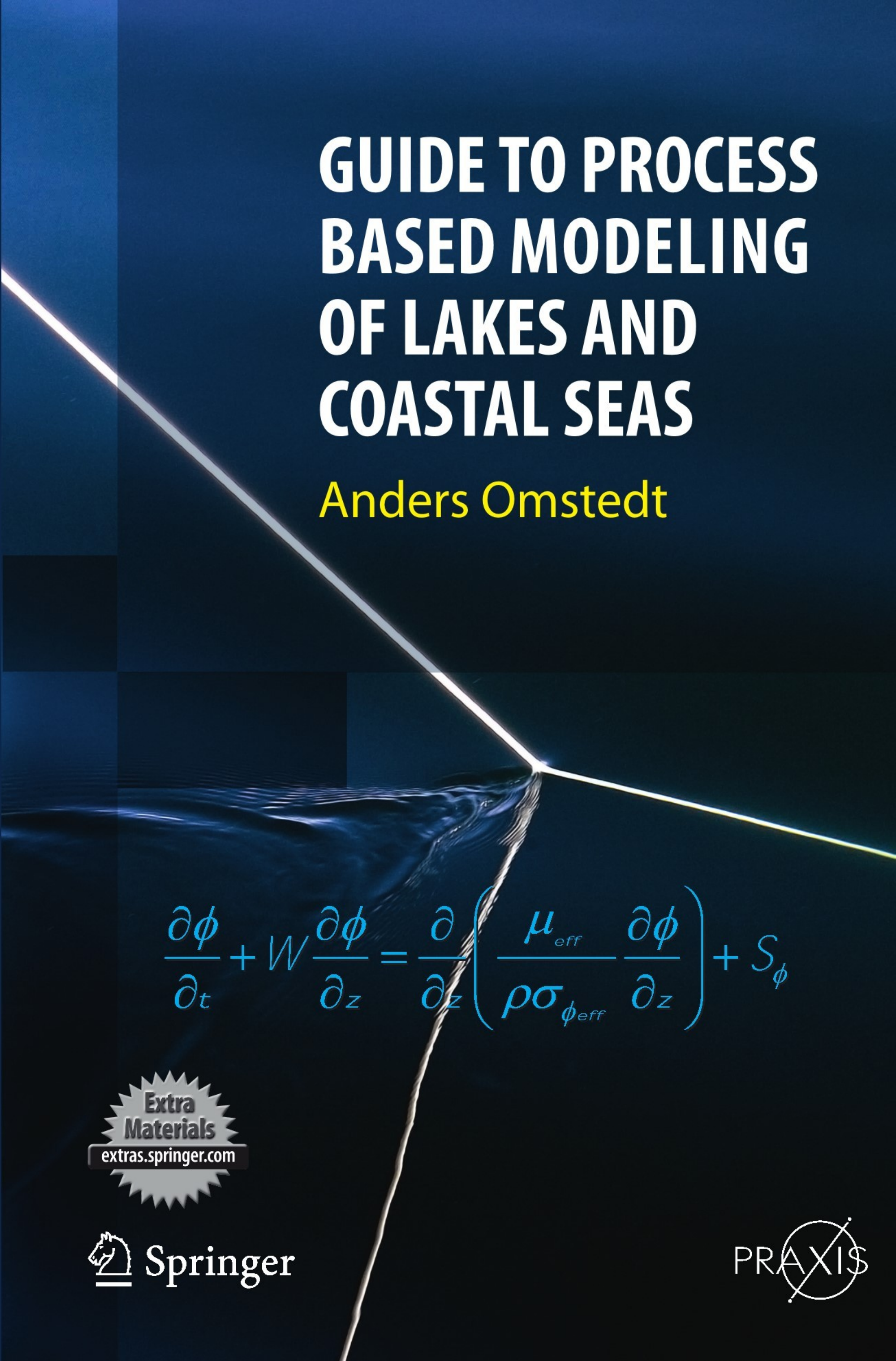

GUIDE TO PROCESS BASED MODELING OF LAKES AND COASTAL SEAS

Anders Omstedt

$$\frac{\partial \phi}{\partial t} + W\frac{\partial \phi}{\partial z} = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho \sigma_{\phi_{eff}}}\frac{\partial \phi}{\partial z}\right) + S_{\phi}$$

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Preface

Guide to Process Based Modeling of Lakes and Coastal Seas is based on a series of lectures delivered to students at advanced and Ph.D. levels at the Department of Earth Sciences, University of Gothenburg. It is intended to provide the reader with a scientific understanding and well-tested computer code for successful aquatic studies. The intended reader should have some knowledge of geophysical fluid dynamics, numerical analysis, and computer programming. The structure of the *Guide* allows readers to develop their understanding gradually. Incorporating a range of exercises with solutions, the *Guide* is a comprehensive teaching aid. Learning via a combination of reading, analyzing observations, and building computer models is a very rewarding process. This approach also makes it possible for the learner to follow scientific developments, test new ideas, and evaluate research results.

The feature most characteristic of valid science is reproducibility. If scientists from different research groups cannot reproduce new results, they must conclude that they are invalid. This is the great strength of science, as it generates a system for self-correction. Earlier efforts and even some current research efforts have had problems in this area. Data and models are often gathered and developed at single institutions by scientists who are largely concerned with completing their research programs. The development of adding supplementary material to published articles represents a step forward. Quality-controlled shared databases are urgently needed, as are peer-reviewed data evaluations. Models introduce an even greater problem, as they are often undergoing development and unavailable to the broader scientific community. The need to make model codes, model forcing data, and output data available to other groups is therefore fundamental. This *Guide* seeks to make aquatic modeling transparent and to share with the reader the joy of discovery inherent in scientific work.

Anders Omstedt
January 2011

Cover photo: Observations and mathematical modeling are the two major tools for learning more about aquatic systems. The photo was taken during turbulence measurements under calm conditions in the Gullmar Fjord on the Swedish west coast
(photo courtesy of Christian Stranne).

Foreword by Urban Svensson

(Computer-aided Fluid Engineering AB)

The Ekman spiral, the benthic boundary layer, and the wind are all responsible for inducing near surface flow in a lake. They are all examples of environmental boundary layers. The atmospheric boundary layer is another member of this class of flows. As heat and matter are transported across these boundary layers it is clear that all contributions to the understanding of the nature of these flows are of great value.

The computer code PROBE (Program for Boundary Layers in the Environment) is intended to be a tool for use in the study of the these classes of flows. The history of PROBE goes back to 1975 when I was a student at Imperial College, London. Professor Brian Spalding supervised me in a number of small projects, dealing with environmental flow and heat transfer. One of these considered the seasonal thermocline in lakes—a project that was later (1978) presented as my Ph.D. In 1982 I took up a position at the Swedish Meteorological and Hydrological Institute (SMHI). Together with my colleagues at SMHI, PROBE was further developed and also used in real world problems. Among the major developments during the early 1980s I would like to single out frazil ice dynamics (work done by Anders Omstedt), heat transfer in lakes including sediments (work done by Jörgen Sahlberg), and transport across the benthic boundary layer (work done by Lars-Arne Rahm). In 1986 I left SMHI, and soon after my involvement in PROBE ended. During the last 20 years Anders Omstedt and Jörgen Sahlberg have successfully continued the development of PROBE and have linked biogeochemical variables to the code.

This book gives a detailed account of PROBE. Emphasis is placed on the basic equations (both physical and biogeochemical) and the methods for their solution. As the computer code and exercises are also included, the reader should be able to get a full understanding of (and be able to repeat) most of the simulations presented in the book.

Finally, I should like to say that it gives me great pleasure to see that the work I once initiated is now the subject of a book.

Foreword by Jörgen Sahlberg

(Swedish Meteorological and Hydrological Institute)

A large step was taken by Anders Omstedt in 1990 when he used PROBE to model the whole Baltic Sea as 13 sub-basins—including the Kattegat, the Belt Sea, and Öresund—and as a result achieved high vertical resolution in each basin. This was the first attempt to use PROBE on more than one coupled sub-basin. This model, called PROBE-Baltic, has been further developed during the last 20 years and has been used in many different applications: for example, it is capable of simulating the effect of climate change on salinity, temperature, and ice conditions in the Baltic. During the last 5–10 years PROBE has also been used for solving biogeochemical equations in both the PROBE-Baltic model and the closely related Coastal Zone model. Anders has used the PROBE-Baltic model to investigate the uptake and release of carbon dioxide in the Baltic and bottom oxygen conditions as a result of different physical forcing.

My own contribution during the last 10 years has been development of the Coastal Zone model—an extension of the PROBE-Baltic model. It was developed mainly to describe the nitrogen, phosphorus, oxygen, and phytoplankton conditions in coastal waters around Sweden. Today, it covers the whole of the Swedish coast and is applied to more than 600 coupled sub-basins. The model has also been applied to Lake Mälaren (situated close to Stockholm).

SMHI recently developed a web-based interface in close cooperation with the Swedish water management authorities. The idea behind this was to enable decision makers to carry out, for example, scenario studies using the Coastal Zone model in order to check whether the Swedish environmental goal of "good water quality by year 2015" was likely to be achieved.

During the last 30 years the PROBE model has been used in many different applications and in more than 100 scientific articles. As a main part of the Coastal Zone model PROBE is today used over the Internet using the web-based interface. In the future we will probably see and use the PROBE model in cloud computing.

Finally, I would like to thank Urban Svensson and Anders Omstedt for all the valuable PROBE discussions we have had over the years. Anders deserves special thanks for his initiative in writing this book.

Acknowledgments

This book started as a collection of lecture notes for students from the Department of Earth Sciences, Oceanography, University of Gothenburg and from SMHI. Many have contributed to the development of this material, including Leif Anderson, Lars Axell, Göran Björk, Ulf Cederlöf, Deliang Chen, Moa Edman, Christin Eriksson, Mattias Green, Bo Gustafsson, Erik Gustafsson, Daniel Hansson, Matti Leppäranta (who added many useful comments to this book), Helma Lindow, Christian Nohr, Leif Nyberg, Johan Rodhe, Anna Rutgersson-Owenius, Bernd Schneider, Artur Svansson, Karin Wesslander, and Anna Wåhlin. Special thanks are extended to the BALTEX Secretariat for their strong support of Baltic Sea research, to Jim Overland for many years of friendly discussions, to Urban Svensson for creating a really useful program, to Anders Stigebrandt for his bold approach to science, to Jörgen Sahlberg for his firm support, and to Gösta Walin for his pure scientific spirit.

Thanks are also due to Krister Boquist, Barry Broman, Phil Graham, Brian MacKenzie, Anders Moberg, and Jörgen Nilsson for making the data available. Agneta Malm is acknowledged for help with several figures.

Capable computer support from Martin Johnsson and Mats Olsson have made the work easier. The positive spirit at the Department of Earth Sciences and in the BALTEX research community have made my time working on modeling very productive and fun.

This work was partly financed by the University of Gothenburg, the Swedish Research Council, and the BONUS/Baltic-C program.

Figures

Tables

Abbreviations and acronyms

BALTEX	The BALTic Sea EXperiment
BONUS	Baltic Organizations Network for fUnding Science
CFD	Computer Fluid Dynamics
FORTRAN	FORmula TRANslation
GOTM	General Ocean Turbulence Model
HIRLAM	HIgh ResoLution Atmospheric Model
HYMEX	HYdrological Cycle in the Mediterranean EXperiment
MIB	Maximum annual Ice extent in the Baltic Sea
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
PROBE	PROgram for Boundary Layers in the Environment
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
T–S	Temperature–Salinity

1

Introduction

The use of computational fluid dynamics to analyze and predict environmental changes has increased considerably in recent decades. Numerical models are now standard tools in research and in a wide range of applications. Increasing concerns about human influence on climatic and environmental conditions has increased the need for multi-disciplinary modeling efforts, including the numerical modeling of oceans, lakes, land surfaces, ice, rivers, and the atmosphere. Scientists have traditionally developed specialized models limited to application within their own disciplines. Today, increasing efforts are being made to develop general equation solvers that allow users to create a code applicable to a broad range of problems.

The book guides its reader through process based modeling, using the PROBE general equation solver and building understanding step by step. The equation solver has been used in many applications, particularly in Sweden and Finland with their numerous lakes, archipelago seas, fjords, and coastal zones. It has also been used for process studies in the Arctic and in the Mediterranean Sea. The process based approach, developed in this book, divides the studied water body into dynamically relevant parts or natural sub-basins and identifies the major processes involved in the problem. Based on field observations and simplifications, the dynamics are expressed mathematically and tested carefully against relevant analytical solutions, extremes, and observations.

Lakes and coastal seas represent important human resources and are often subjected to much human activity. They have various geometries, ranging in size from small ponds to large sea areas, and are strongly influenced by their surrounding land areas. Water bodies are generally considered lakes when they are located inland and are not part of the ocean, which is why the Caspian Sea is regarded as the world's largest lake. At approximately 25 million years old, Lake Bajkal is probably the world's oldest lake; with depths of about 1,700 m, it is certainly the deepest. Most

A. Omstedt, *Guide to Process Based Modeling of Lakes and Coastal Seas,* Springer Praxis Books,
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lakes are much smaller and most lie in the Northern Hemisphere. Canada, the U.S.A., the Nordic countries, and Russia, for example, have many lakes, which often become ice covered in winter as well.

Coastal seas are the water bodies that connect the land with the ocean, and their various types include open broad and flat continental shelves, semi-enclosed seas, fjords, estuaries, archipelago seas, and delta coasts. In the case of both lakes and coastal seas, the geometries of the water bodies can be complex, involving geometric constrictions such as sounds, sills, islands, coral reefs, and sub-basins such as bays and gulfs (Figure 1.1). Bathymetric features, surrounding hydrology, and climate strongly influence the dynamic and thermohaline processes in these aquatic systems. The Baltic Sea, for example, is a non-tidal coastal sea affected by eutrophication and nutrient recycling. The White and North Seas are both strongly influenced by tides and by small and large human populations, respectively. The Caspian Sea and the North American Great Lakes are examples of closed inland seas. The Mediterranean Sea, the Black Sea, Hudson's Bay, and the Baltic Sea, on the other hand, are seas having limited exchange with surrounding coastal zones due to narrow straits and sills.

We often lack complete data series of temperature and other properties for various water bodies. Figure 1.2 shows how the results of a coastal sea model can reproduce the surface temperatures in various parts of the Baltic Sea. The model can be validated over periods and from regions for which measurements are available. Over periods when measurements are sparser—for example, Bothnian Bay in the 1980–1992 period—we are presented with only an approximation from observations of environmental conditions. A combination of models and observations is needed both to detect changes in observations and to attribute causes to the changes by using models.

Another example related to water balance will illustrate model extrapolation. Over the last hundred years, freshwater inflow to the Baltic Sea has hovered around a mean of $15{,}000\,\mathrm{m}^3\,\mathrm{s}^{-1}$. What would happen if the freshwater supply increased? The curves in Figure 1.3 indicate that, if the freshwater inflow were tripled, the Baltic Sea would be transformed into a freshwater sea. Can one rely on that result, and how is one supposed to know? The calculations indicate that the sea is sensitive to variations in freshwater inflow, though it is highly unrealistic to conceive of an increase of several hundred percent. The calculations indicate that the Baltic Sea will remain brackish in the future. This example has interesting implications for the portion of model results that lie outside the observed range. When using models, we of course must be careful with extrapolations as they are unsupported by direct validation data. However, the potential to extrapolate is a major part of the reason we develop models, as they can teach us something outside present observational knowledge.

A third example is how process based modeling can yield important knowledge about marine system dynamics. Björk and Söderkvist (2002) investigated ice thickness in the Arctic Ocean. The basic processes considered in modeling are depicted in Figure 1.4. Modeling only resolves the vertical dimension, and the processes working in horizontal directions were parameterized. The approach ex-

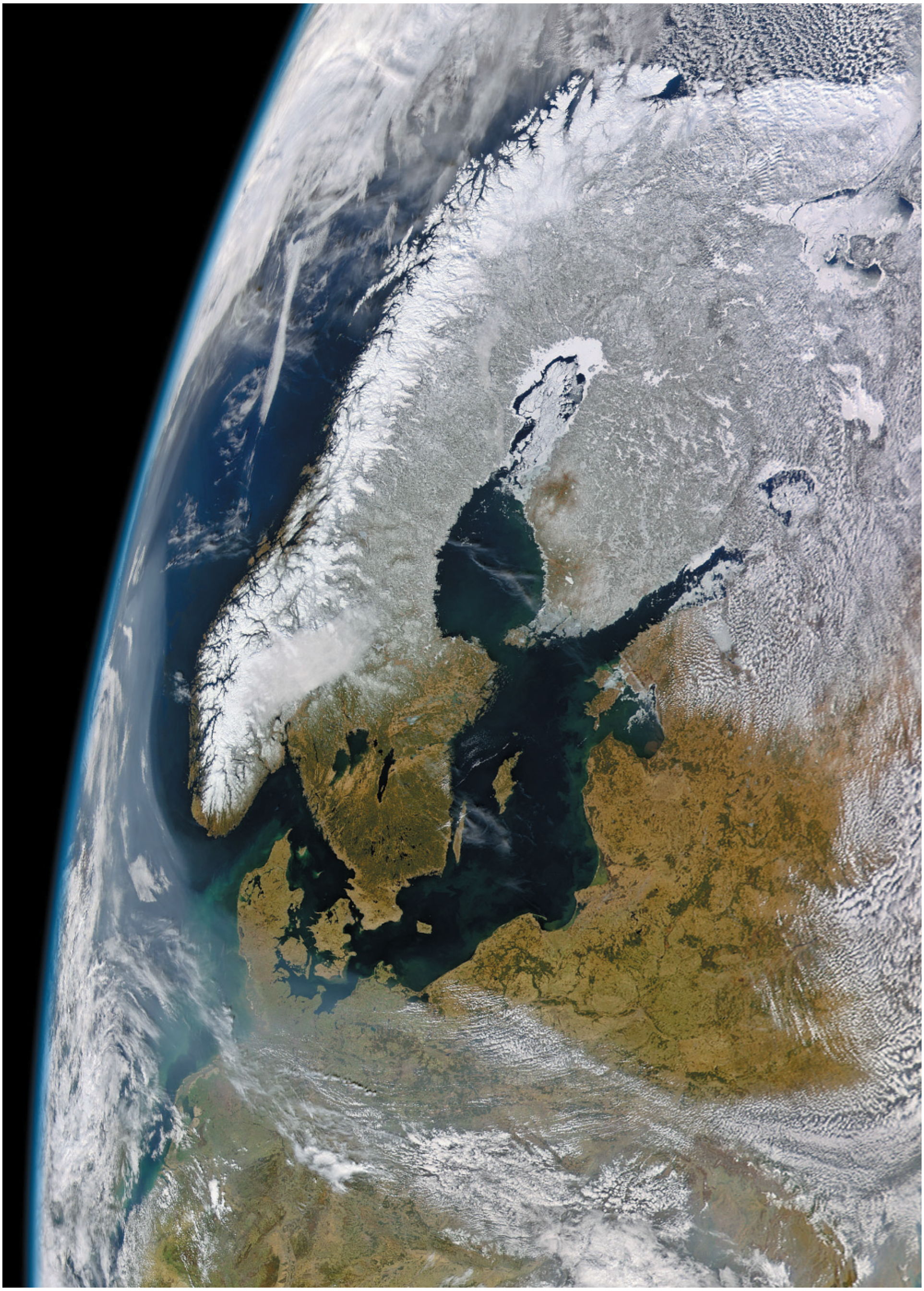

Figure 1.1. Northern Europe on April 1, 2004, as seen from the SeaWiFS satellite (NASA/Goddard Space Flight Center, *http://visibleearth.nasa.gov/*).