The Urban Ocean

This book introduces the new discipline of urban oceanography, providing a deeper understanding of the physics of the coastal ocean in an urban setting. The authors explore how the coastal ocean affects the humans who live, work and play along its shores; and in turn how human activities impact the health and dynamics of the coastal ocean. Fundamental topics covered include the governing dynamical equations, tidal and circulation processes, variation of salinity and freshwater fluxes, watershed pollutants, observing systems, and climate change. Bridging the gaps between the fields of engineering, physical and social sciences, economics and policy, this book is for anyone who wishes to learn about the physics, chemistry and biology of coastal waters. It will support an introductory course on urban oceanography at the advanced undergraduate and graduate level and will also prove invaluable as a reference text for researchers, professionals, coastal urban planners and environmental engineers.

ALAN F. BLUMBERG is an urban oceanographer who studies the interaction between cities and their offshore coastal waters. He is co-founder of Jupiter, a Silicon Valley startup company that is deeply committed to the practical application of the world's best hydroscience, weather prediction and climate modeling. The Princeton Ocean Model, developed by Blumberg and George Mellor, is utilized by scientists and institutions throughout the world. For 15 years, he was George Meade Bond Professor of Ocean Engineering and Director of the Davidson Laboratory at Stevens Institute of Technology where he led several major studies to predict and assess storm flooding events. He is the recipient of the 2001 Karl Emil Hilgard Hydraulic Prize from the American Society of Civil Engineers and the 2007 Denny Medal from the Institute of Marine Engineering. A fellow of both the American Meteorological Society and the American Society of Civil Engineers, Dr. Blumberg is the author of more than 150 journal articles. Because of his extensive research expertise, he is highly sought after by the media during unusual weather conditions.

MICHAEL S. BRUNO is Vice Chancellor for Research and Professor of Ocean Engineering at the University of Hawai'i at Mānoa and Visiting Professor in Mechanical Engineering at University College London. He is the author of more than 100 technical publications regarding coastal dynamics, ocean observation systems and community resilience. He has served on numerous advisory committees, including chairing the Marine Board of the National Academies. A Fulbright Scholar, Dr. Bruno is also a fellow of the American Society of Civil Engineers. He received the Denny Medal from the Institute of Marine Engineering in 2007, the Young Investigator Award from the Office of Naval Research in 1991 and the Outstanding Service Award from the American Society of Civil Engineers in 1988.

"Extremes are becoming more extreme in the most extreme places of our planet where too much water hits us hardest: on our coasts and along our rivers. These coastal areas increasingly urbanize, becoming more and more vulnerable to disasters, with stronger storms and rising sea levels. Blumberg and Bruno argue from their inspiring perspective of hope and belief in impactful human action that these urban hotspots along our coasts and rivers are our best opportunity for a resilient future. Here we can turn climate risks into real urban rewards. But this is only if – by design – we dare to face and better understand our climate challenges, value and manage the urban opportunities, and be radically inclusive in our approaches to produce the best solutions and increase the resilience of our urbanizing coastal regions. We'd better start now with putting their words into practice!"

Henk W. J. Ovink, Special Envoy for International Water Affairs, the Netherlands

"*The Urban Ocean* by Blumberg and Bruno is simply amazing; it is a very large compendium of facts, problem descriptions and deductions concerning the near-shore ocean and inland waters close to where many of us live. Skillfully written, it should be a valuable and unique source for scientists, urban planners, environmental managers and the curious. The use of equations where appropriate will be helpful to some readers, but will not be intimidating to those less mathematically inclined."

George Mellor, Princeton University

"Over land, sea and air, we now live in an urban world. Our cities have become ecosystems of their own, and our deltas have changed colors, transforming from a natural green to an urban red. Our oceans – for centuries a trusted resource in our daily lives – have been impacted by urbanization as well. As we strive for a more sustainable future, oceans need and deserve our attention and respect to safeguard their viability for years to come. If not, our way of life will be threatened with consequences never before experienced or imagined. I commend the authors of this fantastic and unique book that helps show us how to respect the ocean, and better understand how we ensure a resilient and sustainable future."

Piet Dircke, Global Leader Water Management, ARCADIS

"This is a unique and daring book on a fascinating and important topic. The rivers, estuaries and coastal regions of our world have lots to offer. They have therefore become increasingly urbanized. Humans have become a geophysical and a geopolitical force. The concept of *The Urban Ocean* explores and explains the formulae that govern the physics of the ocean and brings people and their habitats fully into the equation. The book bravely links physics and engineering to social studies and behavioral science. Written from an action perspective, it pairs the complex dynamics of our contemporary urbanized deltas with a globally emerging notion and movement of resilience engineering."

Theo Toonen, University of Twente

The Urban Ocean

The Interaction of Cities with Water

ALAN F. BLUMBERG
Jupiter

MICHAEL S. BRUNO
University of Hawai'i at Mānoa

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Alan F. Blumberg

To my parents Lily and Zelig Blumberg ז״ל and my wife Robin Blumberg ז״ל who inspired me to reach higher.

The book would not have been written without the encouragement and loving support of my children, Nathan and Jessica, and my partner, Sara Cass.

Michael S. Bruno

To all who have inspired and guided me along a richly rewarding journey, most especially my parents, Annie Marie and Frank; my brothers and sisters, Kevin, Donald, Denise, and Nancy Anne; and my wife, Cristina. You have taught me so much.

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Preface

This book seems to us to be the inevitable product of a number of influences and events, some long in the making and others much more recent. Both of our work has for decades been focused on developing a better understanding of the dynamics of estuarine and coastal ocean regions, and the application of that understanding to the solution of problems as varied as safe navigation, water pollution, shoreline erosion and coastal flooding. Over these decades, we have witnessed profound changes in the nature and extent of these problems, and the coastal ocean environment in which we have worked. And we have seen technological advances ranging from satellite and remote sensing to high-speed computing, machine learning and artificial intelligence change the manner in which we study the ocean, and alter our understanding of the various ways in which human activities have impacted the oceans and coastal land margins around the world.

The earth has become increasingly urban in character, with the number of megacities (population greater than 10 million) quadrupling to nearly 40 over the last 30 years. A majority of these cities are located on the coastal ocean, meaning that a growing share of the world's population is not only benefiting from the climate and resources of the coastal ocean but also contributing to the myriad environmental stressors to this vital ecosystem. This also means that a growing share of the world's population lives in harm's way due to the risks associated with coastal storms and flooding, and in some areas, tsunamis. These risks have been significantly magnified by climate change, which has produced a gradual – and perhaps accelerating – rise in sea level, thereby increasing the vulnerability of coastal urban areas to catastrophic flooding and inundation. The loss of natural protective features, in particular coral reefs as a result of ocean acidification associated with carbon dioxide emissions, has further increased the risks to many coastal communities. The confluence of these two global phenomena – climate change and population migration to urban areas – as well as our passion

for developing a better understanding of, and solutions to, the threats to coastal communities were the primary driving forces behind this book.

Optimism is also a driving force. The two of us have witnessed in a very personal way both the capacity for humankind to do damage to the coastal ocean environment and the capacity to mitigate or even reverse this damage. We both recall working in the Hudson–Raritan Estuary in the 1980s when concerns about water quality dominated our planning for field experiments and virtually prohibited any contact recreation in the Hudson River and its tributaries. What we remember most about this period is the profound and lasting impact that human-caused degradation of the waters and shorelines in the New York metropolitan region had on the residents' connection to the water. For nearly 100 years, the waterfront in the region was a place to be avoided; a place where commerce was conducted, but where the populace was largely absent because of health concerns. Today, that same waterfront is among the most vibrant and valuable land on earth, with parks, boat marinas, and even kayak and windsurfing launching facilities lining the Hudson River and its tributaries. Remarkably, the millions of citizens in the region have readopted the river and its tributaries as a place of beauty, a place of rest and recreation, and a place to be protected and sustained. This same story has been repeated across the planet, from Hong Kong to Vancouver to Boston; waterfronts in effect have been re-purposed as attractive gathering spaces, common areas where people can work and play in concert with the water rather than in conflict with the water. It is our strong belief that this urban waterfront revitalization will further accelerate both the resolve of coastal communities to restore and preserve their coastal environments, and the efforts of policy makers and planners to address in a pro-active way the threats posed by human activities, from local environmental degradation to global climate change.

This book began as sets of lecture notes for courses we taught in Oceanography, Introduction to Meteorology, Wave Dynamics, Coastal Engineering, Coastal Ocean Dynamics and Introduction to Estuaries at Stevens Institute of Technology where we were both faculty members for more than 15 years. The book is mathematical in the sense that partial derivatives are used to communicate the governing dynamics. But we have attempted to keep the text free of lengthy derivations, wishing to make it more about the urban ocean and not a fundamental ocean dynamics text. Our course based on this book has been taught to juniors and seniors majoring in engineering and physics, as well as first-year graduate students. For some students, Chapters 4, 5 and 7 may be challenging, and instructors may want to expand on those chapters.

People who know us also know we have an interest in numerical ocean modeling, a discipline similar to atmospheric modeling. Although the book is

not about modeling, readers will quickly discover that it is in the back of our minds since the equations of motion and their boundary conditions are presented in Chapters 4 and 5 as if one were poised to set up a numerical model. Chapter 7 explores situations where certain terms in the equations of motion can be neglected, leading to analyses of currents that are very commonly observed in the offshore waters of the urban ocean. These closed-form solutions are quite useful for model validations as well.

This book, then, is intended to provide the reader with an understanding of the dynamics of the coastal ocean and atmosphere, but in the context of the people who live, work and play along its shorelines and in its waters. This context informed our decision to include topics not normally found in a text such as this, including the treatment of issues related to sustainability and community resilience to extreme events such as coastal storms and flooding, and more slowly developing threats such as climate change, water quality degradation and habitat loss. Urban oceanography, as we have termed it, is structured to be attractive to readers ranging from undergraduate and graduate students at engineering and design schools to professionals working in coastal resilience. It is also intended for anyone who wishes to discover the unique characteristics of these vital regions, the opportunities and challenges associated with the ecosystem services that these regions provide to human populations, and the technical, social and policy tools and solution paths that can be pursued to protect and preserve these waters and the populations that rely on them.

Acknowledgments

This book is a product of a lifetime of discovery, a voyage that has benefited from the help and encouragement of friends and colleagues far too numerous to list in full here. As a start, the authors wish to thank their long time mentors George Mellor and Ole Madsen.

We owe an enormous debt to our many colleagues whose ideas and insights fill this book. Collaborators like Nickitas Georgas, Tom Herrington, Richard Hires, Scott Glenn, Hans Graber, Julie Pullen, Claire Weisz, Toni Jordi, and Jim Fitzpatrick provided stimulating conversations and invaluable advice and assistance in fieldwork, data analysis, and numerical modeling over the years. Firas Saleh and Sílvia Anglès made this book a reality by helping with the figures, equation editing, and indexing. Hurricane Sandy opened our minds to a new way of looking at the coastal landscape in which we had always lived and worked, and brought us into contact with innovative urban planners, policy makers, and architects.

This book is in large part based on the lecture notes of classes we taught for several years; we thank the many students in our classes for their patient listening and their important feedback. And finally, we want to acknowledge Stevens Institute of Technology and the University of Hawai'i for their support of our work while writing this book.