterns and currents in the sea 77
4.3 Water masses and water exchange with the Barents Sea 82
4.4 Fronts and frontal zones. 90
  4.4.1 River runoff fronts 90
  4.4.2 Tidal fronts 92
  4.4.3 Upwelling fronts. 93
  4.4.4 The front between the White and Barents Sea waters. . . 93
  4.4.5 Features of marginal filters (barrier zones) in the bays of the White Sea 94
4.5 Variability of water temperature and currents 96
  4.5.1 Large-scale variability 96
  4.5.2 Mesoscale and synoptic variability 101
4.6 Model study of currents and mass transport processes in some bays and estuaries 107
  4.6.1 A brief description of the model for simulating estuarine currents 108
  4.6.2 Onezhskiy Bay 110
  4.6.3 Estuary of the Kem River 112
  4.6.4 Turbulent diffusion of a conservative pollutant in the coastal zone of the Onezhskiy Bay and the Kem River . 114
4.7 Sea level variations and tides. 118
  4.7.1 Large-scale sea level fluctuations 120
  4.7.2 Synoptic variability 128
  4.7.3 Mesoscale sea level variability 138
4.8 Ice regime and wintertime hydrology of the White Sea 144

5 Aquatic ecosystem profile ***(P.R. Makarevich and Ju V. Krasnov)*** 155
5.1 Phytoplankton 155
5.2 Zooplankton. 160

5.3 Sea birds of the White Sea: Concise characterization of the contemporary status 167
  5.3.1 Abundance 168
  5.3.2 Trophic chains 171
  5.3.3 Factors limiting the development of bird populations in the White Sea 172
5.4 Marine mammals of the White Sea 174
  5.4.1 Abundance 174
  5.4.2 Trophic connections 176
  5.4.3 Limiting factors 177

6 Satellite oceanography: New results ***(D.V. Pozdnyakov, L.H. Pettersson, O.M. Johannessen, P. Bobylev, V.V. Melentyev, N.N. Filatov, V.I. Chernook, A.N. Filatov, A.V. Korosov, A.N. Stuliy, and M.W. Miles)*** 179
6.1 Optical remote sensing 179
  6.1.1 Background 179
  6.1.2 A new water quality retrieval algorithm for case II waters 181
  6.1.2 Advanced tool performance verification and seasonal variations of White Sea CPA concentrations as revealed by SeaWiFS data 193
6.2 Patterns of thermo-hydrodynamic processes and fields from NOAA AVHRR data 205
  6.2.1 Introduction 205
  6.2.2 Data and methods 206
  6.2.3 Results of NOAA satellite data analysis 211
  6.2.4 Discussion and main findings 213
6.3 Satellite SAR and passive microwave remote sensing 217
  6.3.1 Satellite SAR monitoring of ice cover parameters 217
  6.3.2 SAR studies of the White Sea ice cover as a habitat of ice-associated marine mammals 221
6.4 Studies of the White Sea ice cover using satellite passive microwave sensors 234
  6.4.1 Introduction 234
  6.4.2 Data analysis 235
6.5 Conclusions 237

7 Economy of the White Sea watershed area ***(A. Yu Terzhevik, A.V. Litvinenko, P.V. Druzhinin, and N.N. Filatov)*** 241
7.1 Natural resources 241
  7.1.1 Mineral resources 241
  7.1.2 Forest resources 244
  7.1.3 Agriculture 246
  7.1.4 Fuel and energy resources 247
7.2 Demography 248
  7.2.1 Population structure 249

7.2.2 Changes in population 250
7.2.3 Natural population change 250
7.2.4 Life expectancy. 253
7.3 Economic indicators. 254
7.3.1 Gross Regional Product 255
7.3.2 Inflation 260
7.3.3 Industrial production. 260
7.3.4 Agriculture 264
7.3.5 Services and trade. 265
7.3.6 Monetary income 265
7.4 Sectors and branches of the economy 270
7.4.1 Arkhangelsk Oblast. 274
7.4.2 Murmansk Oblast. 277
7.4.3 Republic of Karelia. 283
7.5 Investments 287
7.5.1 Foreign investment 287
7.5.2 Domestic investments. 287
7.6 Identification of socio-economic indices and integration of the relevant data into a database. 288
7.7 Identification and substantiation of the most probable scenarios for industrial development in the White Sea Basin 293
7.7.1 Background. 293
7.7.2 The outlook for future industrial developments in the White Sea Basin region 296
7.7.3 Specific features of regional forecasting based on the scenario approach. 298
7.7.4 Scenarios of probable White Sea Basin industrial development. 301

8 Geographic Information Systems for managing the ecosystem and living resources of the White Sea *(V.V. Rastoskuev, V.K. Donchenko, A.N. Filatov, and E.V. Shalina)* 305
8.1 System structure 305
8.2 Software for the formation of the data warehouse 308
8.3 Formation of digital maps. 309
8.4 Data analysis using the ArcView GIS 311
8.5 Analysis of remote sensing data using the IDRISI GIS. 313
8.6 Information system for decision-making support 321
8.7 Conclusions 326

9 Water quality assessment and the problem of marine ecosystem stability *(V.V. Denisov and A.V. Shavykin)* 329
9.1 Background 329
9.2 Assessment of the White Sea ecosystem 331
9.3 Conclusion. 335

10 Numerical simulations of the White Sea hydrodynamics and marine ecosystem ***(I.L. Bashmachnikov, O.M. Johannessen, L.H. Pettersson, G. Evensen, I.A. Neelov, O.P. Savchuk, A.V. Leonov, S. Kaitala, T. Stipa, H. Kuosa, and N.N. Filatov)*** 337
- 10.1 NERSC–HYCOM hydrodynamic model 337
  - 10.1.1 Model overview 337
  - 10.1.2 The HYCOM implementation for the White Sea. 342
  - 10.1.3 Model experiments 348
  - 10.1.4 Conclusions 366
- 10.2 FIMR 1-D ecosystem model 368
  - 10.2.1 Model overview 368
  - 10.2.2 Physical oceanography basics for the ecosystem model of the White Sea 369
  - 10.2.3 Ecosystem model 373
  - 10.2.4 Model validation 377
- 10.3 FIMR model II: Toward a size structured mixotrophic ecosystem model 378
  - 10.3.1 Introduction. 378
  - 10.3.2 Model equations. 379
  - 10.3.3 Results 381
  - 10.3.4 Conclusions 382
- 10.4 IO RAS – model transformations of organogenic substances in the White Sea ecosystem 384
  - 10.4.1 Introduction. 384
  - 10.4.2 Model description 385
  - 10.4.3 Input data for the model 388
  - 10.4.4 Modeling results and their analysis. 396
  - 10.4.5 Conclusions 408
- 10.5 3-D IO RAS–AARI coupled hydrodynamic–biochemical model . 410
  - 10.5.1 Formulation of the model. 410
  - 10.5.2 Set-up of the numerical experiments 419
  - 10.5.3 Hydrodynamic simulations 420
  - 10.5.4 Control simulations of the White Sea nutrient dynamics. 429
  - 10.5.5 Scenario analysis of the possible response of White Sea eutrophication to climate and nutrient loading changes. . 434
- 10.6 Response of the White Sea ecosystem to future climate change and feedback to the socio-economic conditions 440
- 10.7 Conclusions 441

Afterword 443

References 445

Index 463

Preface

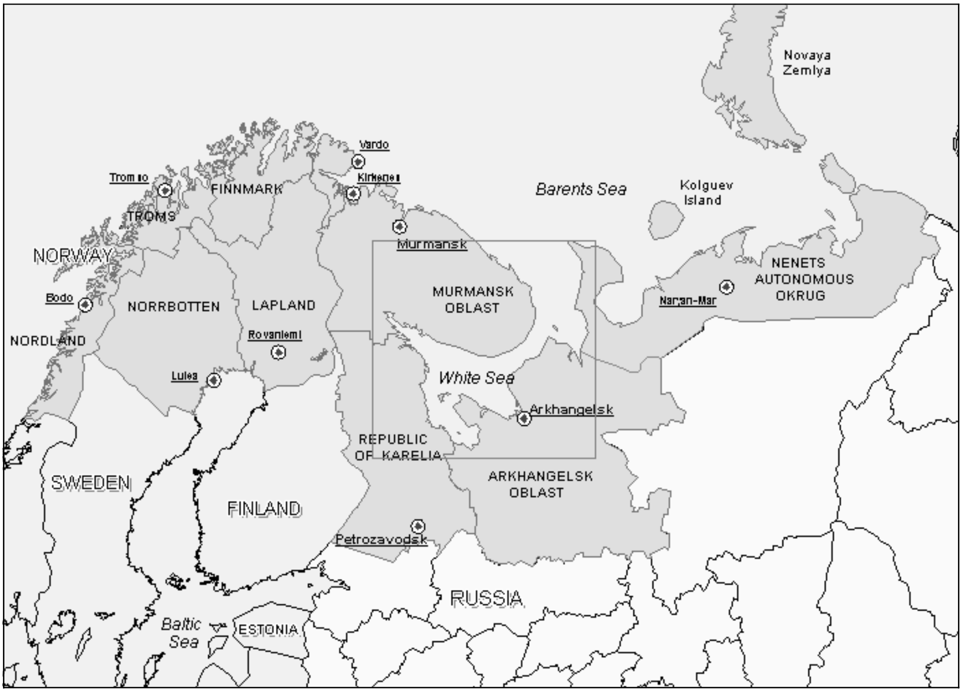
The White Sea, morphologically a shelf marine basin, is located on the periphery of the Arctic Ocean, to which it is connected through the Barents Sea and is essentially a mediterranean sea, being semi-enclosed by the northern European landmass. The White Sea is of significant interest for research of both a scientific and applied nature, owing to its geographical situation, its interactions with the Barents Sea waters, its complex and seasonally ice-covered estuarine and marine environment and ecosytem, as well as its rich natural resources – all under the influence of regional and global change.

This book addresses the contemporary problems of the White Sea and its basin, with special emphasis on the interactions between the marine and socio-economic environments. To investigate the impacts of regional and global change, field observations, remote sensing, numerical modeling, and geographic information system (GIS) technologies are used.

This book is indeed the first attempt to apply a *quantitative*, *multidisciplinary* approach to the assessment of those changes occurring presently and those anticipated in the future to dynamic relationships between the regional socio-economic dimension, global change, and marine ecology. The results presented in this book arise from multiple sources, viz. archival data, contemporary publications and reports, as well as information products obtained using new methods such as satellite remote sensing, GIS, numerical model simulations, and elements of systems analysis. It is this multi-method, multidisciplinary approach that distinguishes this collective work from the previous publications on the White Sea (e.g., Ruchor *et al*., 2000; Berger *et al*., 2001).

To achieve these aims, this book is co-authored by a large team of experts in mathematics, oceanography, sea ice hydrobiology, hydrochemistry, aquatic ecology, economics, and sociology.

The book is organized in ten thematic chapters. *Chapter 1* addresses a range of fundamental aspects related to the geographical position of the White Sea basin.



White Sea on the European map

This chapter characterizes the White Sea as a whole including its principal regions. Morphometric and bottom relief specific features are discussed as related to determining the oceanographic regime in the White Sea. A new digital model of the White Sea bathymetry is presented – a model that has been developed to achieve a high spatial resolution (1–2 km required for precise numerical modeling of the inherent in-water processes). Knowledge of the physical geography of the White Sea and its catchment is important for understanding the essential features of the White Sea basin (both its marine and terrestrial environments). Therefore, special attention is devoted to an analysis of the physical and economic characteristics not only of the White Sea but also of the neighboring regions, namely the Republic of Karelia and the Archangelsk and Murmansk "oblasts".

Chapter 2 is dedicated to the watershed of the White Sea. The discussion here is mostly focused upon water and nutrient input into the White Sea by river discharge. In addition, a range of issues related to the socio-economic status of the coastal area is presented and analyzed for a period covering the second part of the last century. The analyses are performed to trace down the rates of release of pollutants (nutrients primarily) either directly into the sea or via terrestrial pathways.

Chapter 3 is devoted to the regional climate, bringing together the past and present climatic data and analyzing the tendencies of climate variability and change within the White Sea basin. A key factor responsible for the climate formation and variability in the region is atmospheric circulation over the

Atlantic/European sector of the Northern Hemisphere. Based on the analyses of long time series of climate data, numerical simulations were performed in order to explore the options of future change to the regional climate against the background of global climate change scenarios. Possible climate and water balance changes in the studied region were further evaluated for the period 2000–2050 (using two scenarios of CO_2 change: with and without aerosols). Numerical experiments with the ECHAM4 model indicate significant future changes in the climate and hydrological regime of the White Sea. The main thrust of this chapter is to suggest the impact of future changes in regional climate and hydrological regime upon the White Sea basin-associated economy.

Chapter 4 discusses the issues of physical oceanography of the White Sea, based upon the most reliable and recently updated data on water temperature and salinity throughout the year. Circulation patterns and currents in the sea and main shallow bays are also discussed in terms of the influence of atmospheric effects and tides. Special attention is paid to such hydrodynamic features as frontal zones and upwelling. Also discussed are the hydro-optical properties of the White Sea, as these are closely related to spatial and temporal variations of concentrations of color-producing agents (e.g., suspended minerals, dissolved organic matter, and phytoplankton chlorophyll), which are in turn a consequence of both hydrodynamic activity in the White Sea and the inputs from runoff. A hydro-optical model is presented and justified for simulating the aquatic conditions in the White Sea. Additionally, extensive data on specific features of sea-level variations of various natures (including tides) occurring through a range of scales in the White Sea are provided and analyzed. Finally, the ice regime in the White Sea is described based on well-documented evidence obtained from dedicated field experiments and satellite images.

Chapter 5 examines the White Sea ecosystem including phytoplankton, bacterioplankton, zooplankton, sea birds, and mammals. Special emphasis is placed on interactions within the lower part of the trophic chain. Area-specific empirical relationships characterizing the hydrobiont life cycles are given, which is important for further analyses of their responses to changing ambient conditions.

Chapter 6 is dedicated to the use of remote sensing methods for oceanographical investigations. Satellite sensors operating in the visible, infrared, and microwave spectral regions are examined and exemplified. For the first time for the White Sea, remote sensing data from the satellite ocean-color sensor SeaWiFS are used to identify temporal and spatial distributions of the indigenous phytoplankton, suspended minerals, and dissolved organic matter for all vegetation seasons. A new water-quality retrieval algorithm for the White Sea has been developed and validated against concurrent *in situ* measurements. Results of surveillance of spatial and temporal variations of water quality parameters and sea surface temperature, as well as surface manifestations of frontal zones, upwelling events, currents, tides, sea level and sea ice variability are presented. Also used for the characterization of the White Sea, are two decades of satellite passive microwave remote sensing data. For the period 1978–1999 these data have revealed a 16% decrease in sea ice concentration, or $\sim 8\%$ per decade. It is important that the remotely sensed data provided additional evidence that the dynamics of sea ice concentration in the White Sea is in a transitory phase, and is thought to lead to changes in the atmospheric conditions in the region. The chapter also illustrates the feasibility of synthetic aperture radar data to document not only the state of ice cover in the White Sea, but also the dependence of habitats of ice-associated mammals on the state of ice cover throughout the year.

Chapter 7 addresses the socio-economic aspects of the White Sea basin. Characterized are mineral, forestry, fuel/energy resources, as well as demographic features within the White Sea watershed area. Economy-based indicators of the regions development are discussed in detail. Possible changes of these indices under a variety of scenarios are shown for the development of Russia in general and the regions neighboring the White Sea.

Chapter 8 expands on the problem of multidisciplinary data assimilation, creation of value-added digital information products and development of a GIS tailored for the White Sea basin as a prototype of a tool for management and decision-making.

Chapter 9 addresses the most consequential aspects of water pollution and the associated impact on the marine ecosystem. This chapter provides quantitative information on the background sources of White Sea water pollution, as well as the system's reaction to the ongoing degradation of water quality parameters. It is shown that, even if in the case of a revival of the local economic activity and the ensuing regional gross output, the input of industrial and municipal pollutants will not increase more than 10–30%. The assessments made here indicate that this can hardly lead to appreciable changes in the White Sea ecosystem, as such changes would remain within the limits of natural variability. Thus, this multidisciplinary approach suggests that for future scenarios of socio-economic development, the White Sea ecosystem would not be drastically altered.

Chapter 10 presents several thermodynamic and ecosystem models for the White Sea. These numerical models are intended to assess the impact of possible climatic and socio-economic changes on the thermo-hydrodynamics of the White Sea, as well as its marine chemical and biological status. Three 3-D prognostic models (High-Resolution Isopycnic Ocean Model (HYCOM), the IO RAS model developed at the Institute of Oceanology, and the AARI–NIERSC model developed at the Arctic and Antarctic Research Institute and the Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia) were exploited to this end. In addition, models developed at the Institute of Oceanology, Russian Academy of Sciences, Moscow, and the Finnish Institute of Marine Research, Helsinki, were implemented. Descriptions of the models are followed by ample examples of their realization for past, present, and future forecasts. The latter are based on the above-mentioned scenarios of the regional climate change and anthropogenic nutrient loading.

In the *Afterword*, the present state-of-the-art and future developments in the area of nature conservation under conditions of stable socio-economic progress are summarized.

List of contributors

Igor L. Bashmachnikov	Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway/St. Petersburg State University (SpbSU), St. Petersburg Russia. E-mail: `igor.bashmachnikov@horta.uac.pt`
Leonid P. Bobylev	Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia. E-mail: `leonid.bobylev@niersc.spb.ru`
Valentina A. Brizgalo	Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia. E-mail: `brizgalo@aari.nw.ru`
Vladimir V. Chernook	Polar Institute of Fishery and Oceanography (PINRO), Murmansk, Russia. E-mail: `chernook@pinro.murmansk.ru`
Vladimir V. Denisov	Murmansk Marine Biological Institute (MMBI), Russian Academy of Sciences (RAS), Murmansk, Russia. E-mail: `denisov@mmbi.info`
Vladislav K. Donchenko	Scientific Research Centre for Ecological Safety (SRCES), Russian Academy of Sciences (RAS), St. Petersburg, Russia. E-mail: `donchenkovk@mail.ru`
Pavel V. Druzhinin	Institute of Economics (IE), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `pdruzhinin@mail.ru`

Geir Evensen	Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway. E-mail: `Geir.Evensen@hydro.com`
Nikolai N. Filatov	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `nfilatov@ nwpi.krc.karelia.ru`
Andrei N. Filatov	Scientific Research Centre for Ecological Safety (SRCES), Russian Academy of Sciences (RAS), St. Petersburg, Russia. E-mail: `an_fil@mail.ru`
Jury I. Ingebeikin	Institute of Ecological Problems of the North (IEPN), Russian Academy of Sciences (RAS), Archangelsk, Russia. E-mail: `ocean@pomor.su.ru`
Vladimir V. Ivanov	Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia. E-mail: `ivanov@aari.nw.ru`
Ola M. Johannessen	Nansen Environmental and Remote Sensing Center (NERSC)/Mohn–Sverdrup Center for Global Ocean Studies and Operational Oceanography (MSC)/ Geophysical Institute, University of Bergen, Norway. E-mail: `ola.johannessen@nersc.no`
Seppo Kaitala	Finnish Institute of Marine Research (FIMR), Helsinki, Finland. E-mail: `seppo.kaitala@fimr.fi`
Anton A. Korosov	Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia. E-mail: `anton.korosov@niersc.spb.ru`
Jury V. Krasnov	Murmansk Marine Biological Institute (MMBI), Russian Academy of Sciences (RAS), Murmansk, Russia. E-mail: `krasnov@mmbi.info`
Harri Kuosa	Finnish Institute of Marine Research (FIMR), Helsinki, Finland. E-mail: `kuosa@fimr.fi`
Aleksander V. Leonov	Institute of Oceanology (IO), Russian Academy of Sciences (RAS), Moscow, Russia. E-mail: `leonov@sio.rssi.ru`
Aleksander V. Litvinenko	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `litvinenko@nwpi.krc.karelia.ru`

P. R. Makarevich	Murmansk Marine Biological Institute (MMBI), Russian Academy of Sciences (RAS), Murmansk, Russia. E-mail: `makarevich@mmbi.info`
Martin W. Miles	Bjerknes Center for Climate Research (BCCR), Bergen, Norway/Environmental Systems Analysis Research Center (ESARC), Boulder, USA. E-mail: `martin.miles@esarc-colorado.org`
Vladimir V. Melentyev	Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia. E-mail: `vladimir.melentyev@niersc.spb.ru`
Larisa E. Nazarova	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `nazarova@nwpi.krc.karelia.ru`
Ivan A. Neelov	Arctic and Antarctic Research Institute (AARI)/ Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia. E-mail: `neelov@aari.nw.ru`
Lasse H. Pettersson	Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway. E-mail: `lasse.pettersson@nersc.no`
Dmitry V. Pozdnyakov	Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia. E-mail: `dmitry.pozdnyakov@niersc.spb.ru`
Viktor V. Rastoskuev	Scientific Research Centre for Ecological Safety (SRCES), Russian Academy of Sciences (RAS), St. Petersburg, Russia. E-mail: `v.rastoskuev@rambler.ru`
Jury A. Salo	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `salo@nwpi.krc.karelia.ru`
Oleg P. Savchuk	Department of Systems Ecology, University of Stockholm, Sweden/State Institute of Oceanology (SOI), St. Petersburg, Russia. E-mail: `oleg@system.ecology.su.se`
Elena V. Shalina	Scientific Research Centre for Ecological Safety (SRCES), Russian Academy of Sciences (RAS), St. Petersburg, Russia. E-mail: `v.rastoskuev@rambler.ru`

Anatoly A. Shavykin	Murmansk Marine Biological Institute (MMBI), Russian Academy of Sciences (RAS), Murmansk, Russia. E-mail: `anatoli.shavykin@mail.ru`
Tapani Stipa	Finnish Institute of Marine Research (FIMR), Helsinki, Finland. E-mail: `tapani.stipa@fimr.fi`
Alexei N. Stuliy	Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway. E-mail: `alexei.stuliy@unis.no`
Arkady Ju. Terzhevik	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `ark@nwpi.krc.karelia.ru`
Alexey V. Tolstikov	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `tolstikov@nwpi.krc.karelia.ru`
Vladimir A. Volkov	Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia. E-mail: `vladimir.volkov@niersc.spb.ru`
Roman E. Zdorovennov	Northern Water Problems Institute (NWPI), Karelian Research Centre (KRC), Russian Academy of Sciences (RAS), Petrozavodsk, Russia. E-mail: `romga@nwpi.krc.karelia.ru`

Acknowledgements

This book has been based primarily on the results obtained during the European Commission (EC) 5th Framework Programme (FP5) INCO-Copernicus project “Sustainable Management of the Marine Ecosystem and Living Resources of the White Sea – WHITESEA” (contract no. ICA2-CT-2000-10014). The project was coordinated by Prof. Ola M. Johannessen, with Lasse H. Pettersson as deputy coordinator. The project consortium consisted of the Nansen Environmental and Remote Sensing Center (coordinator), Bergen, Norway; Finnish Institute for Marine Research, Helsinki; Nansen International Environmental and Remote Sensing Centre and Scientific Research Centre for Ecological Safety, Russian Academy of Sciences, St. Petersburg, Russia; Northern Water Problems Institute, Petrozavodsk, Karelia, Russia; and Murmansk Marine Biological Institute, Murmansk, Russia. The above project participants acknowledge the financial support received from the European Commission.

The compilation, writing and editing of the book has also been supported by the EC FP5 “EcoMon” project (INCO-CT-2004-003605) as well as a Nordic network grant from the Nordic Council of Ministers, administrated through the Research Council of Norway and the Mohn–Sverdrup Center for Global Ocean Studies and Operational Oceanography (MSC) at the Nansen Center in Bergen. Dr. Igor Bashmachnikov acknowledges his NATO Science Grant for his one-year work at NERSC.

Additionally, included are the research results obtained by the Zoological Institute, Russian Academy of Sciences, and the Arctic and Antarctic Research Institute and Northern Hydrometeorological Service, Russian Federation, under the program of basic studies launched by the Russian Academy of Sciences and Russian Federation program “World Ocean: Seas of the USSR”.

The new digitized bathymetric map of the White Sea presented in Chapter 1 has been purchased from TRANSAS (TRANsport SAfety Systems) electronic technologies company, St. Petersburg. The authors of Chapter 3 thank Dr. S. I. Kuzmina for kindly providing climate simulation data. The authors of Chapter 7 thank Dr. Sh. Baibusinov, Ms. A. E. Kurilo, and Ms. M. V. Belokozova for the provision of socio-economic data for the region.

The authors also express their gratitude to the crew of the R/V *Ecolog* of the Northern Water Problem Institute, especially to Mr. V. Kovalenko for the excellent organization of research cruises in the White Sea and to Dr. P. Bojarinov, Mr. A. Mitrochov, and Mr. M. Petrov, who took part in these cruises and processed and analyzed collected *in situ* data, as well as to Prof. A. Buznikov and Mr. A. Elisov for conducting IR-radiometric measurements on board the R/V *Ecolog*. Additionally the authors thank Drs. E. Lupyan and A. Mazurov from the Space Research Institute of the Russian Academy of Sciences in Moscow for their provision of NOAA data for the White Sea.

The authors extend their gratitude to E. Valikhan and O. Kislova for the translation of parts of the manuscript from Russian to English, to Mr. L .V. Zaitzev, V. Kekkonen, and Ju. Rozanova for their valuable technical assistance, as well as to Mr. I. Yu. Georgievsky for providing photos of the White Sea.

Figures

1.1 Map of the White Sea and adjacent land areas, with reference to the main geographic features . . . . color
1.2 Comparison of the IBCAO and TRANSAS/NIERSC digital bathymetry models for the White Sea . . . . color
1.3 Boundaries of the administrative divisions (oblasts and republics) in the White Sea catchment (indicated by a dotted line) 6

2.1 Location of industrial activities within the catchment of the White Sea 20
2.2 Location of the study areas and duration of observations of river runoff within the White Sea catchment 23
2.3 Long-term variability in the river water runoff into the White Sea 24
2.4 Seasonal variations of the river runoff into the White Sea 25
2.5 (a) Interannual and (b) seasonal variations of the freshwater inflow to the White Sea due to river water inflow and atmospheric precipitaton contribution 28
2.6 Location of the hydrochemical observation stations in the rivers of the White Sea basin performed under the GON 31
2.7 Interannual variability in the concentrations of mineral forms of nitrogen and phosphorus in the estuaries encompassed by the White Sea 34
2.8 Seasonal variability of concentrations of mineral forms of nitrogen and phosphorus in the estuaries encompassed by the White Sea 35
2.9 Interannual variability of the concentrations of pollutants in the estuaries encompassed by the White Sea 38
2.10 Interannual variability in mean annual amounts (thousand of tons year^{-1}) of the most abundant pollutants in the river runoff 44
2.11 Seasonal variations of the water and chemical runoff as assessed by averaging the relevant multi-year data for some rivers 46

3.1 Locations of the SWS stations: ● = hydrological stations; ● = weather stations and sites 54
3.2 Annual cycle of sunshine duration at Kem and Louhi stations 59

3.3 Mean annual air temperature at some weather stations in the White Sea catchment 61
3.4 Fluctuations of near-surface air temperature at the Archangelsk station for 176 years of observations 62
3.5 Frequency spectrum of near-surface air temperature at the Archangelsk station during 176 years of observations 62
3.6 Variability of the surface water temperature in the White Sea 63
3.7 Variability of the mean annual water surface temperature in both the Barents Sea and the White Sea 64
3.8 Multi-year series of annual atmospheric precipitation at (a) Kolezhma, (b) Zasheyek, and (c) Louhi stations 65
3.9 Annual dynamics of relative air humidity 67
3.10 Spatial distribution of mean air temperature in the White Sea region as observed from 1950–1999, and for simulated future options 68
3.11 Observed and modeled time series of the water balance elements for north-western Russia. All values are 15-year moving averages 69
3.12 Time series and linear trend of the total runoff into the White Sea between 1882–1988 72

4.1 Patterns of major currents in the White Sea 78
4.2 Major water circulation patterns as established by Deriugin and Timonov . . . 79
4.3 Water circulation patterns in the White Sea as established from on board the R/V *Ivan Petrov* 80
4.4 System of persistent surface currents in the White Sea 81
4.5 Types of water masses in the White Sea as they are displayed along the White Sea transect, and the *T–S* diagram 83
4.6 Spatial distribution of water surface temperature fields across the White Sea in different seasons: (a) spring, (b) summer, (c) autumn 84
4.7 Distribution of water masses across the White Sea during spring 85
4.8 A vertical profile of water temperature distribution along the Voronka–Gridino transect 86
4.9 Typical stratified vertical distribution of both water temperature and salinity in Kandalakshskiy Bay during summer 89
4.10 Typical mixed distribution of both water temperature and salinity in the shallow part of Onegskiy Bay during summer 90
4.11 Seasonal location of the boundaries of river plumes 92
4.12 Monthly variations of the location of the tidal front in the White Sea 93
4.13 Location of stations at which water temperature is routinely measured in the White Sea 98
4.14 Variability of the water surface temperature in the White Sea (1977–1998) . . . 99
4.15 Surface temperature variations in June–July 1991 99
4.16 Variability of both the water temperature near the bottom and sea level near the Kuzovskie Islands (12–15 July, 2000) 102
4.17 Frequency spectra of sea level and water surface temperature variability in Kandalakshskiy Bay 106
4.18 Variability of current speed and direction in the estuary of the Kem River at an 8-m depth (4–7 July, 2000) 107

4.19 Water temperature fluctuations measured at depths ranging between 1 m and 10 m in the region of the Kuzovskie Islands during 12–15 July, 2000 . . . . color
4.20 Bays and estuaries in the White Sea Basin used for modeling and verification experiments. 109
4.21 Bathymetry of Onezhskiy Bay and location of sea level tide gauges 111
4.22 Calculated current speed and sea level distributions across Onezhskiy Bay . . . 113
4.23 Water level variations as obtained from tide-gauge measurements 114
4.24 Calculated spatial distributions of current speeds and water levels for a single tidal cycle 115
4.25 Areas of propagation of pollution in the Onezhskiy Bay. 117
4.26 Location of the plume three tidal cycles after model initiation for minimal and maximal rates of discharge of the Kem River 119
4.27 The mean square of interannual variations of sea level in the White Sea and fractiles of annual water level at a number of stations 121
4.28 Quantile diagrams of maximal, average, and minimal seasonal variabilities of sea level at the Umba station 124
4.29 Fractal diagrams of maximal, average, and minimal seasonal variabilities in sea level at the Onega station. 125
4.30 Variations of sea level as assessed by the Darwin method at a number of stations 128
4.31 Amplitude and root mean square deviations of the White Sea mean level. . . . 129
4.32 Storm surge distribution in Dvinskiy Bay and across the White Sea. 130
4.33 Frequency spectrum of sea level variations at the Kem-Port and Mudyug stations 131
4.34 Types of cyclonic movements over the White Sea from 1902–1965. 133
4.35 Storm-driven surges at some stations in late 1963. 134
4.36 Variations of sea level at some stations 139
4.37 Spatial distributions of phases and amplitudes for waves K_1, M_2, and M_4 . . . 140
4.38 Spectrum of sea level oscillations as registered at the Onega station. 143
4.39 Spatial distributions of phases and amplitudes corresponding to seishes ranging from one to five nodes. 146
4.40 Distribution of the ice cover in the White Sea in February 149
4.41 Distribution of the ice cover in the White Sea in March 150
4.42 Distribution of ridged ice zones in the White Sea in March. 151
4.43 Monthly mean anomalies of air temperature distribution over the Arctic in March 2002 152
4.44 Ice cover mapped by the DMSP SSM/I satellite passive microwave sensor on 4 March, 2002 . . . . color
4.45 Monthly mean anomalies of air temperature distribution over the Arctic in March 2003 153
4.46 Ice cover mapped by the DMSP SSM/I satellite passive microwave sensor on 17 March, 2003 154

6.1 Retrievals of *chl*, *sm*, and *doc* by the L–M procedure, and comparison with the modeled data 186
6.2 Same as Figure 6.1 but utilizing a NN simulator 189
6.3 Flow diagram of the advanced water quality retrieval algorithm for case II waters 190

6.4 Location of stations and the determined concentrations of *chl* in Onezhskiy Bay 194
6.5 Shipborne measurements of near-surface water temperature in Onezhskiy Bay, 10–13 July, 2001 196
6.6 Shipborne measurements of surface salinity in Onezhskiy Bay, 10–13 July, 2001 197
6.7 SeaDAS-based retrieval of concentration of *chl* from a SeaWiFS image taken over Onezhskiy Bay in July, 2001 198
6.8 New tool-based retrieval of concentrations of *chl* from a SeaWiFS image taken over Onezhskiy Bay in July, 2001 198
6.9 Same as Figure 6.8 but for the *sm* concentration 199
6.10 Same as Figure 6.8 but for the *doc* concentration 199
6.11 Spatial distribution of *chl* in the White Sea as retrieved from a SeaWiFS image of 7 April, 2001 201
6.12 Spatial distribution of *chl* across the White Sea from a SeaWiFS image, 25 May, 2001 201
6.13 Same as Figure 6.11 but for 21 June, 2001 202
6.14 Same as Figure 6.11 but for 28 August, 2001 202
6.15 Same as Figure 6.11 but for 2 October, 2001 203
6.16 Qualitative comparison between the *chl* spatial distribution obtained from a SeaWiFS image taken over the White Sea in early May, 2001 and the simulated phytoplankton biomass for the same time period and year 204
6.17 Same as Figure 6.16 but for late June, 2001 205
6.18 Same as Figure 6.16 but for late October, 2001 205
6.19 Spatial distribution of the mean SST as measured by a shipborne infrared radiometer and retrieved from NOAA AVHRR data, 10–14 July, 2001 208
6.20 Comparison of the SST as (a) measured by an IR radiometer on board the NWPI R/V *Ecolog* and (b) retrieved from NOAA AVHRR 210
6.21 Seasonal variability of the SST in the White Sea . . . . . color
6.22 Seasonal transformations of sea ice fields as revealed from AVHRR images taken in 2002 . . . . . color
6.23 Development of tidal/upwelling fronts and eddies of various spatial dimensions as revealed from the AVHHR data obtained in July, 2001 . . . . . color
6.24 Types of mesoscale and synoptic water circulation patterns in the White Sea as revealed by NOAA images 214
6.25 RADARSAT SAR image of the White Sea and the adjacent part of the Barents Sea taken on 28 February, 1998 215
6.26 RADARSAT SAR imagery of the White Sea and the adjacent part of the Barents Sea (28 February and 4 March, 1998) 216
6.27 ERS-2 SAR image of the White Sea and neighboring regions taken on 12 March, 1997 and aerial photography of the whelping rookery, situated in the Gorlo 223
6.28 DMSP SSM/I image of the White Sea and adjacent regions taken in March, 2000 and 2003 . . . . . color
6.29 Results of the validation performed from on board the PINRO flying laboratory *Arktika* over a zone of whelping rookeries – ice breccia and ice cake color
6.30 RADARSAT SAR image of the White Sea taken on 21 December, 2001 227
6.31 RS-2 SAR image of the White Sea and adjacent regions taken on 4 March, 1999 228
6.32 RS-2 SAR image of the White Sea and the adjacent regions taken on 20 March, 2000 229

6.33 NOAA-14 AVHRR image of the White Sea and the adjacent regions taken on March 21, 2000 . . . color
6.34 RADARSAT and ERS SAR images of the White Sea and adjacent regions taken in March, 1998 . . . 232
6.35 Results of aerial charting of the migration of Greenland seal whelps conducted in March, 2000 . . . color
6.36 Results of aerial charting of migration of Greenland seal whelps accomplished, on 18 March (a) and 19 March, 2000 (b), respectively. According to these airborne data, the ice conditions during the 1999/2000 winter were favorable for the reproduction and migration of harp seals . . . color
6.37 The White Sea Basin as partitioned into five regions: 1. Onezhskiy Bay; 2. Dvinskiy Bay; 3. the Bassein; 4 Mezenskiy Bay; and 5. the Voronka . . . 236
6.38 The ice concentrations across the White Sea (observed from satellite) in November, 1978 . . . color
6.39 Mean monthly sea ice concentration in the White Sea in January for each year as derived from employed passive microwave satellite data for the period 1987–1999 . . . color
6.40 Same as Figure 6.39 but for the mean monthly sea ice concentration in February of each year for the same time period . . . color
6.41 Variations in ice concentration in the White Sea during the winters of 1978–1999 . . . color

7.1 Distribution of mineral resources in the Murmansk Oblast and the Republic of Karelia . . . color
7.2 Distribution of mineral resources in the Archangelsk Oblast . . . color
7.3 Change in the population during the period 1991–2000 and the anticipated demographic development up to 2010 in the White Sea region . . . 251
7.4 Rate of child mortality in the White Sea region during the period 1998–2002. 252
7.5 The GRP growth index. . . . 260
7.6 Electric power production . . . 263
7.7 Agricultural production . . . 269
7.8 Turnover of the retail trade (billions of rubles for the period 1990–1998, and millions of rubles during 1998–2002) . . . 269
7.9 Per capita turnover of the retail trade . . . 270
7.10 Volume of commercial services . . . 270
7.11 Mean monthly per capita money income . . . 271
7.12 Dynamics of the mean per capita real disposable income in Karelia . . . 272
7.13 Fraction of the population in the White Sea region that live below the subsistence level . . . 272
7.14 The GRP as partitioned between different sectors in 2001 . . . 274
7.15 Foreign trade turnover . . . 279
7.16 Unemployment rate for the economically active population . . . 282
7.17 Changes in the ownership structure in industry . . . 282
7.18 Dynamics of the main ecological indices compared to the GRP . . . 287
7.19 Foreign investments in the White Sea region during the period 1995–1999 . . . 288
7.20 Investment into fixed capital . . . 289
7.21 Dynamics of the major environmental indices in comparison with the GRP of the Republic of Karelia . . . 290

7.22 Dynamics of the U index reflecting the impact of the Karelian economy on the environment 291

8.1 The three levels of the information system 306
8.2 General structure of the information system 307
8.3 Structure of the local information system software 308
8.4 Illustration of the GUI 309
8.5 Steps required to create digital maps 310
8.6 Structure of a data warehouse 311
8.7 Illustration of the base Wsea1mdb tables (a fragment) 312
8.8 Illustration of the base Wsea2mdb tables (a fragment) 312
8.9 Map of the White Sea region as displayed in the window of the ArcMap module 313
8.10 Nominal GRP in the White Sea region in the 1994–1998 period in current prices 314
8.11 The White Sea region: structure and output of the regional industry in 1999 . 315
8.12 Main stages of data analysis by means of a raster GIS 317
8.13 Distribution of SST across the White Sea 318
8.14 Signal variations inherent in profile 1 of Figure 8.13 319
8.15 A histogram retrieved from the image displayed in Figure 8.13 319
8.16 Results of classification of the image in Figure 8.13 320
8.17 Structure of the information system intended for the Internet 321
8.18 The White Sea search system using keywords 323
8.19 Operational scheme of the program used to compile the keyword lists 324
8.20 Databases accommodated by the system 324
8.21 Remote sensing data stored in the information system 325
8.22 Decision-making support facility based on running the “IF ... THEN” scenarios 325
8.23 Scenarios considering the nutrient load in the White Sea 326

9.1 Index of water contamination in the White Sea in August 1986 . . . . . color
9.2 Monthly indices of water contamination in the White Sea during 1986 . . . . . color
9.3 Index of water contamination for the White Sea for the 1984–1989 period . . . . . color
9.4 Change of water quality in the White Sea for an increase of pollutants average-weighted concentration of 10% . . . . . color
9.5 Change of water quality in the White Sea for an increase of pollutant average-weighted concentration of 30% . . . . . color

10.1 Correspondence between the water freezing temperature and the temperature of maximum density for the UNESCO-83 and HYCOM equations of state 343
10.2 Normalized histograms for water depth ranges in the NIERSC–TRANSAS data set and the smoothed data used in the White Sea HYCOM 344
10.3 Contours of the model mesh and depth. Only every second meshline is shown 345
10.4 The surface circulation in the White Sea and the circulation in the White Sea at a depth of 100 m 349
10.5 Model experiments on horizontal mixing: WH1 (*top*), WH4 (*middle*), WH5 (*bottom*) with the water salinity varying between 22–28‰ with a 2‰ interval . 352

10.6 Model experiments on horizontal mixing: WH1 (*top*), WH7 (*middle*), WH8 (*bottom*) with the salinity varying as in Figure 10.5 353
10.7 The typical summertime vertical profile of water salinity along the Bassein–Kandalalakshskiy Bay transect 355
10.8 Simulations of the vertical profile of sea temperature along the Bassein–Kandalakshskiy Bay transect in July and February, 1989. 356
10.9 Simulations of averaged (over 1989) summertime surface salinity in the White Sea. 357
10.10 Simulations of averaged (over 1989) summertime circulation patterns of surface waters in the White Sea 358
10.11 Modeled circulation patterns in the White Sea for hybrid layer 5 (at depths of 50–100 m) 361
10.12 Model simulated patterns of currents and surface water salinity in the south-western Gorlo 362
10.13 Simulated circulation of surface water in the White Sea in August and January, 1989. 363
10.14 Simulated variability of water temperature and salinity at a station in the Bassein. 364
10.15 Simulated mean distribution of seawater temperature in the top 10-m layer for the summer of 1989 365
10.16 The observed mean probability of ice coverage in the White Sea in February and May 366
10.17 Simulated ice cover extension in the White Sea in 1989 in late February and early May. 367
10.18 The relative sea ice cover extent and the light penetration into the water column without ice cover and with ice cover 370
10.19 Mixed layer depth M_z: simulations vs. observations 371
10.20 Cone for mixed layer and bottom layer volume calculations 372
10.21 Ecosystem model for validation 374
10.22 Content of inorganic nutrients in the mixed layer. color
10.23 Development of plankton groups . . . . color
10.24 Development of detrital forms of nutrients . . . . color
10.25 Development of inorganic nutrients in the lower layer . . . . color
10.26 Development of inorganic nutrients in the mixed layer . . . . color
10.27 Development of plankton groups . . . . color
10.28 Development of detrital forms of nutrients . . . . color
10.29 Development of inorganic nutrients in the lower layer . . . . color
10.30 Development of inorganic nutrients in the mixed layer . . . . color
10.31 Development of planktonic groups . . . . color
10.32 Development of detrital forms of nutrients . . . . color
10.33 Development of inorganic nutrients in the lower layer . . . . color
10.34 Nutrient flows resulting from a suite of trophic interactions within the model of the ecosystem 379
10.35 Model integration with the closed model. 382
10.36 Model integration with losses. 383
10.37 Model integration with a constant level of nutrient input and sedimentation . 383
10.38 Subdivision of the White Sea into water regions 1–8. 387
10.39 Simulated seasonal variations in the concentaation of phosphorus-containing compounds in the selected aquatic reqions (1–8) of the White Sea 398

10.40 Simulated seasonal variations of concentrations of nitrogen-containing compounds in aquatic regions (1–8) of the White Sea 399
10.41 Simulated seasonal variations of concentrations of compounds in aquatic regions (1–8) of the White Sea 400
10.42 Simulated seasonal variations in the biomass of various hydrobionts in aquatic regions (1–8) of the White Sea 401
10.43 Modular structure of the coupled hydrodynamic–biogeochemical model. 410
10.44 A generalized scheme of biogeochemical fluxes between the variables determining the system state. 418
10.45 Modeled variations of sea surface level and salinity at a 30 m depth 420
10.46 Modeled distribution of sea surface currents in April, as averaged over 1948–2000. 421
10.47 Modeled distribution of sea bottom currents in April, as averaged over 1948–2000. 421
10.48 Modeled distribution of sea surface currents in August, as averaged over 1948–2000. 422
10.49 Modeled distribution of sea bottom currents in August, as averaged over 1948–2000. 422
10.50 Modeled distribution of sea surface salinity in April, as averaged over 1948–2000. 423
10.51 Modeled distribution of sea surface salinity as averaged over 1948–2000 423
10.52 Modeled distribution of the vertical profile of water salinity along the Gridino–Voronka transect in April and August, as averaged over 1948–2000 424
10.53 Modeled distribution of the vertical profile of seawater temperature along the Gridino–Voronka transect in August, as averaged over 1948–2000. 424
10.54 Distribution of the sea surface temperature in August, as averaged over 1948–2000. 425
10.55 Contours of the M2 tidal amplitude at the sea surface 425
10.56 Distribution of sea surface currents in August 1958 426
10.57 Distribution of sea surface currents in August 1958 427
10.58 Temporal variations of water discharge from the Barents Sea through the Gorlo 427
10.59 Long-term seasonal dynamics of five-day means of salinity, sea ice thickness, nitrate concentration, and phytoplankton biomass in the control run averaged over the entire White Sea. 428
10.60 Simulated dynamics of ice thickness . . . . color
10.61 Simulated dynamics of phytoplankton biomass . . . . color
10.62 Simulated average distribution of the zooplankton biomass at 15 m depth . . . color
10.63 Simulated seasonal dynamics of phytoplankton in the major regions of the White Sea. 431
10.64 As for Figure 10.63 but for zooplankton 432
10.65 As for Figure 10.63 but for detritus 433
10.66 As for Figure 10.63 but for ammonium. 434
10.67 As for Figure 10.63 but for nitrite 435
10.68 As for Figure 10.63 but for phosphate 436
10.69 Five-year averaged (1996–2000) seasonal dynamics of salinity and seawater temperature in the White Sea simulated in the control run and climatic scenario 438
10.70 Five-year averaged (1996–2000) seasonal dynamics of biomass of the phytoplankton and zooplankton in the White Sea simulated in the control run and the climatic scenario 438

10.71 Five-year averaged (1996–2000) seasonal dynamics of the concentration of dissolved inorganic nitrogen in the White Sea as simulated in the control run, climatic scenario, and anthropogenic impact scenario (3) 439
10.72 Five-year averaged (1996–2000) seasonal dynamics of the concentration of dissolved inorganic phosphorus in the White Sea as simulated in the control run, climatic scenario, and anthropogenic impact scenario. 439

Tables

1.1 Area and population of units in the White Sea watershed 5

2.1 River catchments in the White Sea region 18
2.2 Amount of pollutants brought into the White Sea annually 21
2.1 River catchment areas in the White Sea region 26
2.4 Basic hydrometeorological variables from the GON (river lowest stations) within the White Sea Basin 32
2.5 Dissolved oxygen, nitrogen, and phosphor-containing compounds in the rivers flowing into the White Sea 33
2.6 Prevailing pollutants identified at the lowest stations on the rivers flowing into the White Sea basin 37
2.7 Ranges in mean annual amounts of chemical substances in river runoff for the catchment area within the Murmansk region 40
2.8 Ranges in mean annual amounts of chemical substances in the river runoff in the Republic of Karelia 41
2.9 Ranges in mean annual amounts of chemical substances in river runoff in the Archangelsk region 43
2.10 Seasonable variability of nitrogen and phosphorus-containing compounds in the river outlets into the White Sea 45
2.11 Quantitative assessment of the spatial variability of the runoff module of most abundant pollutants: coastal zone of the White Sea 48
2.12 "Anthropogenically-altered" natural background for the major pollutants in river outlets of the White Sea basin 50

3.1 Mean wind directions for the White Sea region over the 50°N–70°N latitudinal zone during the period 1951–2000 57
3.2 Mean monthly and annual wind velocities 58
3.3 Mean monthly and annual air temperature 60
3.4 Statistical characteristics of the surface water temperature (mean daily data) at some stations 63

3.5 Mean annual and maximum daily rates of precipitation at some stations in the White Sea 66
3.6 Mean monthly precipitation over the west coast of the White Sea 66
3.7 Observed and modeled changes in the mean annual air temperature and water balance elements within the WSC 70
3.8 The mean annual water income from the WSC 71

4.1 Monthly mean values of variables characterizing the light climate and water temperature in the White Sea 74
4.2 Observed mean monthly and annual freshwater inflow into the White Sea . . . 86
4.3 Main characteristics of the mean annual water surface temperature in the White Sea. 88
4.4 Linear trend of sea level variations at various stations in the White Sea, and the contribution of different mechanisms to the trend 122
4.5 Mean and maximal heights and periods of "negative" surges (numerator) and positive surges (denominator) in various regions of the White Sea 137

6.1 Results of the NASA OC4 algorithm application for retrieving the concentrations of *chl* in case I and II waters (numerical experiments). 184
6.2 The architecture and respective retrieval errors for a set of built up NNs 188
6.3 Improvement of the CPA retrieval accuracy due to a sequential use of a "rough" NN in combinations with "specialized" NNs 191
6.4 Improvement of the tool performance in comparison with the facility of the L–M procedure *per se* 191
6.5 Admissible errors in the retrieval of *chl* in case II waters 191
6.6 Concentration ranges for *sm* and *doc* given a 10% uniform λ-independent noise 192
6.7 Concentration ranges for *sm* and *doc*, given a 15% uniform and λ-independent noise 192
6.8 Concentration ranges for *sm* and *doc*, given a 10% uniform λ-dependent noise 192
6.9 Concentration ranges for *sm* and *doc*, given a 15% uniform and λ-dependent noise 193
6.10 Concentration ranges for *sm* and *doc*, given a 15% normal and λ-independent noise 193
6.11 Results of *in situ* measurements in Onezhskiy Bay, July 2001, surface layer . . 195
6.12 A comparison of water quality variables retrieved for Onezhskiy Bay with the SeaDAS code and the advanced bio-optical algorithm (July, 2001) with respective *in situ* data. 200
6.13 The comparative characteristics of satellite sensors 225
6.14 A summary of trend analyses of changes in the ice concentration in the White Sea. 236

7.1 Estimates of resources of some minerals in the Murmansk Oblast.. 242
7.2 State Forest Fund of the Russian Federation and north-western Russia as of 1 January,1998.. 245
7.3 Timber resources of the White Sea regions as assessed in 1993 and 1998. 245
7.4 Distribution of forests by vegetative zones in the White Sea region.. 245
7.5 Forest classification in the White Sea region performed in 1993. 246

7.6 Volumes of standing timber distributed by main tree species in the White Sea region as assessed in 1993 247
7.7 Partitioning of the forested area by tree age in the White Sea region as assessed in 1998 248
7.8 Demography of the White Sea region on 1 Jan, 2003.. 249
7.9 Change in population of the White Sea region during the 1991–1999 period. . 250
7.10 Forecast population in the White Sea region in 2000–2010.. 251
7.11 Growth of the population in the White Sea region during 1997–2002. 252
7.12 Net migration of the populace in the White Sea region during 1993–2002 . . . 253
7.13 Life expectancy in the White Sea region during 1990–2002 254
7.14 Distribution of the population in north-western Russia among various sectors of the economy 256
7.15 Enterprises in different sectors of the economy as of 1 January, 2003. 258
7.16 Indicators of the privatisation process 258
7.17 Small enterprises in different sectors of the regional economy as of January 1, 2003. 259
7.18 Nominal GRP during the 1994–2001 period 259
7.19 Mean annual RUR/USD Exchange Rates. 259
7.20 Volumes of industrial production 261
7.21 Per capita volumes of industrial production. 261
7.22 Industrial production as partitioned between different branches in 2002 262
7.23 Sawn-timber resources 263
7.24 Roundwood production. 263
7.25 Paper production 264
7.26 Walling material production. 264
7.27 Production of other products 266
7.28 Change of the industrial production during 1990–2002 268
7.29 Mean monthly implicit wages (in thousand rubles per employee in the period 1990–1998, and in rubles during 1998–2002) 271
7.30 Population with the income below the subsistence level. 273
7.31 Main features of the largest industrial enterprises in northwestern Russia in 2002. 274
7.32 Timber harvesting volumes during 1992–1997 276
7.33 Volumes of forestry industry production 276
7.34 Structure of the regional export 277
7.35 Export of forestry products from the Arkhangelsk oblast during 1997–1999 . . 278
7.36 The flux of foreign investments. 288
7.37 Relative investments into the fixed capital 289
7.38 Per capita investments into fixed capital 290

8.1 Nominal GRP in 1994–1998 in current prices 316
8.2 The structure and output of the industry in the White Sea region in 1999 . . . 316
8.3 Description of the columns in Table 8.2 316

9.1 MPCs of pollutants and indices of the environment state of seawater 333
9.2 Assessment criteria of seawater pollution. 333

10.1 Topographic characteristics of the White Sea Basin 344
10.2 Initial layering and mixing parameters for the White Sea HYCOM 350
10.3 Mixing parameters for the White Sea HYCOM 351

10.4 Water masses inherent in the White Sea 354
10.5 Seasonal variability of the total river discharge into the White Sea 359
10.6 Observed and simulated seawater temperature in the upper 10-m layer for some regions in the White Sea 364
10.7 Calculated mean monthly values of flow rates at the boundaries of water areas 1–8 of the White Sea, in river mouth zones, and at the abutment with the Barents Sea. 389
10.8 Initial concentrations of the biogenic substances taken into account for simulations of the annual dynamics in water areas 1–8 of the White Sea 394
10.9 Mean seasonal observations of concentrations of oxygen, phosphate, silicate, nitrite, and nitrate in different water areas of the White Sea 397
10.10 Simulated annual production by hydrobionts in various regions of the White Sea. 406
10.11 Estimated monthly and annually averaged values of the productivity rate of diatoms 407
10.12 A comparison between the simulated and actual harmonic constants for the M2 tide at several locations in the White Sea. 426
10.13 Annual and basin averaged concentrations of oxidized nitrogen and phosphate 429
10.14 Ranges of variations for hydrographic and nutrient variables in the different water masses of the White Sea 430
10.15 Simulated long-term (1995–2000) mean monthly concentrations of oxidized nitrogen and phosphate averaged over the surface layer in different regions of the White Sea. 437

Abbreviations

AARI	Arctic and Antarctic Research Institute
AREC	Arkhangelsk Regional Environmental Centre
ASAR	Advanced Synthetic Aperture Radar
AT	advanced tool
AVHRR	Advanced Very-High Resolution Radiometer
BOD	biological oxygen demand
CARDINAL	Coastal Area Dynamics Investigation Algorithm
chl	chlorophyll
CIS	Commonwealth of Independent States
CPA	color-producing agents
DFI	direct foreign investment
DMSP	Defence Meteorological Satellite Program
doc	dissolved organic carbon
dom	dissolved organic matter
EOOC	easily oxidizable organic compound
ESA	European Space Agency
FIMR	Finnish Institute for Marine Research
GCM	general circulation model
GDP	gross domestic product
GON	governmental observation network
GIS	geographic information system
GRP	gross regional product
GRPI	GRP index
GUI	Graphical User Interface
HEPS	hydroelectric power station
HYCOM	Hybrid Coordinate Ocean Model
II	industry index
INCO	International Cooperation (EC program)

IO	Institute of Oceanology
IR	infrared
ISS	Institute for Space Sciences
KPP	K-Profile Parameterization
KRC	Karelian Research Centre
LM	Levenberg–Marquardt
LMMVOA	L–M Multivariate Optimization Algorithm
MAL	maximal admissible loads
MEPC	maximum ecologically permissible concentration
MLP	multi-layer perceptron
MMBI	Murmansk Marine Biological Institute
MODIS	Moderate-Resolution Imaging Spectroradiometer
MPC	maximum permissible concentration
MUMM	Management Unit of the Northern Sea Mathematical Models
NAO	North Atlantic Oscillation
NDVI	normalized difference vegitation index
NERSC	Nansen Environmental and Remote Sensing Centre
NIERSC	Nansen International Environmental and Remote Sensing Center
NIS	New Independent States
NN	neural network
NOAA	National Oceanic and Atmospheric Administration
NORSEX	Norwegian Remote Sensing Experiment
NWPI	Northern Water Problems Institute
PCA	principal component analysis
PF	production function
PINRO	Polar Institute of Fishery and Oceanography
PSA	Production Sharing Agreement
RAS	Russian Academy of Science
RHS	Russian Hydrometeorological Service
RSSOMEP	Russian State Service of Observation and Monitoring of Environmental Pollution
SAR	synthetic aperture radar
SAS	surface-active substance
SD	Secchi Depth
sd	sunshine duration
SeaDAS	SeaWiFs Data Analysis System
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SLP	sea level pressure
SLR	side-looking radar
sm	suspended minerals
SMMR	Scanning Multichannel Microwave Radiometer
SSAS	synthetic SAS
SSL	sea surface level
SSM/I	Special Sensor Microwave/Imager
SST	sea surface temperature

SWS	State Weather Service
TEP	thermal-electric power station
UV	ultraviolet
WBS	water balance stations
WPI	water pollution index
WSC	White Sea catchment
WSL	loads on the White Sea ecosystem
WSMES	White Sea Marine Experimental Station

Introduction

The White Sea is attracting increasing attention from both scientists and society. This is due to a new stage in developing the resources of the White Sea and its catchment. These regional developments include diamond and gold mining, fishing, farming of mariculture, transport of natural gas from the Stockmann gas deposit of the Barents Sea to western Europe, and consequently, a major change in the entire infrastructure for new enterprises. Nearby, Sweden, Norway, Finland, and other countries are taking an interest in the development of this region, as are the neighboring parts of Russia. Thus, the territory of interest is a large area that may be called the Euro–Barents Region with the White Sea at its centre. The region also includes the "Northern Dimension" of the European Commission.

It is probable that during the forthcoming few years, the role of Belomorsko-Baltiysky Channel will increase. The channel links the Baltic, White, Caspian, and Black Seas with the Arctic Ocean. The importance of the White Sea proper, as a transport corridor linking numerous regions with the Arctic seas, would therefore increase accordingly.

The above-mentioned challenges, together with quite a few traditional ones (such as the use of marine bio-resources, wood cutting, the impacts of the pulp-and-paper industry, and waste discharges from cities and towns located on the shores and in the catchment) will require scientific recommendations for the rational use and protection of the marine resources.

Historically, the White Sea region is a unique Russian territory, where, throughout the ages, various paths in man's economic activity, based on the use of diverse natural resources, were developed successfully. These include: fish and marine mammal harvesting and processing; fur-bearing animal hunting and the fur trade; agriculture and cattle breeding; timber production; and others. All these activities were developed both within and outside the region (Alekseev and Kulachkova, 2001). For a long time, the White Sea was used jointly by the Russian coast-dwellers (the so-called pomors) and Norwegians; shipping trade routes linked it with foreign countries. The pomor trade between Norway and Russia reached significant dimensions during the 18th century. These circumstances created the necessary prerequisites for the relative well-being of the population in the region. However, in recent years the White Sea region's population has had difficulties related to fishing (the main local occupation). A tendency of declining industrial and agricultural production has also been observed over the entire White Sea region. However, this has not improved the marine ecosystem because the municipal and industrial waste discharge has not been reduced.

During the 1970–1980s, when the White Sea resources were being extensively exploited, numerous investigations of the White Sea were initiated under several scientific programs of various scopes, such as "The World Ocean", "Study of the Arctic and Antarctic Oceans and Seas", and "The Seas of the USSR". The results of these investigations have been summarized in a number of monographs. However, these have been published nearly exclusively in the Russian language.

During and since the 1990s, many of the Russian government-supported programs (such as "The World Ocean") have had their budgets appreciably cut and the extent of field campaign activities in the White Sea has become significantly reduced. However, studies addressing the White Sea continued to steadily enlarge due to international projects (INTAS, EC INCO-Copernicus) and some other projects, including the Russian Foundation for Basic Research (RFBR) programs. Comprehensive studies performed since 1981 within the government-supported project "The White Sea" (coordinated by the Zoological Institute of the Russian Academy of Sciences (RAS)) made it possible to work out a scientific basis for the potential enhancement of the White Sea's bio-productivity. The developed scientific recommendations have been tested in practice. It has been revealed that regardless of the Arctic/sub-Arctic nature of the White Sea, it has a number of specific features, including sufficiently clean water, that are beneficial for the development of fish, mussels, and seaweeds. Clearly, at the present time, along with bio-resources exploitation, shipping, and diamond and gas development, some importance should be attributed to the exploitation of the unique and yet untapped recreation potential of the region through attracting tourists from Russia and other countries.

Despite the previous efforts, we still lack systematic knowledge of the functioning of the White Sea marine ecosystem and its response to external forcing. The required configurations of coupled marine thermo-hydrodynamic and ecosystem models have not been developed. The processes and transformation of the aquatic environment constituents, as well as the regularities in water exchange have not yet been adequately studied. The same is the case for studies of the impacts of climate change and anthropogenic forcing upon the marine ecosystem dynamics.

The number of autonomous buoy stations for current measurements remains insufficient. *In situ* determinations of water exchange through the Gorlo (see Figure 1.1) as well as that between the Barents and White Seas are particularly scarce and inadequate. Numerous investigations have been recently conducted by a number of organizations (e.g., Russian Hydrometeorological Service (RHS); Zoological and Oceanological Institutes of the RAS in St. Petersburg; Murmansk Marine Biological Institute (the Kola Scientific Centre); Northern Water Problems

Institute (NWPI), Karelian Research Centre (KRC) of the RAS in Petrozavodsk; Polar Institute of Fishery and Oceanography (PINRO) in Murmansk; All-Russia Research Institute of Fishery and Oceanography; State University of Moscow; and the State University of St. Petersburg). These studies, as a rule, were carried out as isolated, non-coordinated research instead of being integrated into a solid and sustainable comprehensive program. At the same time, very significant contributions to marine studies from numerous scientific institutions of the former USSR should be mentioned. In particular, the results achieved between 1991–1999 under the above-mentioned programs "The Seas of the USSR" and "The World Ocean" (with the Zoological Institute, RAS, as a leading team with academicians E. A. Scarlato and A. F. Alimov as scientific supervisors). Large amounts of data, including those obtained by the Roshydromet (RHS) network, can only be purchased from its commercial branches, and are frequently not affordable for many governmental organizations and the international scientific community.

Special attention should be given to studying important factors that determine the particular features of the sea's regime, such as quantitative estimation of the water exchange rate and advection of heat and salt by Barents Sea currents. According to Elisov (1997), the Barents Sea current brings about 26% of the heat accumulated within it throughout the year into the White Sea. Characteristic features of the White Sea water dynamics, producing an essential influence on the water exchange rate and ecological conditions in the coastal zone and estuaries, are coastal mesoscale eddies, upwelling and entrained waves; these have not yet been studied adequately.

It is equally important to study the "biohydrochemical barrier zones" originating in the riverine estuaries of the White Sea (Lisitsyn, 1994; Skibinsky, 2001). It is assumed that the convergence zone formed therein cuts off, at least partially, the deep central part of the sea from the influence of the coastal region and estuaries, and thus "protects" the deeper part of the water body of the White Sea from contamination by various pollutants. Therefore, along with an integrated multidisiplinary approach to the investigation of the whole marine ecosystem, a comprehensive study is also required of numerous bays and estuaries of the White Sea, because they play an essential role in the formation of the overall marine ecosystem, as well as in its functioning.

The ecosystem studies of inlets, bays, and estuaries are also important for the solution of both scientific and practical problems (for instance, the development of mariculture (aquaculture), which was successfully completed here in the early 1990s) – including interdisciplinary studies addressing the formation of the pool of organic matter, production–decomposition processes, all forms of nutrients, phytoplankton, etc.

A thorough investigation of responsiveness of the White Sea ecosystem to anthropogenic impacts is also needed. Its starting point may be the data that characterize the state of the White Sea ecosystem during the 1950s and 1960s, when the anthropogenic forcing was not large enough to cause significant alterations. This period may conventionally be taken as a "background" or reference period. Comprehensive investigations of the White Sea conducted in 1956 and further in 1982 revealed an appreciable increase in the concentration of organic matter in the marine water over the 25-year period of strong anthropogenic forcing. The weighted average content of C_{org} in the marine water has increased by more than 50% from 3.0 to 4.7 mg/l (Maksimova, 1978). In recent years, there have been certain negative changes in the White Sea basin's rivers due to petroleum products and industrial discharge. The marine biota also revealed some unfavorable changes (e.g., a decreased number of mollusks and an increased amount of *Polychaeta* worms, distorted proportions between the counts of mussels and sea-stars, as well as changes in the structure of salmon shoals (Alimov, 2001)).

During 1999–2003, the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, and the Nansen International Environmental and Remote Sensing Centre (NIERSC) in St. Petersburg, in cooperation with a number of Russian and European research institutions (namely, NWPI, KRC, RAS; the Arctic and Antarctic Research Institute (AARI) in St. Petersburg; the Murmansk Marine Biological Institute (MMBI); the Kola Research Centre, RAS, in Murmansk; the Scientific Research Centre for Ecological Safety (SRCES), RAS, in St. Petersburg; the Max-Planck Institute of Meteorology in Hamburg, Germany; and the Finnish Institute for Marine Research (FIMR) in Helsinki), coordinated (by Prof. Ola M. Johannessen) and implemented the following international research projects: the EC INCO-Copernicus project "WHITESEA" No. ICA2-CT-2000-10014, "Sustainable Management of the Marine Ecosystem and Living Resources of the White Sea", and the INTAS projects: INTAS-97-1277 "Detection and Modeling of Greenhouse Warming in the Arctic and Sub-Arctic".

As a result of the studies conducted within the scope of the INCO-Copernicus project, a dedicated geographic information system (GIS) has been developed for the White Sea. Databases have been compiled for the estimation of the current state of, and anticipated and potential variations in, the marine ecosystem due to anthropogenic forcing and climate change. The developed GIS and databases are presently accessible to a wide circle of researchers and society, including decision-makers. For the first time, coupled thermo-hydrodynamic and ecosystem models were implemented to assess the White Sea marine ecosystem's functioning and prediction of its potential future variations.

In the course of the above projects, it has become clear that of primary importance, for an adequate estimation of the state of the sea and its catchment, is the use of advanced up-to-date techniques such as satellite remote sensing methods and numerical modeling in combination with dedicated field experiments. The contemporary state of the socio-economic development in the White Sea region has also been considered. In summary, the following work has been completed:

- Collection of long-term, multi-year hydrometeorological observational data obtained from the investigations and network monitoring by the RHS in the vicinity of the White Sea, as well as from the data provided by a number of the Russian academic institutions.
- Development of unique databases encompassing satellite remote sensing observations from SeaWiFS, NOAA AVHRR, ERS SAR, Envisat ASAR, and satellite passive microwave sensor systems.

- Analyses of long-term observations for climate variability.
- Multi-year calculations using the ECHAM-4 coupled climate model to assess changes in the atmosphere and the ocean for the White Sea region.
- Simulations performed with the use of several ecosystem models.
- Evaluation of variations in the marine ecosystem for some scenarios of socio-economic changes.

As a result, some scenarios have been formulated for the estimation and assessment of possible changes in the White Sea ecosystem in response to external forcing. Our scientific studies can also be used by decision-makers in government and industry.