FLUID MECHANICS OF ENVIRONMENTAL INTERFACES

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Dragutin T. Mihailović

To my family
Carlo Gualtieri

Fluid Mechanics of Environmental Interfaces

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Preface

The field of Environmental Fluid Mechanics (EFM) abounds with various interfaces, and it is an ideal place for the application of new fundamental approaches leading towards a better understanding of interfacial phenomena. In our opinion, the foregoing definition of an environmental interface broadly covers the unavoidable multidisciplinary approach in environmental sciences and engineering also includes the traditional approaches in sciences that are dealing with an environmental space less complex than any one met in reality. An environmental interface can be also considered as a biophysical unit lying between the environment and the organization having the following major functions: (a) to prevent the harmful signals from being injected into the system directly and attacking the valuable structures and channels; (2) to unify the various directions from sub-systems and recursive operations towards the environment; and (3) to fully utilize the internal resources by resolving external variables. The wealth and complexity of processes at this interface determine that the scientists, as it often seems, are more interested in a possibility of non-linear dislocations and surprises in the behavior of the environment than in a smooth extrapolation of current trends and a use of the approaches close to the linear physics. In recent times, researches on fluid mechanics processes at the environmental interfaces have been increasingly undertaken but within different scientific fields and with various applicative objectives.

The aim of the book is to present a comprehensive overview of fluid mechanical processes at the several environmental interfaces. Hence, the matter collected in the book can be considered as a part of the broader context of Environmental Fluid Mechanics in which strong emphasis is placed on the processes involving the exchange of momentum, mass and heat across an environmental interface. The book is aimed at graduate students, doctoral students as well as researchers in civil and environmental engineering, environmental sciences, atmospheric sciences, meteorology, limnology, oceanography, physics, geophysics and applied mathematics. The book can be adopted as a textbook or supplementary reading for courses at the graduate level in environmental fluid mechanics, environmental hydraulics, physics of the atmosphere, water quality modeling, air quality modeling, atmospheric turbulence and bio-fluid mechanics.

Previous books within the EFM field covered only partially the topics presented here. In fact, books on atmosphere dynamics or on air pollution cover only the chapters in Part one of the book. Also, existing books on water quality issues deal only partially with the processes at the environmental interfaces of the hydrosphere. Furthermore, some topics treated in this book, such as momentum and mass-exchange in vegetated open channels, could be found only in papers published in scientific journals. It should be stressed that the book has the unique feature of covering a broad range of scientific knowledge where all the topics are considered from the point of view of the concept of environmental interface. Finally, the team of the contributing authors is mostly consisting of researchers with many years of experiences in the topics they are covering.

The book is organized in three parts with an introductive chapter by B. Cushman-Roisin, C. Gualtieri and D. Mihailović, where scope, scales, processes and systems of EFM are described and discussed together with an overview of EFM processes at environmental interfaces and of challenges to be expected in the future.

Part one deals with the processes at the atmospheric interfaces. First, the chapter by B. Rajković, I. Arsenić and Z. Grsić covers some theoretical aspects, including molecular and turbulent diffusion, and several areas of modeling of atmospheric dispersion of a passive substance for a point source, such as *Gaussian* and *puff* models. Following this, the chapter by V. Djurdjević and B. Rajković introduces the basic concepts of the air–sea interactions, also discussing the influence of boundary layers on both sides of the air–water interface, and presents the most common approaches to air–sea exchange modeling together with results of sea surface temperature (SST) simulation for the Mediterranean sea obtained by a coupled model with specific modeling of fluxes. The next chapter, by D. Mihailović and D. Kapor is devoted to the modeling of flux exchanges between heterogeneous surfaces and the atmosphere. The three approaches commonly applied for calculating the transfer of momentum, heat and moisture from a grid cell comprised of heterogeneous surfaces are discussed. This begs for a combined method and highlights the uncertainties in the parameterization of boundary layer processes when heterogeneities exist over the grid cell. Part one ends with a chapter by G. Kallos that covers the matter related to transport and deposition of dust, the cycle of which is important in the atmosphere and ocean, since dust particles can have considerable impacts on radiation, clouds and precipitation. In this chapter, the state of the art for modeling dust production are reviewed and the impacts on atmospheric and marine processes are discussed.

Part two of the book covers some fluid mechanics processes at the interface between the atmosphere and inland free surface waters. The chapter by C. Gualtieri and G. Pulci Doria deals with gas-transfer at an unsheared free surface, which can have significant impacts on water quality in aquatic systems. First, the effects of the properties of the gas being transferred and of turbulence on gas-transfer rate are discussed. Then, conceptual models are proposed to calculate the gas-transfer rate, including recent developments resulting from both experimental and numerical methods. The next chapter by H. Chanson covers advection-diffusion of air bubbles in turbulent water flows. Herein, air bubble entrainment is defined as the entrainment or entrapment of undissolved air bubbles and air pockets by the flowing waters. After a review of the basic mechanisms of air bubble entrainment in turbulent water flows, it is shown that the void fraction distributions may be represented by analytical solutions of the advection-diffusion equation for air bubbles. Later the microstructure of the air–water flow is discussed, and it is argued that the interactions between entrained air bubbles and turbulence remain a key challenge.

Part three of the book deals with fluid mechanical processes at the interface between water or atmosphere and biotic systems. The chapter by D. Mihailović presents transport processes in the system comprised of the soil vegetation and lower atmosphere. The chapter shortly describes the interaction between land surface and atmosphere, such as interaction of vegetation with radiation, evaporation from bare soil, evapotranspiration, conduction of soil water through the vegetation layer, vertical movement in the soil, run-off, heat conduction in the soil, momentum transport, effects of snow presence, and freezing or melting of soil moisture. The chapter also includes a detailed description and explanation of governing equations, the representation of energy fluxes and radiation, the parameterization of aerodynamic characteristics, resistances and model hydrology. The next chapter by B. Lalić and D. Mihailović covers turbulence and wind above and within the forest canopy and is focused on forest architecture and on turbulence produced by the friction resulting from air flow encountering the forest canopy. An overview of different approaches oriented towards their parameterization (forest architecture) and modeling (turbulence) is presented. The chapter by P. Gualtieri and G. Pulci Doria deals with vegetated flows in open channels. Particularly, the equilibrium boundary layer developing on a submerged array of rigid sticks and semi-rigid grass on the vegetated bed is characterized based on experimental results carried out by the authors. The last chapter, by G. Nishihara and J. Ackerman discusses the interaction of fluid mechanics with biological and ecological systems. Transport processes in aquatic environments are considered for both pelagic and benthic organisms (those respectively within the water column and at the bottom). The particular issues related to mass transfer to and from benthic plants and animals are considered in detail.

The editors wish to thank all the chapter authors for their continuous and dedicated effort that made possible the realization of this book. The editors also thank the anonymous reviewers of the project for their thoughtful and detailed suggestions that have improved both the contents and presentation of this book. The editors finally acknowledge with gratitude the assistance of the Editorial Office of Taylor & Francis and, especially, of Dr. Janjaap Blom and Richard Gundel.

Carlo Gualtieri
Dragutin T. Mihailović

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Josef Ackerman is the Associate Dean of the Faculty of Environmental Sciences at the University of Guelph, where he administers an interdisciplinary faculty that serves all academic units at the university. He is an Associate Professor in the Department of Integrative Biology where he conducts research on the physical ecology of aquatic plants and animals, as well as environmental issues. Most of this research is focused on small-scale fluid dynamic and ecological processes. He holds adjunct faculty positions in the School of Engineering at Guelph and the Environmental Science & Engineering Programs at the University of Northern British Columbia. Before coming to Guelph, he was a faculty member at the UNBC, where he played a leading role in founding the university's environmental science and environmental engineering programs and held the *Canada Research Chair in Physical Ecology and Aquatic Science*. He is currently an Associate Editor of the journals *Limnology & Oceanography* and *Aquatic Sciences.* Ackerman is the editor of one book and two special issues of international journals, and the author of over 45 peer-reviewed publications.

Ilija Arsenić is the Assistant of the Meteorology, Physics and Biophysics at the Department for Field and Vegetable Crops, Faculty of Agriculture, University of Novi Sad, Serbia. He conducts laboratory classes in Meteorology to the students of various courses and exercises in Biophysics to the students of Veterinary medicine at Faculty of Agriculture. Additionally, at the Faculty of Sciences he conducts laboratory classes in Atmospheric turbulence, Micrometeorology, Instrumental techniques and Air Pollution Modelling courses, and he teaches a course on Air Pollution Modelling to the students of Physics, Meteorology and Environmental Modelling. He received a B.S. in Physics and M.Sc. in Agrometeorology at the University of Novi Sad. His main research interest is the numerical modeling of air pollution transport, turbulent processes and processes connected to the dynamic meteorology. Great part of his activities is connected to the constructing and programming cluster computers at the OS level and parallelizing numerical models. Also, he has experience in constructing meteorological measurement sensors and devices and programming appropriate computer programs for them.

Hubert Chanson is a Professor in Civil Engineering, Hydraulic Engineering and Applied Fluid Mechanics, at the University of Queensland, Brisbane, Australia. His research interests encompass the design of hydraulic structures, experimental investigations of two-phase flows, coastal hydrodynamics, environmental hydraulics and natural resources. His publication record includes 12 books and over 350 international refereed papers. He authored the student textbook *The Hydraulics of Open Channel Flows: An Introduction* (1st edition 1999, 2nd edition 2004) currently used in 50 universities worldwide. In 2003, the IAHR presented Hubert Chanson with the 13*rd Arthur Ippen Award* for outstanding achievements in hydraulic engineering. The American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) presented him with the 2004 award for the Best Practice paper in the *Journal of Irrigation and Drainage Engineering*. Prof. Chanson was invited to deliver keynote lectures in several international conferences and he lectured several short courses in Australia and overseas. He was member of the organizing committee of several scientific conferences. He also contributed as reviewer for over 50 among scientific journals and international conferences and as expert reviewers for research funding agencies.

He is also member of the *International Association of Hydraulic Engineering and Research* (IAHR) and of the *Institution of Engineers, Australia* (MIEng.Aust.). His Internet home page is http://www.uq.edu.au/∼e2hchans/.

Benoit Cushman-Roisin is Professor of Engineering Sciences at Dartmouth College, where he teaches a series of courses in environmental engineering and fluid mechanics in the Thayer School of Engineering. He received his B.Sc. in engineering physics at the University of Liège, Belgium, and his doctorate in geophysical fluid dynamics at the Florida State University, where he also taught physical oceanography. He later moved to Dartmouth College to teach fluid mechanics and environmental engineering, the intersection of which is environmental fluid mechanics. He is the author of the first introductory textbook on geophysical fluid dynamics (Prentice Hall, 1994) and the lead author of a monograph on the physical oceanography of the Adriatic Sea (Kluwer, 2001). He has authored a number of research articles on various aspects of numerical analysis, physical oceanography and fluid dynamics. He is also the founding and chief editor of *Environmental Fluid Mechanics*, a peer-reviewed journal published by Springer since 2001. His current research is devoted to the variability of coastal waters (with particular focus on the mesoscale variability in the Adriatic Sea), fluid instabilities, turbulent dispersion, and particle entrainment by jets. Aside from his academic position, Cushman-Roisin also advices various groups and companies on topics related to environmental quality, fluid mechanics and alternative energies.

Vladimir Djurdjević is teaching assistant at the department for Physics, Institute for Meteorology, Belgrade University. He graduated from Faculty of Physics, Department of Meteorology, in 1998 with the average grade of 9.80, the highest average in the history of the department. In 2002 he defended his master thesis *The air-sea interaction in the Mediterranean area*. His main area of interest is atmosphere and ocean modeling. Currently he is involved in the project SINTA, simulation of Mediterranean climate as regional climate problem. Starting from the climate integrations done by the Bologna climate model, which is a version of ECHAM-4 model he performs long term integrations (30 years) in the same mode as a limited area model does weather forecast. The model that is used is a coupled atmosphere-ocean model whose atmospheric component is NCEP's meso-scale (ETA) model and the ocean POM (Princeton Ocean Model). Using the same coupled model he does investigations of the air-sea interaction in the Mediterranean basin and in particular in the Adriatic sea. As a expert in ocean and atmospheric modeling he was invited to the University of Lisbon, Department of Oceanography, where he spent two months. Currently he is involved in three international projects related to the various aspects of the air-sea interaction and its influence in a localized area.

Zoran Grsić is currently head of the Micrometeorology and air pollution division in the Institute for nuclear sciences in Vinca, Belgrade. He received bachelors degree at Belgrade University, department for Physics, Institute for Meteorology. At the same department he received his M.Sc. degree. Most of his work concerns modeling of the pollution from industrial sources, but his main occupation was and is design and improvement of the acquisition network of the possible nuclear pollution near the nuclear reactor in Vinca and its modeling as a part of the comprehensible warning and accident management. He was and is involved in several international projects concerning the safety of a nuclear and chemical installations. Currently he is leading meteorologist in three national projects. The first one is in the project of the decommissioning of the nuclear reactor in Vinca, near Belgrade, the second one is: *Automated air quality system in industrial zone of Pancevo* and the third one: *Design of continual observing system for the assessment the influence of thermo power plant Nikola Tesla*, which is located in the vicinity of Belgrade. He is member of *Air Protection*

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Petros Katsafados is Lecturer at the Harokopio University of Athens, Department of Geography. He is also a senior research associate at the Atmospheric Modeling and Weather Forecasting Group – AM&WFG (http://forecast.uoa.gr). He is originally studied Mathematics and acquired a Bachelor degree in this subject at the National and Kapodistrian University of Athens (NKUA) on 1993. He then switched scientific field to Environmental Physics and he finally completed his Master degree from the School of Physics on 1996. As a postgraduate student he joined Atmospheric Modelling and Weather Forecasting Group (AM&WFG) of NKUA mainly participating in EU funded SKIRON project. Getting the achievements of this research he became a Ph.D. candidate on 1998 supervised by Prof.

Kallos head of AM&WFG. In his Ph.D. thesis factors that influence the forecast skill in numerical weather prediction were examined in conjunction with the development of a methodology for expanding the forecast period. The regional climatic patterns and variability for temporal periods, which may vary from medium-range to seasonal weather forecasts, were also analyzed throughout his thesis. On 2001 he took position as a senior research associate in the School of Physics at NKUA but he also continued the cooperation with AM&WFG. From that period up today he participated in a number of EU and national funded projects mainly related with regional climate dynamics and impacts (CIRCE), air-sea interactions (MFSTEP), natural and anthropogenic air pollution modelling (MEDUSE, ADIOS), wind energy applications (ANEMOS). Since 2002 he has 9 articles in international peer-reviewed journals and more than 21 announcements and publications in conference proceedings in subjects related to atmospheric physics and regional climate impacts. An additional 4 manuscripts are presently either under review with minor revisions or in preparation. He has also participated in more than 20 EU and national funded projects in 1 of them as coordinator.

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