Foreword

The simulation of turbulent mixing processes in marine waters is one of the most pressing tasks in oceanography. It is rendered difficult by the various complex phenomena occurring in these waters like strong stratification, external and internal waves, wind-generated turbulence, Langmuir circulation etc. The need for simulation methods is especially great in this area because the physical processes cannot be investigated in the laboratory. Traditionally, empirical bulk-type models were used in oceanography, which, however, cannot account for many of the complex physical phenomena occurring. In engineering, statistical turbulence models describing locally the turbulence mixing processes were introduced in the early seventies, such as the k-ε model which is still one of the most widely used models in Computational Fluid Dynamics. Soon after, turbulence models were applied more and more also in the atmospheric sciences, and here the k-kL model of Mellor and Yamada became particularly popular. In oceanography, statistical turbulence models were introduced rather late, i.e. in the eighties, and mainly models were taken over from the fields mentioned above, with some adjustments to the problems occurring in marine waters. In the literature on turbulence-model applications to oceanography problems controversial findings and claims are reported about the various models, creating also an uncertainty on how well the models work in marine-water problems. The author and his co-workers have done much clarifying research in this area and have also developed new model versions, and this work is now comprehensively summarised in this book.

The author gives an introduction to the modelling problems and an extensive overview on turbulence models used for applications in oceanography, focusing then on the highest level models in use, namely two-equation models with algebraic-stress relations and on extensions accounting for special problems occurring in marine waters. These models are described in detail and analyses on homogeneous shear flows are presented as well as extensive tests for idealised mixing situations and real-life oceanic and limnic applications, performed with the computer code GOTM (General Ocean Turbulence Model). The interested reader should note that the source code of GOTM containing many of the turbulence models discussed as well as the application examples is available freely on the internet. Of special value for the readers of the book is the extensive comparative study of the various models and the reconciliation between the different modelling schools which the author has achieved.

In the field of engineering, more advanced, quite complex models were developed since the 70's employing model transport equations for the individual turbulence stresses and heat and mass fluxes. This level of modelling has not received much consideration in oceanography, probably because of the considerable uncertainties about the boundary conditions there. However, also in engineering practice these models were never really accepted; rather the simpler two-equation models (or even one-equation models) are still used whose performance and range of applicability has been increased by non-linear eddy-viscosity and algebraic-stress- model versions. It is therefore interesting to note these are also the types of models on which this book focuses. Engineering turbulence models have been covered well in a number of books, but there was so far no comprehensive treatise on the subject of turbulence modelling in marine waters. The author has filled this gap and has produced a much needed book that provides invaluable information for everybody who sets out to simulate turbulent mixing processes in marine water problems.

W. Rodi

Preface

The original manuscript for this book has been submitted as a Habilitation thesis at the Institute for Oceanography of the University of Hamburg about fifteen months ago. The amount of updates I had to consider now for this published version even after such a short time shows that there is still a lot of research activity going on in the field of marine turbulence. This is motivated to a great extent by the steadily growing available computer power, which allows not only to increase the spatial resolution and temporal coverage, but also the physical resolution of ocean models. Ten years ago, ocean modellers could probably argue that higher-order turbulence closure models were computationally too expensive for consideration in their modelling studies, but nowadays this is only true for climate models simulating several hundreds or thousands of years.

In contrast to that higher-order turbulence closure models have been popular in hydraulic engineering since about thirty years, see the state-of-the-art review by *Rodi* [1980]. Such a model review has however not been written so far for the field of marine turbulence modelling. That might explain why different schools of marine turbulence modelling (basically the European k-ε modellers and the American k-kL modellers) could co-exist more or less peacefully until today, not knowing much of each other. The recently finished concerted action CARTUM (Comparative Analysis and Rationalisation of Second-Moment Turbulence Models, funded by the European Commission) clearly demonstrated persisting misunderstandings between these two schools. The present book tries to fill this gap by presenting applicable turbulence closure models in a general notation.

This book is written not only for all those who work with numerical ocean models. It is also designed for graduate students since it does not require a deep insight into the field of turbulence modelling. It is written as well for observing oceanographers who are interested in the assumptions made for deriving these models and who would like to explain their observational data by means of a water column model. However, a general understanding of applied mathematics and physics is essential for working with this book.

The book is structures as follows: After a general introduction, the full derivation from the Navier-Stokes equations to mathematically complete statistical turbulence closure models is shown. Then the numerical discretisation of these equations is carried out, followed by a brief overview on the computational implementation into the Public Domain water column model GOTM. Finally, a number of idealised test cases and simulations of in-situ data from field campaigns are discussed. The book is then completed by a list of ten future research perspectives, an appendix with notation rules, transformations between different notations and a list of symbols, a reference list and an index.

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- The first three years from 1992 to 1995 were paid by the GKSS Research Centre in Geesthacht, Germany in the framework of a cooperation with the University of Hamburg.
- In 1996 my research activities were carried out at the International Centre for Computational Hydrodynamics in Hørsholm, Denmark, funded by the Danish National Research Foundation.
- Three projects within the framework of the European Communities' Program in Marine Science and Technology (MAST) under the contract numbers MAS3-CT96-0053 ('PHASE'), MAS3-CT96-0051 ('MTP II-MATER') and MAS3-CT97-0025 ('PROVESS') supported my studies on turbulence modelling during the years 1997-1998 and 2000.
- The actual compilation of this study was funded by a Habilitation Grant given by the German Research Foundation for the years 1999 and 2001.

There are further two projects which gave me a scientific home during the last years. One of them is a real project, CARTUM (Comparative Analysis and Rationalisation of Second-Moment Turbulence Models) a brainstorming activity funded by the European Community (MAS3-CT98-0172) which brought together turbulence specialists from all over the world. In the framework of this activity, regular meetings were held which gave important impulses to future research in the field of turbulence, also to my personal investigations. The other project is GOTM (General Ocean Turbulence Model, `http://www.gotm.net`), an idealistic software project without any funding initialised by Karsten Bolding (Ispra, Italy) and myself with the aim of constructing a unified computer code for simulating the water column with various turbulence closure schemes. Later, others joined GOTM, Manuel Ruiz Villarreal (Hamburg, Germany), Pierre-Philippe Mathieu (Reading, England), Georg Umgiesser (Venice, Italy), Encho Demirov (Bologna, Italy) and Lars Umlauf (Lausanne, Switzerland). Without the ordering strictness of the GOTM model in the background, the various idealised and real model simulations presented in this study could never have been performed. It is furthermore the scientific discussion with all the GOTM users which broadened my understanding of turbulence modelling.

My scientific understanding of marine turbulence has been strongly influenced by many researchers. Jürgen Sündermann (Hamburg, Germany) opened for me the doors into oceanography and turbulence research. Helmut Baumert (Hamburg, Germany) made me familiar with the basics of turbulence modelling and gave me many useful hints throughout the last years. Eckhard Kleine (Hamburg, Germany) helped me a lot with setting up a working water column model and inspired the idea of Neumann-type boundary conditions for turbulent quantities. I had the pleasure to meet George Mellor (Princeton, New Jersey) occasionally and to discuss problems of k-ε and k-kL models. His statement that he never saw a k-ε model properly reproducing the Monin-Obukhov similarity theory motivated me to start many of these model comparisons. Ole Petersen (Hørsholm, Denmark) opened my eyes for convective turbulence and gave me a lot of insight into modelling details. From Jean-Marie Beckers (Liège, Belgium) I learned a lot about specific numerical problems in oceanography. With Walter Eifler (Ispra, Italy) I had many turbulent

discussions on turbulence and turbulence modelling, especially on the skin effect and non-local transport. Karsten Bolding (Ispra, Italy) introduced me to the miracles of structured programming, UNIX and LINUX operating systems and other such useful features. Encho Demirov (Bologna, Italy) was the person to convince us to separate the GOTM turbulence module from the rest of the model in order to better integrate it into three-dimensional models such as MOM. Eric Deleersnijder (Louvain-la-Neuve, Belgium) was always interested in discussing about the numerical stability of turbulence closure models. Vittorio Canuto (New York, New York) visited me in autumn 1999 with five submitted manuscripts in his suitcase. We found that his new algebraic second-moment closure exactly filled the gap of the missing physically complete, numerically stable and computationally efficient turbulence closure model. Patrick Luyten (Brussels, Belgium) gave me at several occasions insight into his experience and understanding in the theory of oceanic turbulence. With Peter Craig (Hobart, Australia) I had some enlightening discussions about the effect of breaking surface waves on near-surface turbulence. Markus Meier (Norrköping, Sweden) is maybe the scientist with the most experience in embedding the k-ε model into three-dimensional circulation models and I felt during many discussions that we often had the same ideas independently. With Boris Galperin (St. Petersburg, Florida) I had some intense discussions on the basic difference between k-ε models and k-kL models, and we both concluded that there are none. I did not meet Lakshmi Kantha (Boulder, Colorado) before August 2000, but was impressed about the fact that he did some of the essence of my work already 10 years earlier, but never published it. Eric Skyllingstad (Sequim, Washington) gave me some useful hints on parameterisations of Langmuir circulation. Finally, I profited very much from the recent cooperation with Lars Umlauf (Lausanne, Switzerland) on the generic two-equation model.

There are two groups from which I learned all about observing turbulent dissipation rate in the field. One group is the MST team Adolf Stips (Ispra, Italy) and Hartmut Prandke (Petersdorf, Germany) who made their technology surviving the breakdown of the Berlin Wall in 1989. The other group is the FLY team from Bangor in Wales with John Simpson, Tom Rippeth and Neil Fisher. With the latter group, I was happy to have access to fresh first hand data from Liverpool Bay and they were happy to get them numerically reproduced in turn.

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Furthermore, I am grateful to Wolfgang Rodi (Karlsruhe, Germany), from whose publications I profited a lot, for writing the foreword to this book.

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