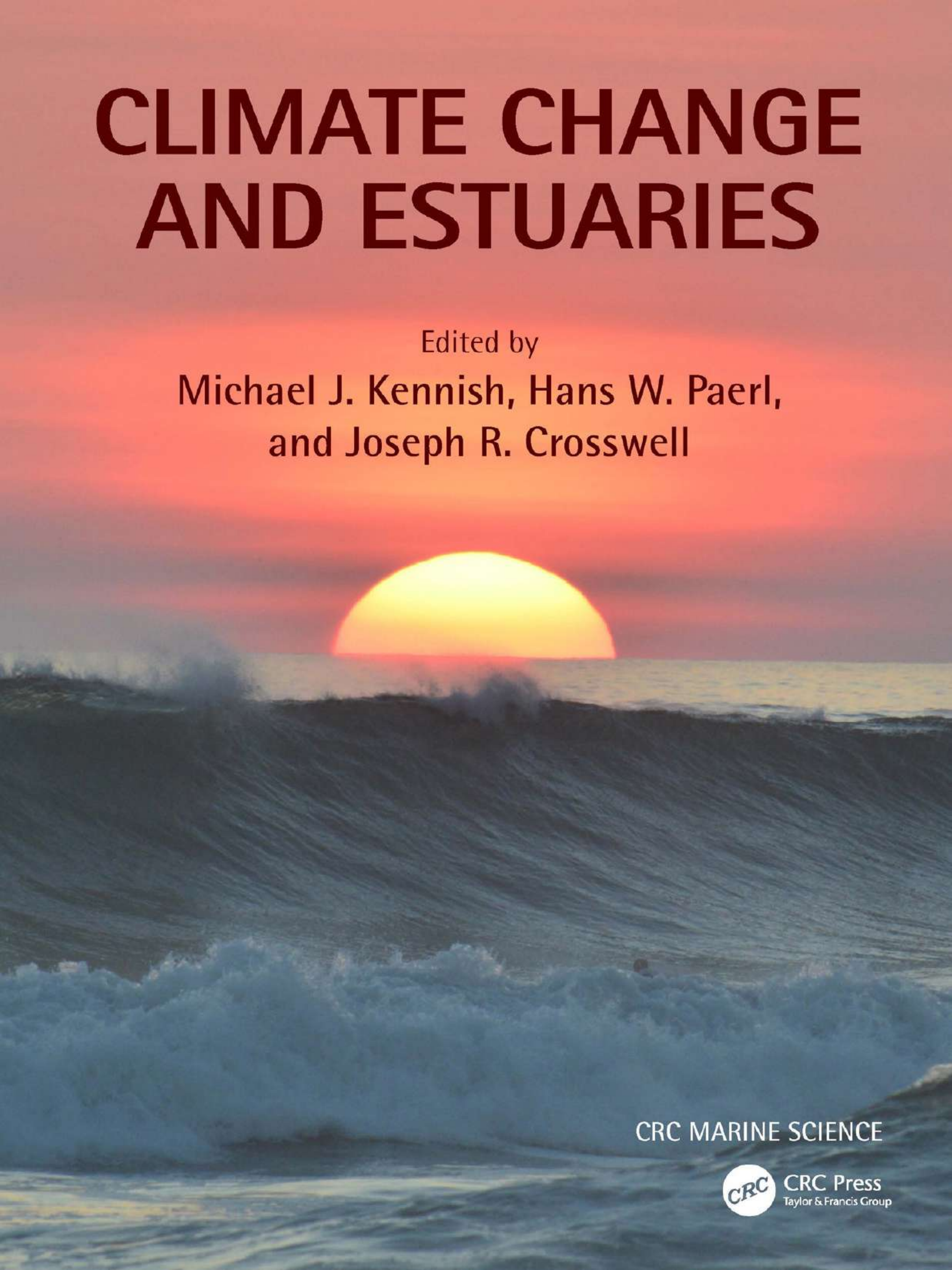

CLIMATE CHANGE AND ESTUARIES

Edited by
Michael J. Kennish, Hans W. Paerl,
and Joseph R. Crosswell

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Climate Change and Estuaries

Climate change is having an increasing impact on coastal, estuarine, and marine environments worldwide. This book provides state-of-the-art coverage of climate change effects on estuarine ecosystems from local, regional, and global perspectives. With editors among the most noted international scholars in coastal ecology and estuarine science and contributors who are world-class in their fields, the chapters in this volume consist of comprehensive studies in coastal, estuarine and marine sciences, climate change, and coastal management and provide an extensive international collection of data in tabular, illustrated, and narrative formats useful for coastal scientists, planners, and managers.

Comprised of three sections: (1) physical-chemical aspects; (2) biological aspects; and (3) management aspects, the book not only examines climatic and non-climatic drivers of change affecting coastal, estuarine, and marine environments but also their interactions and effects on populations of organisms, communities, habitats, and ecosystem structure and function.

Pulling together today's most salient issues and key literature advances for those concerned with coastal management, it allows the reader to see across direct and indirect interactions among disciplinary and ecosystem boundaries.

Climate Change and Estuaries meets the research needs of climate scientists, estuarine and marine biologists, marine chemists, marine geologists, hydrologists, and coastal engineers, while students, professors, administrators, and other professionals will also find it an exhaustive reference.

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Foreword

Among all the features of nature that a climate scientist ponders, estuaries exercise a special grip on me that is as much personal as professional. I grew up less than three miles from Long Island Sound and did my first shell fishing there as a child (long before the US Clean Water Act was adopted; the oysters were inedible due to pollution). I have lived most of my adult life within walking distance of the Hudson River estuary – and I start most of my days with an early walk along its banks (where the water quality has improved markedly despite dense urban settlement on both banks). I studied the effects of nitrogen pollution originating from acid rain on the Chesapeake Bay estuary at a time when climate change was starting to emerge as an issue for governments. One of my early professional writings on the subject noted the special vulnerability of estuaries as the new threats from warming and sea-level rise interact with a pre-existing stew of environmental insults.

Estuaries were then and still are locations of heavy urban and industrial development that remakes their contours. Estuaries are the places where major rivers discharge to the ocean the sewage, agricultural nutrients, atmospheric pollution, and toxins that drain from urban and industrial pipes, farmland, and the sky. The consequences have, in many cases, made the surviving fish too contaminated to be eaten and swimming unpleasant and unhealthy.

The pattern is repeated worldwide, despite improvements resulting from the determined efforts of scientists, citizen-activists, and some governments. From a scientific perspective, the situation is complex with many detrimental stresses abounding, so that the chief cause of deterioration is often difficult to determine. At a time when the health of some estuaries is improving, climate change and sea-level rise are accelerating. We need to learn a lot more, very fast. *Climate Change and Estuaries* takes a critical step in that direction by laying out the challenges and identifying ways to accommodate the effects of climate change while governments struggle to rein in the emissions of the greenhouse gases that are causing the warming. If someone, or just happenstance, desecrates a great work of art, as fire did Notre Dame, we do not throw it away or let it deteriorate until unrecognizable – we learn from experience, reduce the future threat, and call in the restoration crews to do their magic. Saving estuaries is more difficult than saving a masterpiece, but there is no other option.

Michael Oppenheimer
Albert G. Milbank Professor of Geosciences and
International Affairs and the High Meadows
Environmental Institute
Princeton University

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Preface

Estuaries are vital transitional environments where the land meets the sea and freshwater runoff mixes with seawater, resulting in salinity gradients, a continuum of biogeochemical cycles and biota from freshwater to marine, supporting an array of distinctive habitats. Collectively, they cover more than 400,000 km of global coastline with an estimated surface area of 1.1 × 10^6 km^2 (Dürr et al. 2011; Lonsdale et al. 2022). Estuaries rank among the most productive ecosystems on earth, generating exceptional ecological and economic provisional services for contemporary society. However, their location in the coastal zone, often downstream of highly developed and densely populated watershed areas with escalating human pressures, renders them vulnerable to numerous anthropogenic and environmental stressors that can threaten ecosystem structure, function, and sustainability while concurrently reducing ecosystem services and the resilience of coastal habitats and their biotic communities. Indeed, much of the world's coastal population, infrastructure, industry, fisheries, and tourism is located around estuaries, and the potential impacts of climate change on engineering infrastructure alone are substantial. Because of this, rising sea-levels threaten many coastal communities and metropolitan centers through a range of interconnected hazards and risks. Furthermore, anthropogenic forcing in the coastal zone, supporting increasing population growth and development concomitant with greater regional and global effects of climate change, is modulating physical–chemical and ecological conditions in estuarine ecosystems. This poses ever-increasing challenges for management and conservation programs.

Climate change is a major driver of shifting estuarine dynamics. For example, the mechanisms driving biogeochemical cycling in estuaries are being altered by disturbances and stressors associated with climate change. Among the most profound consequences of climate change in estuaries are warming and altered hydrologic and biogeochemical conditions resulting from more intense wet/dry cycles, including a rise in intense storms. These shifting conditions have altered watershed nutrient and contaminant delivery, resulting in accelerating eutrophication, proliferation of harmful algal blooms, and depletion of dissolved oxygen, exacerbating natural and anthropogenic hypoxia detrimental to biotic communities and their habitats. In addition, climate change can play a significant role in the establishment, spread, and impact of non-native invasive species commonly leading to the degradation of ecosystem components. Increasing sea-level rise, water temperature, salinity variation, altered freshwater inputs and circulation, nutrient enrichment, deoxygenation, acidification, invasive species, and resulting changes in physical, chemical, and biotic characteristics of estuarine environments are outcomes of escalating climate change.

The IPCC (2012) has defined climate change as regional or global changes in mean climate state or in patterns of climate variability over decades to millions of years often identified using statistical methods and sometimes referred to as changes in long-term weather conditions. Increasing atmospheric concentrations of greenhouse gases (primarily carbon dioxide, nitrous oxides, and methane) due to the burning of fossil fuels, deforestation, and changing land use have led to significant changes in the Earth's climate system, more rapidly now during the Anthropocene than at any point in human history. The resulting outcomes have generally been detrimental to estuarine and coastal marine environments.

There is an array of climate change stressors affecting estuarine organisms and habitats. Responses to these stressors are typically non-linear because they do not occur in isolation but have synergistic, cumulative, or antagonistic interactions that may increase, add to, or decrease the effect of individual stressors alone. Multiple direct anthropogenic drivers of change often interact synergistically with climatic drivers (e.g., higher intensity storms, increasing temperatures, heatwaves, rising sea-levels, extreme floods, and droughts) to amplify impacts in these environments. The effects can be transformative. In fact, some local anthropogenic activities, such as land reclamation, flow diversions, shoreline hardening, and channel dredging, are dominant drivers of hydrodynamic and other changes in estuarine systems that significantly affect biotic communities and habitats. Estuaries occur across diverse environmental settings, ranging, for example, from low-relief tropical coastlines to deep glaciated fjords. These characteristics influence how estuaries are variably impacted by climate change, and how they affect the role that estuaries play as a feedback in the global carbon cycle (Crosswell et al. 2022). Sea-level rise driven by climate change is likely to have the most profound impact on the structure and function of intertidal environments, which are a dominant feature along gently sloping coastal margins. By contrast, steeper coastlines like fjords may be impacted more by altered freshwater input and meltwater cycles resulting from climate change. Other climate change drivers, such as increasing air and water temperatures and extreme storm events, will interact with and amplify the effects of sea-level rise on these environments. Interactive drivers, in particular, have accelerated estuarine ecosystem degradation and the loss of ecosystem services by altering basic properties, physical and chemical characteristics, and ecological processes (Kennish 2021).

Climatic and non-climatic drivers of change vary significantly in space and time, influencing physiological responses of microbes, flora and fauna, their behavior, and trophic interactions, frequently culminating in altered demographic characteristics, biotic community structure, and ecosystem function. Biotic responses to these drivers of change include marked changes in organism abundance, distribution, diversity, community composition, productivity, phenology, predator–prey interactions, and food web dynamics. Some responses are overtly damaging to estuarine environments, such as the development and proliferation of opportunistic harmful (toxic, hypoxia-generating, and food web altering) bloom-forming algal taxa (HABs) that impair estuarine water quality and degrade biotic communities and habitats (Paerl et al. 2018). The loss and fragmentation of estuarine habitats including salt marshes, mangroves, and seagrasses due to climatic forcing factors cause acute changes in biotic communities of coastal wetlands. These blue carbon ecosystems are important for the sequestration of carbon and the mitigation of climate change effects, as significant amounts of atmospheric CO_2 are stored in wetland soils and sediments. Rising sea-levels and the consequent submergence of salt marshes reduce carbon sequestration processes in these critical coastal wetlands. Efforts to rehabilitate, revegetate, and restore these essential habitats are ongoing, although with variable success over protracted time intervals.

Climate change presents major challenges in understanding the responses of planktonic, benthic, and nektonic organisms. Changes in estuarine circulation affect egg and larval transport, as well as organism recruitment, with significant consequences on estuarine population and community-level dynamics. Climate-mediated differential effects on reproduction, growth, and mortality will have an increasingly greater influence on the demographics of estuarine organisms during the 21st century. Of great concern is the sustainability of fisheries' resources in the face of climate change and the conservation practices needed to support them. The cumulative effects of climate change impacts will increase the vulnerability of finfish and shellfish species, communities, and estuarine ecosystems. Aquaculture is emerging as a driving force for shellfish restoration and conservation in estuaries. Natural oyster reefs are vulnerable to biogeochemical fluxes, sediment inputs, and increased storm intensity, and aquaculture can augment shellfish production in estuarine waters. Because of concerns about fisheries and other biotic resources in estuarine and coastal marine environments, more investigations are also underway to assess climate-mediated effects on fish, mammals, and avian populations to determine the totality of climate effects on higher trophic-level organisms in these environments.

Difficulties in assessing interactive drivers of change in estuarine environments are complicating the prediction and projected outcomes of ecologic and economic impacts important for the development of coastal management programs and their remedial measures (e.g., restoration and conservation initiatives) to address them and ultimately strengthen ecosystem resilience and sustainability. Integrated ecosystem-based management, which considers the connectivity of land, atmosphere, estuary, and ocean, as well as ecological components and ecosystem services, is an effective approach to protecting and maintaining these coastal environments. Managing for their future requires an appreciation of the socio-economic-ecologic context, decision-making frameworks, management options, and strengthening of resilience in response to the climate crisis itself.

Climate Change and Estuaries examines the drivers of change in estuarine environments, notably the interactive effects and impacts of multiple anthropogenic climatic and non-climatic drivers that affect the structure and function of estuarine ecosystems. It also assesses the management approaches implemented to mitigate the impacts and increase adaptation, resilience, and sustainability of these environments as well as built coastal communities. An example in estuaries is the sequestration of carbon in wetlands as a pathway to mitigate climate change impacts. Because of the danger that climate change poses to natural and built environments along the coast, conservation and restoration programs supporting the goals of long-term sustainability and resilience of coastal habitats and communities in the face of rising sea-levels and other climatic-driven effects must also be important elements of a holistic management program. Examples include the siting of Marine Protection Areas (MPAs), shoreline stabilization, wetland drainage restoration, and thin-layer sediment application to increase marsh elevation. The tasks to achieve management goals to halt or reverse the effects of climate change on estuaries over the succeeding decades of the 21st century will be difficult because of ongoing greenhouse gas emissions and the persistence of elevated CO_2 concentrations in the atmosphere.

This book consists of three sections: (1) physical–chemical aspects; (2) biological aspects; and (3) management aspects. It not only examines climatic and non-climatic drivers of change affecting estuarine environments but also their interactions and effects on populations of organisms, communities, habitats, and ecosystem structure and function. The management of climate change effects in estuaries considers both natural and built communities and includes mitigation, adaptation, and resilience programs. The vulnerability and sustainability of estuaries to climate change are also assessed in response to temperature increases, precipitation patterns, extreme storm and drought events, rising sea-levels, and other drivers of change.

Chapter 1 is an overview of *Climate Change and Estuaries*. Chapter 2 covers the dynamics of climate change in the earth system. Chapter 3 provides a description of estuaries, their historical development, and classifications. Ensuing chapters examine specific aspects of climate change and interactive factors: (Chapter 4) sea-level rise; (Chapter 5) anthropogenic drivers of estuarine change; (Chapter 6) saltwater intrusion; (Chapter 7) biogeochemical changes; (Chapter 8) hypoxia; (Chapter 9) acidification; (Chapters 10) carbon dynamics; (Chapter 11) blue carbon; (Chapter 12) circulation and hydrological responses; (Chapter 13) sediment dynamics; (Chapter 14) intertidal and subtidal environments; (Chapter 15) organism responses; (Chapter 16) microbial ecology; (Chapter 17) nutrients, phytoplankton, and harmful algal blooms (HABs); (Chapter 18) macroalgae; (Chapter 19) salt marshes; (Chapter 20) mangroves; (Chapter 21) seagrasses; (Chapter 22) benthic communities; (Chapter 23) shellfish; (Chapter 24) fish; (Chapter 25) estuarine and coastal birds; (Chapter 26) invasive species; (Chapter 27) faunal response to estuarine deoxygenation; (Chapter 28) estuarine management, mitigation, and future conditions; (Chapter 29) sea-level rise risk and adaptation in estuaries; (Chapter 30) resilience of estuarine and coastal marine environments to climate change; (Chapter 31) climate change adaptation of engineering infrastructure; and (Chapter 32) conservation and management strategies dealing with climate change impacts in estuaries.

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Michael J. Kennish
Hans W. Paerl
Joseph R. Crosswell

About the Editors

Dr. Michael J. Kennish is a professor emeritus in the Department of Marine and Coastal Sciences, School of Environmental and Biological Sciences, Rutgers University, New Brunswick, New Jersey. His career in coastal, estuarine, and marine sciences spans 50 years and has included extensive multidisciplinary research on coastal, estuarine, and marine ecosystems. He has taught coastal and marine science classes at Rutgers University for many years, while also supervising undergraduate and graduate students. In addition, he has been active for decades in the outreach of science to coastal communities and K–12 schools. As a member of the Climate Institute at Rutgers University, Dr. Kennish has been involved in the study of long-term climate change impacts on the New Jersey coast and elsewhere. He was an expert reviewer of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2021 (WGI) and 2022 (WGII and WGIII). Dr. Kennish is the author or editor of 16 scholarly books on various topics in coastal, estuarine, and marine sciences, the author of more than 200 research articles in science journals and other publications, and the editor of 9 peer-reviewed compendium science journal special issues.

Dr. Kennish has maintained a wide range of research interests in marine ecology and marine geology. He has been most actively involved in leading research teams investigating estuarine and coastal marine environments in New Jersey. Much of this research has involved the development and application of innovative methods to determine the condition and ecosystem health of coastal ecosystems in the state. Dr. Kennish is widely known for his work on the human impacts of coastal, estuarine, and marine environments and has served on environmental panels and workgroups assessing these problems in New Jersey, the mid-Atlantic region, and nationwide, while concomitantly collaborating extensively with state and federal government agencies to remediate degraded water quality and habitats. Most notably, he has been heavily engaged in investigations of impairment and remediation of impacted estuarine and coastal marine environments. These include studies of the natural and anthropogenic stressors that effect change in coastal ecosystems as well as the dynamics of environmental forcing factors that generate imbalances in biotic community structure and ecosystem function. His research, which has been funded by the USEPA, NOAA, USDA, state environmental agencies, and other federal and state sources, is multidisciplinary in scope. It has addressed an array of nationally significant problems, such as habitat loss and alteration of aquatic systems, nutrient enrichment and eutrophication, hypoxia and anoxia, organic pollution, chemical contaminants, climate change, sea-level rise, overfishing, invasive species, watercraft effects, dredging and dredged-material disposal, freshwater diversions, calefaction of estuarine waters, entrainment and impingement of electric generating stations, and the effects of watershed development on coastal systems. In addition, he has examined the effects of the construction and operation of industrial facilities, maintenance of shorelines and waterways, and human use of coastal space and aquatic systems. He has also studied the biology and geology of mid-ocean ridge and deep-sea hydrothermal vent systems as a member of the Center for Deep-Sea Ecology and Biotechnology at Rutgers University.

Dr. Kennish is the recipient of many awards, including the 2008 Guardian of the Barnegat Bay Award (Barnegat Bay National Estuary Program/USEPA), 2009 NOAA/NERRA National Award for outstanding contributions to the National Estuarine Research Reserve System of NOAA, 2010 Graham Macmillan Award of the American Littoral Society for significant contributions to marine science and conservation, 2010 Sierra Club Award for outstanding environmental accomplishments, 2011 Pearl S. Schwartz Environmental Award of the League of Women Voters for work on New Jersey's coastal environments, 2013 Frank Oliver Award of the New Jersey Environmental Lobby for contributions to the protection of New Jersey's environments, and the 2017 Albert Nelson Marquis Lifetime Achievement Award for dedication to the environmental and oceanographic sciences.

Dr. Hans W. Paerl is the Kenan Professor of Marine and Environmental Sciences at the University of North Carolina's Institute of Marine Sciences. He holds a joint appointment with the Departments of Earth, Marine and Environmental Sciences and Environmental Sciences and Engineering. His collaborative research addresses microbially mediated nutrient cycling and primary production dynamics, environmental controls, and management of harmful algal (specifically cyanobacterial) blooms. Dr. Paerl's research spans freshwater lakes, reservoirs (including ones used as drinking water supplies), estuarine, and coastal marine waters in the USA and globally (see: https://paerllab.web.unc.edu/research/). He has published over 350 peer-reviewed articles and book chapters on these subjects. His work has been supported by the NSF, EPA, NIH, NOAA/NC Sea Grant, USDA, the NC Water Resources Research Institute, the UNC Collaboratory, the California Bay Delta Science Program, various state environmental agencies and private foundations, the Chinese Academy of Sciences and Ministry of Science and Technology, and the Netherlands Academy of Sciences. He also manages several estuarine water quality monitoring and assessment programs, including the Neuse River Estuary (NC) Modeling and Monitoring Program, ModMon (https://paerllab.web.unc.edu/projects/modmon/) and the Ferry-based Water Quality Monitoring Program for the Pamlico Sound System, FerryMon (https://paerllab.web.unc.edu/projects/ferrymon/). Dr. Paerl has supervised over 70 graduate students, 12 postdocs, and advises undergraduate students at UNC-CH as well as other institutions. He received the 2003 G. Evelyn Hutchinson Award from the Association of the Sciences of Limnology and Oceanography (ASLO), and the 2011 Odum Award from the Coastal and Estuarine Research Federation (CERF) for addressing the causes, consequences, and controls of eutrophication and harmful algal blooms in aquatic ecosystems. In 2015, he was named a Fellow of the American Geophysical Union (AGU), and in 2022 he received the Lifetime Achievement Award from the US Harmful Algal Bloom Committee. He is a fellow of the Royal Dutch Academy of Sciences and holds honorary joint faculty positions at the Hohai University and the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, both located in Nanjing, China.

Dr. Joseph (Joey) Crosswell is a senior research scientist at the Commonwealth Scientific and Industrial Research Organization (CSIRO). Dr. Crosswell's core research examines the connectivity of coastal systems, particularly carbon and nutrient cycling between sediment, ocean, and atmosphere (see https://people.csiro.au/c/j/joey-crosswell). He is particularly interested in exploring diverse and remote coastal systems, ranging from mangroves to mesoscale eddies and from arid tropical estuaries in northern Australia to fjords in southern Chile. Dr. Crosswell has served as Chief Scientist on 22 research voyages at CSIRO, leading cruises to more than 70 estuaries and coral reefs in the Great Barrier Reef ecosystem as well as voyages to other remote regions of Australia, Patagonia, Fiji, Papua New Guinea, and Indonesia. He has supervised seven graduate students, two postdocs, and several undergraduate students at institutions spanning six countries.

A key element of Dr. Crosswell's research involves developing new tools and methods for coastal observations. These include instrument platforms for measuring carbonate chemistry and physical processes in estuaries, which have been deployed over the past 15 years in waters along the mid-Atlantic coast of the USA, the east Australian coast, and in Chilean fjords. More recently, Dr. Crosswell has collaborated with CSIRO researcher-engineers on the application of computer vision to detect crown of thorns starfish outbreaks in the Great Barrier Reef as well as machine learning models for mapping seagrass across the Indo-Pacific.

Dr. Crosswell plays an active role in advancing national and international research strategy and collaboration. Since 2020, he has been co-leader of the research domain *Coastal Mapping and Monitoring* within CSIRO's Environment Business Unit. He has served as a nominated author for expert scientific assessments in the USA and Australia, such as the 2nd State of the Carbon Cycle Report. He is a founding member of an international working group focused on feedback between carbon cycling and extreme events, e.g., tropical cyclones, floods, and wildfires. He leads research and field studies for multi-lateral initiatives exploring blue carbon as a resource for climate action and sustainable livelihoods across the Indo-Pacific. Dr. Crosswell has received an Innovators Fellowship from the Deshpande Foundation, a Collaborative Research Award from the Burroughs Wellcome Fund, a Research Impact Award from the University of North Carolina, and the 2022 CSIRO Collaboration medal.

List of Contributors

Kenneth W. Able
Department of Marine and Coastal Sciences
Rutgers University Marine Field Station
Tuckerton, New Jersey, United States

Janine Adams
Department of Botany
Nelson Mandela University
Port Elizabeth, South Africa

Thomas S. Bianchi
Department of Geological Sciences
University of Florida
Gainesville, Florida, United States

K. A. Bishop
Aquatic Ecologist
Sugar Creek Road
Bungwahl, Australia

Donald F. Boesch
University of Maryland Center for Environmental Science
Annapolis, Maryland, United States

E. E. Bockmon
Chemistry and Biochemistry Department
California Polytechnic State University
San Luis Obispo, California, United States

Jennifer L. Bowen
Department of Marine and Environmental Sciences
Marine Science Center
Northeastern University
Nahant, Massachusetts, United States

Melissa L. Britsch
Maine Department of Marine Resources
Augusta, Maine, United States

Joanna Burger
Department of Biological Sciences
Rutgers University
New Brunswick, New Jersey, United States

Wei-Jun Cai
School of Marine and Science Policy
University of Delaware
Newark, Delaware, United States

Jacob Carstensen
Department of Ecoscience
Aarhus University
Roskilde, Denmark

Robert J. Chant
Department of Marine and Coastal Sciences
School of Environmental and Biological Sciences
Rutgers University
New Brunswick, New Jersey, United States

Luzhen Chen
Key Laboratory of the Ministry of Education for Coastal and Wetland Ecosystems
Xiamen University
Xiamen, China

Kelsey Chenoweth
The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts, United States

John A. Church
Climate Change Research Centre
University of New South Wales
Sydney, Australia

and

Australian Centre for Excellence in Antarctic Science (ACEAS)
University of New South Wales
NSW, Australia

Nicole Cormier
Department of Earth and Environmental Sciences
Macquarie University
Sydney, Australia

R. J. Cox
Australian Climate Change Adaptation Research Network for Settlements and Infrastructure
University of New South Wales Sydney
Sydney, Australia

Joseph R. Crosswell
Oceans and Atmosphere
Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Brisbane, Australia

Marina Cucuzza
South Central Climate Adaptation Science Center
Norman, Oklahoma, United States

David R. Easterling
National Climate Assessment Technical Support Unit
National Centers for Environmental Information
National Oceanic and Atmospheric Administration
Asheville, North Carolina, United States

Alexa L. Fredston
Department of Ocean Sciences
University of California, Santa Cruz
Santa Cruz, California, United States

Jon French
Coastal and Estuarine Research Unit
Department of Geography
University College London
London, UK

Daniel A. Friess
Department of Earth and Environmental Sciences
Tulane University
New Orleans, Louisiana, United States

Neil K. Ganju
U.S. Geological Survey
Woods Hole Coastal and Marine Science Center
Woods Hole, Massachusetts, United States

Kunshan Gao
State Key Laboratory of Marine Environmental Science
College of Ocean and Earth Sciences
Xiamen University
Xiamen, China

and

Co-Innovation Center of Jiangsu Marine Bio-industry Technology
Jiangsu Ocean University
Lianyungang, China

Bronwyn M. Gillanders
Southern Seas Ecology Laboratories
School of Biological Sciences
University of Adelaide
Adelaide, Australia

Christopher J. Gobler
School of Marine and Atmospheric Sciences
Stony Brook University
Stony Brook, New York, United States

M. Goodman
Hopkins Marine Station
Stanford University
Pacific Grove, California, United States

G. Grimsditch
United Nations Environment Programme
Nairobi, Kenya

Edwin D. Grosholz
Department of Environmental Science and Policy
University of California, Davis
Davis, California, United States

Benjamin S. Halpern
Bren School of Environmental Science and Management
University of California, Santa Barbara
Santa Barbara, California, United States

Jochen Hinkel
Global Climate Forum
Berlin, Germany

and

Resource Economics Group
Albrecht Daniel Thaer-Institute and Berlin Workshop in Institutional Analysis of Social- Ecological Systems (WINS)
Humboldt University
Berlin, Germany

Charles S. Hopkinson
Department of Marine Sciences
University of Georgia
Athens, Georgia, United States

Jessie C. Jarvis
Department of Biology and Marine Biology
University of North Carolina, Wilmington
Wilmington, North Carolina, United States

Yan Ji
State Key Laboratory of Marine Environmental Science
College of Ocean and Earth Sciences
Xiamen University
Xiamen, China

and

School of Biological and Chemical Engineering
Qingdao Technical College
Qingdao, China

Jeffrey Kelleway
School of Earth, Atmospheric and Life Sciences
University of Wollongong
Wollongong, Australia

Michael J. Kennish
Department of Marine and Coastal Sciences
School of Environmental and Biological Sciences
Rutgers University
New Brunswick, New Jersey, United States

Ken W. Krauss
U.S. Geological Survey
Wetland and Aquatic Research Center
Lafayette, Louisiana, United States

Kenneth E. Kunkel
Cooperative Institute for Satellite Earth System Studies
North Carolina Institute for Climate Studies
North Carolina State University
Asheville, North Carolina, United States

Arnaud Laurent
Department of Oceanography
Dalhousie University
Halifax, Nova Scotia, Canada

Heather M. Leslie
University of Maine Darling Marine Center
Walpole, Maine, United States

and

School of Marine Sciences
University of Maine
Orono, Maine, United States

Jeffrey S. Levinton
Department of Ecology and Evolution
Stony Brook University
Stony Brook, New York, United States

Ming Li
Horn Point Laboratory
University of Maryland Center for Environmental Science
Cambridge, Maryland, United States

Javier Lloret
The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts, United States

Catherine E. Lovelock
School of Biological Sciences
The University of Queensland
St Lucia, Queensland, Australia

M. A. Madej
Coastal Ecosystems Institute of Northern California
Humboldt, California, United States

A. Mohammed
United Nations Environment Programme
Nairobi, Kenya

Kenneth A. Moore
Department of Biological Sciences
The Virginia Institute of Marine Science
College of William and Mary
Gloucester Point, Virginia, United States

Allison Myers-Pigg
Marine and Coastal Research Laboratory
Pacific Northwest National Laboratory
Sequim, Washington, United States

and

Department of Environmental Sciences
University of Toledo
Toledo, Ohio, United States

Robert J. Nicholls
Tyndall Centre for Climate Change Research
University of East Anglia
Norwich, UK

J. K. O'Leary
Wildlife Conservation Society
Mombasa, Kenya

Christopher L. Osburn
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina, United States

L. Fernando Pareja-Roman
Department of Marine and Coastal Sciences
School of Environmental and Biological Sciences
Rutgers University
New Brunswick, New Jersey, United States

Hans W. Paerl
Institute of Marine Sciences
University of North Carolina at Chapel Hill
Morehead City, North Carolina, United States

Kara E. Pellowe
University of Maine Darling Marine Center
Walpole, Maine, United States

and

School of Marine Sciences
University of Maine
Orono, Maine, United States

and

Stockholm Resilience Centre
Stockholm, Sweden

William Peirson
New College
University of New South Wales Sydney
Sydney, Australia

Jacqueline L. Raw
Department of Botany and Institute for Coastal and Marine Research
Nelson Mandela University
Port Elizabeth, South Africa

Sarah C. Risley
University of Maine Darling Marine Center
Walpole, Maine, United States

and

School of Marine Sciences
University of Maine
Orono, Maine, United States

Kerrylee Rogers
School of Earth, Atmospheric and Life Sciences
University of Wollongong
Wollongong, Australia

Neil Saintilan
Department of Earth and Environmental Sciences
Macquarie University
Sydney, Australia

Mark Schuerch
Department of Geography
University of Lincoln
Lincoln, UK

Brad A. Seibel
College of Marine Science
University of South Florida
St. Petersburg, Florida, United States

Frida Sidik
Institute for Marine Research and Observation
Ministry of Marine Affairs and Fisheries
Perancak, Bali, Indonesia

Natalie Snider
Environmental Defense Fund
Washington, D.C., United States

Joshua S. Stoll
University of Maine Darling Marine Center
Walpole, Maine, United States

and

School of Marine Sciences
University of Maine
Orono, Maine, United States

Jeremy M. Testa
Chesapeake Biological Laboratory
University of Maryland Center for Environmental Science
Solomons, Maryland, United States

Stephen J. Tomasetti
Department of Natural Sciences
University of Maryland Eastern Shore
Princess Anne, Maryland, United States

J. Tyburczy
California Sea Grant
Humboldt, California, United States

Ivan Valiela
The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts, United States

Arnoldo Valle-Levinson
Department of Civil and Coastal Engineering
University of Florida
Gainesville, Florida, United States

Nicholas D. Ward
Marine and Coastal Research Laboratory
Pacific Northwest National Laboratory
Sequim, Washington, United States

Nathaniel Weston
Department of Geography and the Environment
Villanova University
Villanova, Pennsylvania, United States

Alan K. Whitfield
South African Institute for Aquatic Biodiversity
Somerset Street
Grahamstown/Makhanda, South Africa

Lisamarie Windham-Myers
U.S. Geological Survey
Water Resources Mission Area
Menlo Park, California, United States

Xuebin Zhang
Climate Science Centre
Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Hobart, Australia

Section 1

Physical–Chemical Aspects

1 Introduction to Climate Change and Estuaries

Michael J. Kennish, Hans W. Paerl, and Joseph R. Crosswell

CONTENTS

ABSTRACT

Estuaries are highly variable, complex coastal environments that rank among the most productive aquatic ecosystems on earth. They have great value to humans because of their diverse and extensive services. However, estuaries are particularly susceptible to human impacts because of burgeoning population growth and development in the coastal zone as well as multiple climatic stressors. Climate change affects estuaries in a myriad of ways, most notably by increasing water temperature, sea-level, tropical cyclone intensity, storm surge, extreme precipitation, and freshwater flux interspersed with record droughts, resultant major salinity shifts, as well as altered biogeochemical cycling and circulation processes, accelerating shoreline erosion, and degrading wetlands habitat; all of which is leading to major alterations of the structure and function of biotic communities (e.g., species abundance, distribution, diversity, reproduction, phenology, production, and trophic interactions) worldwide. Climatic drivers often interact with anthropogenic non-climatic drivers, including nutrient over-enrichment, sediment loads, and xenobiotic pollutant inputs to exacerbate adverse effects in estuaries. The overall impact of climate change on estuarine and coastal marine environments is increasing, and thus effective management strategies are needed to mitigate these adverse effects while also effectively increasing resilience and environmental sustainability. Restoration efforts must also be implemented for the recovery of estuaries that are already severely impacted and no longer sustainable.

Key Words: estuaries, climatic drivers, non-climatic drivers, anthropogenic impacts, ecological changes, mitigation, adaptation, resilience, sustainability

1.1 INTRODUCTION

Estuaries are complex and dynamic coastal ecosystems. They are transitional environments where the land meets the sea and freshwater runoff mixes with seawater, resulting in salinity gradients, a continuum of biogeochemical cycles and biota from freshwater to marine, as well as an array of distinctive habitats. They rank among the most productive ecosystems on earth, rivaling those of coral reefs and tropical rain forests.

About 40% of the world's more than 8 billion human population lives within 100 km of the coast, with many depending on the provision of estuarine environments (Kennish 2019). The global value of estuarine ecosystem services and that of adjoining coastal wetlands is estimated to be in the trillions of dollars and includes broad and essential ecological, economic, and societal benefits (Barbier et al. 2011; Costanza et al. 2014). Among the most highly valued human services associated with estuaries are recreational and commercial fisheries, tourism, aquaculture, electric power generation, oil and gas operations, transportation, and shipping, as well as a source of natural substances used in the production of specialty chemicals and foods, medicines, and pharmaceuticals. Many large and vibrant cities of the world are located near estuaries, and hence the real estate value bordering these coastal

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water bodies is typically high (Thrush et al. 2014). They are important venues for coastal tourism, being heavily utilized by swimmers, fishers, boaters, hunters, and birdwatchers. Clearly, the world economy relies heavily on the human use of estuaries and the rich resources and services they provide.

Numerous environmental factors affect the structure (biotic community composition, species abundance, and biodiversity) and function (biotic production of organic matter, biogeochemical cycling, including the transformation of nutrients, filtration of pollutants, capture and storage of carbon, and trapping of sediments) of estuarine ecosystems (Kennish 2016, 2017). An array of habitats supports numerous populations of estuarine and marine organisms many of recreational and commercial importance. As noted by Kennedy et al. (2002), about 75% of commercially harvested marine fish and shellfish species representing up to 90% of the recreational harvest of marine species in the USA depend on estuaries for reproduction and spawning, nursery and refuge habitats, feeding grounds, and migration routes between spawning and feeding habitats.

The buffering capacity of coastal wetlands and estuaries helps protect and sustain upland habitats and infrastructure against the insidious and acute impacts of climate change, including sea-level rise, storm surge, shoreline erosion, inundation, flooding, and salinity intrusion. Because coastal development is escalating with millions of new inhabitants living in watersheds surrounding estuaries, management strategies are being developed to ensure the long-term sustainability and resilience of coastal habitats and communities in the face of rising sea-levels and other climate-driven effects (Kennish 2021, 2022). Since 1950, the world population has more than tripled (~2.5 billion in 1950 to >8 billion in 2022; United Nations Department of Economics and Social Affairs Population Dynamics 2022) with a major fraction of the total growth occurring in coastal regions. In the USA alone, more than 130 million people (~42% of the nation's population) inhabited coastal shoreline counties in 2013 (Kildow et al. 2016; Payne et al. 2018). These population figures are similar to those of other countries. Human population growth and urbanization are increasing substantially in coastal zones, with an estimated 75% of the world's population expected to live there by 2025 (Bianchi 2007; Bianchi and Allison 2009). Not surprisingly, anthropogenic stressors are major drivers of change in estuarine environments.

Coastal erosion coupled with rising sea-levels impacts beaches, dunes, estuarine basins, and shoreline habitats worldwide. In the USA, for example, Hapke et al. (2011) reported long-term erosion rates of 0.5 ± 0.09 m/yr along the Mid-Atlantic and New England coasts. More than 80% of the beaches on the east coast of the USA are now eroding. Beach renourishment projects are on the rise in many coastal regions to help maintain these habitats.

The objective of this book is to examine and assess the interactive effects and impacts of multiple anthropogenic climatic and non-climatic drivers that affect and alter the structure and function of estuarine ecosystems, as well as the management approaches to mitigate the impacts and increase sustainability and resilience of these ecosystems and coastal communities. Climatic drivers include "any climate-induced factor that directly or indirectly causes a change" (Wong et al. 2014). Climate change is defined as regional or global changes in mean climate state or in patterns of climate variability over decades to millions of years often identified using statistical methods and sometimes referred to as changes in long-term weather conditions (IPCC 2012).

Climate change effects in estuaries must be assessed in conjunction with direct anthropogenic drivers in coastal watersheds that can exacerbate overall impacts, including removal of natural vegetation, erosion of soils, mobilization of sediments, associated nutrients and other pollutants, construction of impervious surfaces and hardened shorelines, application of fertilizers, diversion of freshwater, and infrastructure expansion, as well as estuarine basin effects, such as dredging, marina and harbor construction, shipping, and aquaculture (Table 1.1). Improved land-use policies and water management plans are necessary to reduce interactive effects of anthropogenic climatic and non-climatic drivers of change that are adversely affecting estuaries and other coastal environments (Breitburg et al. 1998, 2018; Scavia et al. 2002; Crain et al. 2008; Monbaliu et al. 2014; Robins et al. 2016; Bindoff et al. 2019). Management strategies are focusing on the mitigation of anthropogenic climatic and non-climatic stressor impacts, adaptation to changing conditions, an increase in resilience of coastal communities, and sustainability of habitats.

1.2 PLAN OF THE VOLUME

Climate Change and Estuaries consist of three major sections: (1) physical–chemical aspects; (2) biological aspects; and (3) management aspects. The book not only examines climatic and non-climatic drivers of change affecting estuarine environments but also their interactions and effects on populations of organisms, communities, habitats, and ecosystem structure and function. The management of climate change effects in estuaries considers both natural and built communities and includes mitigation, adaptation, and resilience programs. The vulnerability and sustainability of estuaries to climate change are also assessed in response to temperature increases, altered precipitation amounts and patterns, more extreme storm and drought events, rising sea-levels, and other drivers of change.

Chapters in the book discuss how climate change affects estuaries by modulating water temperature, salinity, sea-level, storm intensity and storm surge, precipitation and freshwater flux, as well as biogeochemical and circulation processes, shoreline erosion, sediment delivery and deposition, and other phenomena. For example, warming waters and density changes, shifting currents and water masses, reduced dissolved oxygen and acidification, and other factors are affecting the biogeochemical cycling of carbon and

TABLE 1.1
Major anthropogenic drivers of change in estuaries

Drivers

- Class 1 (Degrade Water Quality)
  - Nutrient Enrichment/Eutrophication
  - Organic Carbon and Thermal Loading
  - Biogeochemical Alteration
  - Chemical Contaminants
  - Sediment/Particulate Inputs
  - Sewage Inputs
  - Pathogens

- Class 2 (Impact Habitat)
  - Watershed Development
  - Watershed Impervious Cover
  - Dredging and Dredged-Material Disposal
  - Shoreline Hardening
  - Lagoon Construction
  - Land Reclamation and Impoundments
  - Coastal Subsidence

- Class 3 (Alter Biotic Communities)
  - Human-altered Hydrological Regimes
  - Overfishing
  - Intensive Aquaculture
  - Invasive/Introduced Species
  - Floatables/Plastics/Debris

- Class 4 (Climate Linked)
  - Climate Change Drivers
    - CO_2, CH_4, NO_2, Chlorofluorocarbons, (Greenhouse Gases)
      - Warming Temperatures
      - Precipitation and Land Runoff
      - Extreme Events
        - Hurricanes and Other Major Storms
        - Storm Surges
        - Tornadoes
        - Droughts

Source: Modified from Kennish (2021).

nutrients (N, P, Si, Fe, and micronutrients), and from the organismal perspective, abundance, distribution, diversity, reproduction, phenology, species interactions, food web dynamics, and community structure of estuarine and marine organisms. Climate-driven biotic invasions and extinctions are increasing. Fishery yields are changing in different regions, some driven by overfishing and others by water quality and habitat declines. Rising sea-level, mainly attributable to the thermal expansion of the oceans and melting of ice sheets, is responsible for the increasing loss of essential coastal habitat (e.g., salt marshes, seagrasses, and mangroves) and an array of diminishing ecosystem services. Rising sea-level reduces the resilience and sustainability of many coastal wetlands and other essential estuarine and coastal marine habitats that provide a protective buffer for natural and developed communities from extreme weather events, inundation, and flooding. Increasing frequencies of extreme rainfall and flooding events, and associated accelerated loading of nutrients and organic matter in runoff, are accelerating eutrophication, increasing HABs, and expanding hypoxia in receiving waters (Figure 1.1).

Chapter 1 is an overview of *Climate Change and Estuaries*. Chapter 2 covers the dynamics of climate change in the earth system. Chapter 3 provides a description of the origin, historical development, and classifications of estuaries. Ensuing chapters examine specific aspects of climate change and interactive factors: (Chapter 4) sea-level rise; (Chapter 5) anthropogenic drivers of estuarine change; (Chapter 6) saltwater intrusion; (Chapter 7) biogeochemical changes; (Chapter 8) hypoxia; (Chapter 9) acidification; (Chapter 10) carbon dynamics; (Chapter 11) blue carbon; (Chapter 12) hydrological responses and circulation changes; (Chapter 13) sediment dynamics; (Chapter 14), intertidal and subtidal environments; (Chapter 15) organism responses; (Chapter 16) microbial ecology; (Chapter 17) nutrients, phytoplankton, and harmful algal blooms (HABs); (Chapter 18) macroalgae; (Chapter 19) salt marshes; (Chapter 20) mangroves; (Chapter 21) seagrasses; (Chapter 22) benthic communities; (Chapter 23) shellfish; (Chapter 24) fish; (Chapter 25) avifauna; (Chapter 26) invasive species; (Chapter 27) deoxygenation and estuarine fauna; (Chapter 28) estuarine management; (Chapter 29) risks and adaptation; (Chapter 30) resilience; (Chapter 31) effects on engineering infrastructure; and (Chapter 32) conservation and management strategies.

1.3 CLIMATE CHANGE DRIVERS

1.3.1 TEMPERATURE INCREASES

The global mean surface temperature (GMST) of the earth is increasing. It increased by 1.09°C between 1850–1900 and 2011–2020 (Gulev et al. 2021). The 20th century was the warmest in more than 1000 years; however, the highest temperature increases have occurred since 1970. The last two decades (2001-2020) were warmer than those during the past century, with the decade of 2011–2020 being the warmest on record (IPCC 2021). As noted by Robert Kopp, a climate scientist in the Department of Earth and Planetary Sciences at Rutgers University, more than 90% of the warmest years on record have occurred since 2000. Among the warmest years recorded by NASA and NOAA (i.e., 2015–2020), 2016 and 2020 were the warmest, reaching 1.02°C above the baseline 1951–1980 mean.

Between 1880 and 2012, the globally averaged combined land and ocean surface temperature increased by 0.85°C (0.65 to 1.06°C) (Wong et al. 2014). The highest combined temperatures were observed after 2000, with 2010 tying with 2005 as the warmest combined global land and ocean annual surface temperature increase of 0.62 ± 0.07°C (IPCC 2014). Global climate models predict that anthropogenic and natural forcing factors will lead to significant

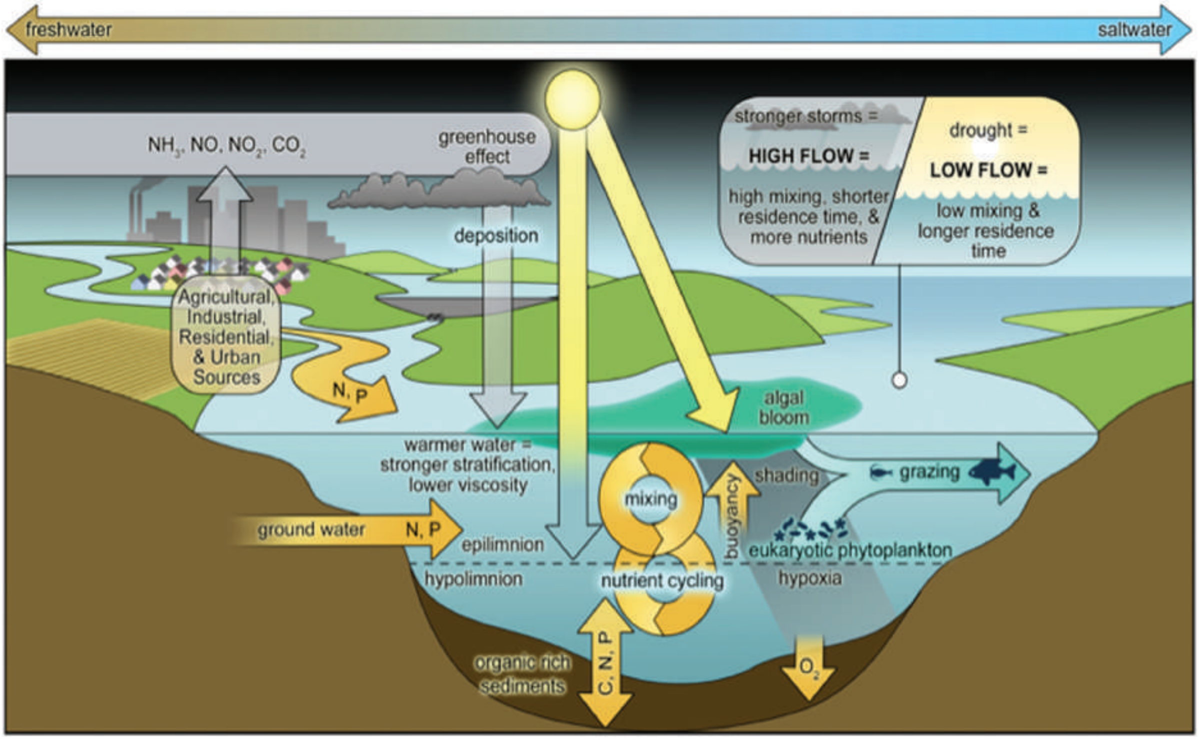

FIGURE 1.1 Conceptual diagram, adapted from Paerl (2014), of interactive physical, chemical, and biological controls on eutrophication, harmful algal bloom formation, and hypoxia along the freshwater-to-marine continuum.

planetary temperature increases during the 21st century, likely exceeding 1–2°C unless significant measures are taken to mitigate greenhouse gas emissions (IPCC 2021).

Water temperatures in the estuaries and oceans of the world are increasing as well (Kennish 2019; Bindoff et al. 2019; Fox-Kemper et al. 2021). However, the temperature increases have been significantly less than over land; for example, for the period from 1850–1900 to 2011–2020, the GMST increased by 0.88°C on the ocean surface compared to 1.59°C over the land (Gulev et al. 2021). Most of the warming in the oceans (0.60°C) has occurred since 1980, with the rate of ocean warming more than doubling since 1993 (Pörtner et al. 2019; Gulev et al. 2021). Marine heatwaves (i.e., sustained periods of anomalously high near-surface temperatures that can lead to severe and persistent impacts on marine ecosystems) are becoming more frequent, doubling in number since the 1980s (Fox-Kemper et al. 2021). Ocean surface temperatures are projected to increase further during the 21st century (on average by 0.86°C for the period from 1995–2014 to 2081–2100 in the SSP1-2.6 emission scenario and by 2.89°C in the SSP5-8.5 emission scenario) (Fox-Kemper et al. 2021).

The oceans are the primary sink for the increase in energy storage in the earth's climate system, accounting for more than 90% of the heat energy accumulated from 1971 to 2000. Much of the added global heat is concentrated in the upper ocean (Levitus et al. 2012). Between 1955 and 1995, water temperature for the combined Atlantic, Pacific, and Indian Oceans increased by 0.06°C in the upper 3000 m and 0.31°C in the upper 300 m. Similarly, water temperature in the Southern Ocean between the 1950s and 1980s increased by 0.17°C at mid-depths (700–1100 m) (Moran 2011). The mortality rates of many marine organisms will increase with rising ocean temperatures, as will range shifts in organism geographic distributions and altered trophic interactions (Robins et al. 2016; Hoegh-Gulberg et al. 2018; Bindoff et al. 2019; Fox-Kemper et al. 2021). These changes will significantly affect ecosystem services (IPCC 2021).

More than 70% of the world's coastlines have experienced significant increases in sea surface temperature over the past three decades at a rate of 0.18 ± 0.16°C per decade (Lima and Wethey 2012). The mean rate of increase in sea surface temperature along coastlines has been greater than that of the open ocean (Wong et al. 2014). Rising temperatures will significantly change the physical state of high-latitude systems (e.g., reduction in glaciated fjords and loss of permafrost in watersheds) (IPCC 2021).

Rising global temperatures are greatly affecting estuarine organisms by altering physiological and reproductive processes, as well as growth and survival rates (Robins et al. 2016; Frid and Caswell 2017; Kennish 2019). Warmer estuarine waters promote algal blooms, and greater precipitation and runoff driven by climate change increase bacterial and viral pathogens (e.g., *Vibrio* spp., adenovirus, and norovirus), facilitating disease transmission via waterborne and foodborne sources (Paerl et al. 2014, 2017; Kennish 2019). Such transmission increases in estuaries receiving heavy microbial loads in agricultural runoff and sewage inputs from combined sewer overflows (CSOs), particularly after storm events that deliver large amounts of precipitation (Kennish 1997, 2002, 2016; Robins et al. 2016). These effects can significantly degrade water quality (Kennish 2019).

Increasing atmospheric and ocean temperatures are coupled with escalating greenhouse gas emissions, most notably carbon dioxide (CO_2), largely driven by human-induced fossil-fuel combustion. Deforestation also has contributed to the increase in atmospheric CO_2 concentrations observed over the past century (IPCC 2021). CO_2 concentrations in the atmosphere now exceed 410 ppm, up from 285.5 ppm in 1850 (Gulev et al. 2021), and likely reaching their highest level in the last 15 million years in 2020. In addition, watershed land-use changes, urbanization, as well as agricultural and industrial expansion are responsible for increased emissions of other potent greenhouse gases, including methane (CH_4) and nitrous oxides (N_2O). For example, CH_4 and N_2O levels reached levels of 1866.3 ppb and 332.1 ppb, respectively, in 2019 far exceeding pre-industrial levels (Gulev et al. 2021).

A long-term goal of the 2015 Paris Climate Agreement is to limit the increase in global mean temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Limiting temperature increases below these levels will substantially reduce the environmental risk and effects of climate change on estuarine and marine organisms and habitats. However, the current rate of CO_2 and other greenhouse gas emissions will lead to higher levels of temperature increases and more intense and persistent droughts. Unless these emissions are substantially curtailed or eliminated, the global mean surface temperature increase will exceed 2°C or even 3°C by the end of the 21st century. Currently, less than 20 of the 195 countries in the Paris Climate Agreement are on track to meet their CO_2 emission goals.

1.3.2 SEA-LEVEL RISE

The mean ocean heat content has steadily increased over the past 50 years. Thermal expansion of ocean waters and the melting of polar ice sheets and continental glaciers are the primary drivers of rising sea-levels worldwide (Bindoff et al. 2019; Kennish 2019; Pörtner et al. 2019; Fox-Kemper et al 2021). Global warming projections indicate significant increases in oceanic mass and higher sea-levels during the 21st century as well. The Greenland and Antarctic (western Antarctic Peninsula) ice sheets, which have been losing mass over the past two decades because of increasing temperatures and meltwater generation, contribute substantially to the observed increases in sea-level. The volume of Arctic sea ice has also been rapidly declining over the past four decades, and projections indicate that extensive areas in the Arctic will be ice-free during the 21st century. NASA has reported that the extent of Arctic sea ice is decreasing at a rate of 12.9% relative to the 1981 to 2010 average. Overall, Arctic sea-ice cover has declined by ~50% since 1980.

It is important to differentiate global mean sea-level (GMSL) rise and relative sea-level (RSL) rise. Horton et al. (2018) defined GMSL as the areal mean of either RSL or sea surface height over the global ocean. They defined RSL as the difference in elevation between the sea surface and the land. RSL rise determinations must consider climate-induced GMSL rise, regional sea-level variations, and local non-climate-related sea-level changes (Wong et al. 2014). The rate and magnitude of RSL vary geographically with the occurrence of various drivers of change including: (1) atmosphere/ocean dynamics (e.g., winds and currents); (2) static-equilibrium effects (i.e., gravitational, rotational, and elastic deformational effects) of ocean/cryosphere/hydrosphere mass distribution on the height of the geoid and the earth's surface; (3) glacio-isostatic adjustment (GIA); (4) coastal subsidence due to sediment compaction, groundwater removal, and oil and gas withdrawals; (5) tectonics (seismic movement); and (6) mantle dynamic topography (Horton et al. 2018).

According to Pörtner et al. (2019), there is a high degree of confidence that the rates of GMSL increases were 1.5 mm yr^{-1} for the period 1902–2010, 2.2 mm yr^{-1} for 1970–2015, 3.2 mm $year^{-1}$ for 1993–2015, and 3.6 mm yr^{-1} for 2006–2015. More recently, Gulev et al. (2021) reported that GMSL increased at a rate of 1.35 mm yr^{-1} for the period 1901–1990 to 3.25 mm yr^{-1} for 1993–2018. Fox-Kemper et al. (2021) noted that sea-level rise has accelerated since the late 1960s at an average rate of 2.3 mm yr^{-1} for the period 1971–2018 to 3.7 mm yr^{-1} for 2006–2018. The dominant cause of GMSL rise since 1970 has been attributed to anthropogenic forcing (Dangendorf et al. 2015, 2017; Slangen et al. 2016; Horton et al. 2018; Fox-Kemper et al. 2021).

GMSL increased by 0.20 (0.15–0.25) m over the period 1901 to 2018 (Fox-Kemper et al. 2021). It is projected to increase through the 21st century and beyond (IPCC 2021). GMSL rise projections have been estimated for 2050 and 2100 based on physical modeling and statistical techniques. Best estimates of GMSL rise for 2050 range up to 0.5 m. Fox-Kemper et al. (2021) proposed that, relative to the period 1995–2014, GMSL will increase between 0.18 m and 0.23 m by 2050. GMSL rise estimates for 2100 range up to 1.0 m under 1.5°C stabilization and up to 1.1 m under 2.0°C stabilization (Bittermann et al. 2017; Rasmussen et al. 2018). Gulev et al. (2021) also reported that GMSL could increase up to 1.1 m by 2100.

Arias et al. (2021) conveyed that GMSL is projected to increase between a median of 0.38 m (0.28–0.55 m likely range) under a lower temperature increase scenario (SSP1-1.9) and 0.77 m (0.63–1.02 m likely range) under a higher temperature increase scenario (SSP5-8.5) by 2100. Further, a study by Bamber et al. (2019) showed that under a high-temperature scenario, sea-level rise could even exceed 2 m by 2100. A long-term increasing trend of sea-level rise is projected for most coastlines of the world, which will have a marked impact on the structure and function of estuarine and coastal marine ecosystems.

Sea-level changes are not spatially or temporally uniform but vary over a wide range in large part because anthropogenic climatic and non-climatic drivers are highly variable. As a result, the rate of sea-level rise in many areas can deviate considerably from the global mean value as is evident by RSL rise measurements at the local scale, which often differ from GMSL rise measurements. Geographically variable, anthropogenic non-climatic drivers of change, such as coastal development, land-use changes, altered sediment delivery due to dam building and other structural elements, and human-induced coastal subsidence, cause large variations in local RSL rise that may exceed GMSL rise by an order of magnitude or more.

Among the areas experiencing the most rapid changes of RSL are large cities on coastal plains and deltas that are subsiding because of heavy building loads, groundwater withdrawal, oil and gas extraction, sediment accumulation, and compaction (Mazzotti et al. 2009). Examples include the Po delta, eastern Tokyo, and Shanghai. In the USA, the Mississippi River delta is subsiding at a much greater rate than other coastal areas, leading to a high rate of inundation and coastal wetlands habitat loss. White and Tremblay (1995) noted that sea-level rise and subsidence were largely responsible for nearly 60% of the wetland loss along the northern Gulf of Mexico. Jankowski et al. (2017) reported a total land-surface subsidence rate of ~10 mm yr^{-1} over decadal timescales along the Louisiana coastline. GMSL rise, land-surface subsidence, and sediment deficits are the primary drivers of the rapid coastal land loss in the Mississippi River delta region (Frederick et al. 2019).

Vertical crustal movements along active tectonic plate margins can also account for substantial RSL change. For example, the Great Alaskan Earthquake of March 27, 1964, the largest ever recorded in North America (magnitude 9.2), caused abrupt subsidence of extensive areas near Anchorage amounting to ~2.5 m. By contrast, other coastal areas affected by this subduction zone earthquake were raised nearly 10 m (Hansen 1967). Similarly, the Tōhoku Earthquake of March 11, 2011, the largest ever recorded in Japan (magnitude 9.0), resulted in ~0.6 m of coastal subsidence along a 400-km stretch of coastline, with some areas subsiding up to 1.2 m (Norio et al. 2011). Crustal tectonic movements in other regions of the world are not rapid, but sustained, generating considerable RSL change over time.

The rate of coastal sea-level rise varies regionally as well due to changing climate and ocean dynamic processes (e.g., air-sea heat and freshwater fluxes, as well as variable winds, air pressure, and ocean currents) (Wong et al. 2014). Regional climate variability occurs on interannual, decadal, and interdecadal timescales driven by large-scale climate phenomena that also affect sea-level (Zhang and Church 2012). For example, the El Niño–Southern Oscillation (ENSO), the dominant source of interannual variability, induces significant sea-level changes in the tropical Pacific Ocean, varying from GMSL by up to 40 cm (Landerer et al. 2008; Walsh et al. 2012). Similarly, the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) are ENSO-like climate variability patterns in the Pacific Ocean occurring on decadal and interdecadal timescales. Zhang and Church (2012), using near-global TOPEX/Poseidon and Jason altimetry data, ascribed the rapid rates of sea-level rise in the western tropical Pacific Ocean in part to basin-scale decadal climate variability. They also attributed the negligible sea-level rise (or even falling sea-level) in the eastern tropical Pacific Ocean and west coast of the USA to a combination of decreasing sea-levels associated with decadal climate variability and a positive sea-level trend.

Glacial isostatic rebound is another driver of RSL rise variation. Coastlines near melting glaciers and ice sheets exhibit falling sea-levels (Milne et al. 2009). This is because of decreasing gravitational attraction of the melting ice sheet on ocean waters as well as rising lands in response to the loss of ice mass, changing shape of the seafloor under the reduced load of ice sheets, and the altering of the earth's rotation in response to a change in mass distribution (Gomez et al. 2010; Wong et al. 2014).

1.3.3 OTHER CLIMATIC DRIVERS

Increasing temperature and sea-level rise are accompanied by other climate change effects. Changing wind patterns coupled with rising regional and global temperatures can significantly affect coastal and estuarine circulation patterns, altering upwelling and downwelling, wave heights, and other water movements in the sea. High wind stress driven by extreme weather events, such as tropical and extratropical cyclones and other major coastal storms raises sea-levels, albeit ephemerally, as do astronomical tides. Falling atmospheric pressure during major storms also raises sea-levels. For example, a storm surge along the New Jersey coast (USA) during Hurricane Sandy in October 2012 raised sea-levels by ~3–4 m, impacting estuarine basins. The highest sea-levels observed in coastal regions have occurred when tropical cyclones made landfall concurrently at the time of spring tides, such as in New Jersey during Hurricane Sandy. While there has been an increase in the frequency and intensity of the strongest tropical cyclones since the 1970s, future trends are unclear, although it is very likely that the global mean tropical cyclone precipitation and maximum wind speed will increase (Wong et al. 2014). Future projections of storm surges are uncertain as well because of the vagaries of tropical cyclones and coastal storm characteristics. However, it is likely that storm surges will continue to be an important factor in the genesis of extreme sea-levels locally or regionally on an ephemeral basis. GMSL rise will exacerbate these effects by raising the sea-level platform and causing greater storm surges and inundation impacts on estuaries, coastal landforms, and bayshore communities.

Shifts in coastal ocean currents near estuaries could result in significant physico–chemical and biotic changes in these systems. Phytoplankton productivity often significantly increases in areas of greater coastal upwelling and declines in areas where upwelling decreases. Phytoplankton blooms occurring in some wind-driven coastal upwelling areas enhance organic carbon production and elevate BOD, leading to a reduction in dissolved oxygen levels, which has been the recurring case in nearshore ocean waters of New Jersey (USA). Seafloor topographically controlled coastal upwelling centers along the New Jersey coast are co-located with historical regions of low dissolved oxygen (Glenn et al. 2004). Increasing wind stress linked to ongoing climate change will be a potentially significant driver of coastal upwelling events during the 21st century.

Predictive models indicate greater global precipitation (up to ~15–20%) in the future; however, for some locations (Southwest USA) more droughts are predicted, which will negatively impact freshwater delivery to estuaries. A significant effect of ocean warming is the increasing frequency and intensity of high rainfall tropical cyclones, which have major impacts on coastal flooding, nutrient/organic matter loading, biogeochemical changes along the estuarine aquatic continuum, and salinity regimes (Figure 1.2) (Paerl et al. 2019). However, there will be important regional differences in precipitation, and significant geographic variation in freshwater runoff as well, with up to a 50% increase in precipitation above 50°N latitude and a 20% decrease between 20 and 50°N and °S latitudes (Frid and Caswell 2017). In contrast, there will be a local reduction in freshwater runoff and sediment delivery to estuaries and coastal waters in many areas due to the location of dams, dikes, levees, reservoirs, and other upland anthropogenic structures together with freshwater diversions for agricultural and domestic water use. Although large regional variability exists in freshwater delivery to coastal waters, there is a net global declining trend in freshwater input (Wong et al. 2014).

Decreased freshwater delivery reduces the flushing rate, increases salinity, and protracts water residence time in estuaries, affecting the distribution and abundance of organisms. Variability of water residence time strongly influences phytoplankton biomass and community composition, which have important consequences for energy flow through food webs in estuarine ecosystems (Paerl et al. 2006, 2014). For estuaries receiving high freshwater runoff from coastal watersheds in response to hurricanes and other storms, greater sediment and nutrient delivery is characteristic, as is salinity reduction (Paerl et al. 2019). Changes in vertical stratification and mixing affect biotic production and food web structure (Scavia et al. 2002; Kennish 2016). Increasing nutrient inputs promote eutrophication with a greater incidence of algal blooms, reduced dissolved oxygen levels, and loss of seagrass and other essential habitats, particularly in the more susceptible coastal lagoons (Figure 1.2) (Kennish et al. 2007; Howarth et al. 2011; Kennish and Paerl 2010; Paerl and Paul 2012; Paerl 2017;

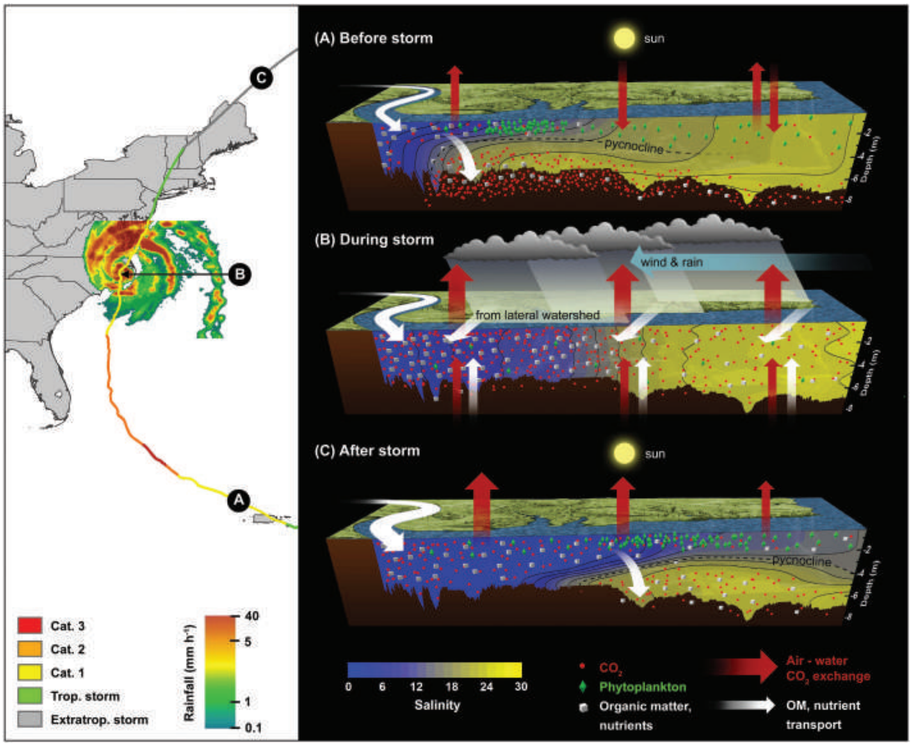

FIGURE 1.2 Conceptual diagram, adapted from Crosswell (2013), showing the biogeochemical response of a lagoonal estuary (right) to the passage of Hurricane Irene (2011) along the US Atlantic coast (left). Salinity profiles are constructed from direct measurements in the Neuse River Estuary, North Carolina, before and after the storm. Data shown are from August 15, 2011 (A), hypothetical salinity values under well-mixed conditions (B), and August 30, 2011 (C).

Paerl et al. 2018; Kennish 2019). Biogeochemical changes will affect organisms in bottom sediments as well as in the water column. Deoxygenated conditions in many coastal water bodies have been on the rise for decades concomitant with greater nutrient loading and ongoing climate change (Diaz and Rosenberg 2008; Diaz 2015; Kennish 2017; Breitburg et al. 2018). The structure and function of biotic communities in estuaries are affected by these changes, most notably those in the benthos. For example, altered nutrient recycling in bottom sediments can significantly affect primary production, particularly in shallow estuaries.

There are increasing challenges to determining changes in local and regional conditions affecting climate change forcing factors, and the physical, chemical, and biological changes that occur in response to these factors. These challenges require more effective monitoring and modeling of climate change factors, as well as greater resolution of climate and impact predictions (Robins et al. 2016). Local changes in precipitation, occurrences of drought, and resulting shifts in freshwater flows in particular are difficult to predict and directly measure because of the spatial and temporal variability of forcing factors.

1.4 ANTHROPOGENIC NON-CLIMATIC DRIVERS

There are numerous anthropogenic non-climatic drivers of change in estuaries that interact with climate drivers to create more deleterious conditions than those attributed to climatic change alone. Many of these drivers are linked to human development and activities in coastal watersheds. Anthropogenic non-climatic drivers can be organized into 12 major categories including: (1) habitat loss and alteration (lagoon construction, shoreline hardening, and land reclamation); (2) watershed impervious cover; (3) enrichment (nutrients, organic carbon, and thermal loading); (4) sewage and pathogenic inputs; (5) chemical contaminants; (6) human-induced sediment/particulate inputs; (7) dredging and dredged-material disposal; (8) human-altered hydrological regimes; (9) invasive/introduced species; (10) overfishing and intensive aquaculture; (11) coastal subsidence; and (12) floatables/plastics/debris (Table 1.1) (see Chapter 5). These 12 major categories can be organized further into three broad classes. Class 1 drivers are those that degrade water quality and are primarily chemical and biological in nature (e.g., nutrient enrichment, organic and thermal loading, chemical contaminants, sediment/particulate inputs, and pathogens). Class 2 drivers are those that impact habitat and are mainly physical factors (e.g., watershed impervious cover, shoreline hardening, lagoon construction, and land reclamation). Class 3 drivers are those that alter biotic communities; they are linked to multiple drivers (e.g., overfishing, aquaculture, invasive/introduced species, and human-altered hydrological regimes). Chapter 5 provides comprehensive coverage of these classes of drivers.

1.5 INTERACTIVE DRIVERS OF CHANGE

Estuaries are highly susceptible to human impacts because of dense human populations inhabiting upstream and proximate coastal watersheds and the multiple drivers originating in both terrestrial and coastal marine environments (Monbaliu et al. 2014). Notably, direct anthropogenic non-climatic factors – land-, estuarine-, and ocean-based impacts – rather than climate-related factors are the primary drivers of change in most estuaries often linked to overdevelopment, overexploitation of resources, freshwater diversions and upstream reservoir construction, chemical pollution, shoreline hardening, and habitat fragmentation or destruction (Kennish 2002, 2016, 2017, 2021, 2022). For example, the input of pollutants from industrial and domestic sources (e.g., sewage and pathogens, fertilizers, metals, persistent organic pollutants, and plastics), freshwater diversions, and hardening of shorelines have adversely affected estuaries, most greatly in urbanized areas. The introduction of invasive species is increasing in estuaries, and these species often outcompete and replace many endemic forms (Austin et al. 2010).

Storm surges and rising sea-levels linked to climate change are significant coastal drivers, causing salinization of estuarine waters and saline intrusion of coastal watersheds. These factors can significantly compromise reproductive success, abundance, and distribution of estuarine organisms while concurrently impacting intertidal and subtidal habitats via inundation and erosion. Based on a study of 96 estuaries, Prandle and Lane (2015) found that a sea-level rise of 1 m increases saline intrusion length by >7% in deep estuaries and by >25% in estuaries <10 m deep.

More frequent extreme rainfall events associated with higher-intensity tropical cyclones and other major coastal storms driven by climate change increase freshwater runoff resulting in higher nutrient and sediment loads that impact estuarine organisms and habitats. Spatial and temporal variation in precipitation with climate change affect the rate, magnitude, timing, and quality of freshwater inputs to estuaries (James et al. 2013), altering thermal and/or salinity stratification and biogeochemical processes. Changing rainfall patterns are amplified in estuaries in two principal ways: (1) more frequent extreme events and (2) altered spatial and temporal trends.

The flux of freshwater inputs to estuaries and coastal marine waters can greatly shift sediment, nutrient and xenobiotic pollutant loading, salinity, and flushing, which will place greater stress on many estuarine organisms. The relationship between precipitation and river flow depends on watershed characteristics and anthropogenic activities as well (Robins et al. 2016). Higher sediment loads and turbidity increase shading effects on benthic communities, decreasing the productivity of submerged aquatic vegetation, coral reefs, and other vital habitats.

Shallow enclosed estuaries with poor flushing and protracted residence time are more vulnerable to eutrophication driven by human activities in watersheds and climate change (Howarth et al. 2000, 2011; Scavia et al. 2002; Paerl et al. 2006; Kennish 2009, 2016). Eutrophication is coupled to an array of cascading environmental problems manifested by a reduction in water quality and alteration of ecosystem structure and function (Kennish et al. 2007; Jordan et al. 2018). Higher inputs of nutrients and organic matter with increasing freshwater flow stimulate primary production and occurrence of harmful algal blooms (HABs) (Paerl et al. 2018) and can cause a decrease in dissolved oxygen levels, biodiversity, essential habitat (e.g., seagrass and shellfish beds), harvestable fisheries and other ecosystem services, leading to imbalanced food webs and declining resilience (Howarth et al. 2011; Kennish and de Jonge 2011; Kennish et al. 2011). Estuaries are susceptible to eutrophication when primary production exceeds the demands of consumers (Anthony et al. 2009). Nutrient and organic matter inputs to estuaries have increased substantially since the 1970s, consistent with a greater incidence of bacterial degradation and eutrophication in these coastal ecosystems over the past several decades (Maavara et al. 2017; Fennel and Testa 2019). The co-occurrence of increasing climate change and eutrophication drivers also poses an escalating threat of oxygen depletion in coastal ocean waters outside of impacted estuaries, with the frequency and extent of oxygen-depleted dead zones projected to increase in these waters, threatening the viability of their biotic communities (Breitburg et al. 2018; Laurent et al. 2018).

Shallow estuaries and coastal lagoons are most susceptible to changes in precipitation and freshwater inflow, sea-level rise, sediment and nutrient influx, and energy input from waves, tides, and storms (Kennish et al. 2014). The balance between these forcing mechanisms influences estuarine hydrodynamics and morphology. Changes in local forcing conditions by anthropogenic climatic and non-climatic drivers will shift estuarine morphodynamics toward a new equilibrium which may fundamentally alter estuarine function (Prandle 2009). For example, a rising sea-level that is not balanced by local sediment supply can shift shallow tidal estuaries from flood to ebb dominance, thereby increasing coastal erosion and changing estuaries from nutrient sinks to nutrient sources along an aquatic continuum (Crosswell et al. 2020).

The most rapid hydrological changes occur when natural barriers are modified by intense storms and human development. Gupta et al. (2008) provide an example of where new inlet construction led to increased tidal energy, shifting a microtidal lagoonal estuary toward a more tide-dominated system and influencing stratification, nutrient budgets, and system ecology. Rising sea-levels and increasing flux of freshwater flow shift the salinity regime, position of turbidity maxima, and flushing times, which also affect estuarine biotic communities. Higher precipitation, runoff, river flows, nutrient loads, and organic matter inputs promote eutrophication and a greater incidence of HABs and hypoxia (Robins et al. 2016). Warming of estuarine waters due to climate change, most pronounced in temperate and high-latitude regions (Bindoff et al. 2019), reduces mixing, strengthens stratification of the water column, stimulates cyanobacterial bloom taxa that "like it hot" (Paerl and Huisman 2008, 2009), and increases bacterial respiration, as well as the occurrence of hypoxia (Hallett et al. 2018; Warwick et al. 2018).

Estuaries exhibit high biotic and habitat heterogeneity in response to variable environmental conditions and anthropogenic drivers. Estuarine and marine biotic communities are shaped by multiple interactive drivers that elicit synergistic, antagonistic, or additive responses (Boyd and Hutchins 2012; Griffen et al. 2016; Gunderson et al. 2016; Boyd et al. 2018). However, the interactive and cumulative effects of multiple drivers on these communities are not well constrained, limiting their usefulness in predicting the responses of communities and ecosystems to climate change (Boyd and Hutchins 2012; Breitburg et al. 2018). More research is required, therefore, to effectively assess and predict multiple stressor effects on populations, communities, and habitats. Determination of higher-order interactions, while challenging, is important in predicting cumulative driver effects (Boyd et al. 2018).

The overall impact of interactive anthropogenic climatic and non-climatic drivers on estuarine and coastal marine ecosystems is increasing (Roessig et al. 2014; Kennish and Elliott 2011; Frid and Colwell 2018; Kennish 2019). For example, nutrient inputs and deoxygenation attributable in part to climate change–driven increases in precipitation and land runoff are leading to escalating estuarine and coastal eutrophication and hypoxia (Breitburg 2002; Breitburg et al. 2009, 2018; Howarth et al. 2011; Diaz 2015; Paerl et al. 2018). Since 1950, global fertilizer use has increased 10-fold (Breitburg et al. 2018). Between 1970 and 2000 alone, nitrogen inputs to estuaries and other coastal waters increased by 43%, accounting for a significant decline in the water quality of many coastal waterbodies (Seitzinger et al. 2010).

Some investigators use the term "stressor" synonymously with "driver" (see Côté, et al. 2016). Breitburg et al. (1998, 2018) emphasize the importance of multiple stressor interactions on biotic communities and habitats. For example, they cite several studies indicating that as oxygen concentrations in coastal and open ocean waters have decreased since at least the middle of the 20th century, their interactive effects with other stressors in these ecosystems have escalated (Diaz and Rosenberg 2008; Stramma et al. 2008; Keeling et al. 2010). In estuarine and coastal marine waters, multiple stressors or drivers are responsible for the decline of oxygen levels, including increased loadings of nutrients (nitrogen and phosphorus) and organic matter from coastal watersheds, more specifically eutrophication effects primarily coupled to domestic fertilizer use, agriculture, livestock, sewage waste inputs, and the combustion of fossil fuels from land-based sources. Greater inputs of nutrients stimulate algal growth and bloom formation in receiving coastal waters, thereby increasing biological oxygen demand. Deoxygenation of these waters occurs where biological oxygen consumption through microbial respiration exceeds oxygen supplied by air–sea fluxes, physical transport, and photosynthesis (Breitburg et al. 2018). These effects are exacerbated by rising temperatures due to climate change, which decreases oxygen solubility in water and increases oxygen consumption via respiration. Deoxygenation of estuarine and coastal marine waters negatively impacts system productivity, biodiversity, and biogeochemical cycles. Hypoxia and anoxia are recurring phenomena in some estuaries due to enhanced production of organic matter, such as in Chesapeake Bay, where about 30% of the estuarine area is impacted by deoxygenation from late spring to early fall (Breitburg et al. 2018).

In a synthesis of 171 studies of multiple stressors in coastal and marine ecosystems, Crain et al. (2008) determined that cumulative effects in individual studies were antagonistic (38%), synergistic (36%), and additive (26%), although the overall interaction across all studies was synergistic, indicating that multiple stressor cumulative effects are often worse than expected based on single stressor impacts. The investigators also found that the interactive type varied by response level (i.e., population level vs. community level). Comprehensive studies of multiple stressor effects on estuarine ecosystems and their biotic communities are needed to inform management strategies that effectively address climate change impacts (Kennish 2021, 2022). Of particular note is the need for a greater understanding of the linkages and feedback among multiple environmental stressors. The ecological effect of one stressor in an estuary often depends on the magnitude of another, and the interactions of multiple stressors in these ecosystems can lead to non-additive synergistic or antagonistic outcomes (Griffen et al. 2016; Gunderson et al. 2016; Kroeker et al. 2017).

There is concern that direct anthropogenic activities interacting synergistically with climate drivers will exacerbate estuarine ecosystem impacts during the 21st century, although the patterns of anthropogenic non-climatic drivers can be difficult to predict (Robins et al. 2016). Joint influences of anthropogenic climatic and non-climatic drivers, which vary locally and regionally, affect estuaries through fluxes of temperature, freshwater flow, salinity, sediment delivery, water quality, and altered vegetated beds, as well as shifts in species composition, abundance, and distribution (Kimmerer and Weaver 2013). Ongoing coastal development and infrastructure construction will increase land-use changes in coastal watersheds by converting natural habitat to impervious cover, altering hydrological and sediment delivery systems to estuaries (via dams, dikes, reservoirs, and freshwater diversions), and creating hardened shorelines. In some areas, coastal development will act synergistically with rising sea-levels to accelerate the impacts of storms and other coastal hazards on developed communities and their infrastructure (Kennish 2016).

Water quality and habitats in many estuarine and coastal marine environments have been significantly affected by human activities (Kennish 1997; Kennish and Paerl 2010; Kennish and Elliott 2011; Kennish 2016). Loss of essential salt marsh, mangrove, and seagrass habitats removes important buffers against storm effects, sea-level rise, and erosion. Areal loss of these habitats has been primarily ascribed to anthropogenic non-climatic drivers, such as freshwater diversions, diking, ditching, land reclamation, agriculture, coastal development, and water quality changes (Adam 2002, 2019; Kroeger et al. 2017; Li et al. 2018). However, climatic drivers are having an increasing impact on wetlands habitat loss as well, notably temperature increases and sea-level rise. Salinization of wetlands habitat is also coupled with climate change (Wong et al. 2014). Total areal reduction of coastal wetlands habitat has been substantial over the years, with 50% of salt marshes, 35% of mangroves, and 29% of seagrasses being lost or degraded worldwide (Barbier et al. 2011). The effects have been most acute in human-dominated estuarine ecosystems, which have also experienced an increasing reduction of biodiversity (Worm et al. 2006). In addition, vital ecosystem services have decreased concurrently, notably the number of viable fisheries (37% decline), provision of nursery habitats such as oyster reefs and wetlands (69% decline), and filtering and detoxification services of suspension feeders, submerged aquatic vegetation, and wetlands (63% decline) (Worm et al. 2006; Barbier et al. 2011). Depending on the level of CO_2 emissions, additional coastal wetland losses of 20–90% are projected by 2100 (Bindoff et al. 2019).

Ocean acidification linked to climate change is an emerging crisis. Increasing atmospheric CO_2 and the uptake of CO_2 in the sea have led to a decrease in pH as carbonic acid increases. An important climate change indicator, pH is a dimensionless measure of acidity in the ocean. While the decrease in ocean pH has amounted to 0.1 units since 1850, models predict a decline of an additional 0.3–0.4 units by 2100 under a scenario of moderate levels of CO_2 emissions (Frid and Caswell 2017). A decrease of 0.1 units on the logarithmic pH scale translates into a ~30% increase in hydrogen ion concentration; thus, while the absolute decline of pH may seem slight, the ecological ramifications can be substantial. For example, the resulting acidification of ocean waters reduces the amount of bioavailable carbonate needed for organism skeletal growth.

Higher acidity leads to the dissolution of biogenic calcium carbonate and the decrease in the capacity (or increase in the energy requirements) of shell-bearing marine organisms to build shells. Acidification exacerbates the impact of coral bleaching by increasing the energy requirement for recovery, a process responsible for a significant decline in the abundance of coral, which will increase with rising seawater temperatures projected through the 21st century. The greatest biotic impact of acidification is currently the damage to coral reefs and shellfish beds that form important habitats for biotic communities. Furthermore, the reproduction and larval development of these organisms can be impaired or inhibited. Reduction in shellfish resources could be detrimental to natural shellfisheries and aquaculture operations (Barton et al. 2015).

The pH of estuarine waters is more spatially and temporally variable than that of open ocean waters, and it can alter water quality and biotic productivity. Increasing atmospheric CO_2 levels have only a limited impact on the pH of estuaries, whereas other environmental drivers, such as freshwater inputs and deoxygenation, are frequently more significant. Su et al. (2020) show that spatial decoupling of carbonate cycling between connected habitats in Chesapeake Bay acts as a buffer for ocean acidification. The efflux of CO_2 is decreasing with the increase of atmospheric CO_2 (Wong et al. 2014). There is no evidence that acidification is taking place in estuaries to any great extent (see Baumann and Smith 2017), in part due to the offsetting effects of eutrophication.

Global sea-level rise is increasing seawater intrusion and salinization of estuarine waters, as well as inundation, flooding, land erosion, and wetlands habitat degradation often worsened by interactive anthropogenic non-climatic disturbances (Bindoff et al. 2019). Modulated salinity regimes coupled with seawater intrusion and salinization promote upestuary movement of brackish and marine benthic and pelagic communities that can significantly alter species abundance and diversity (Robins et al. 2016; Hallett et al. 2018; Addino et al. 2019; Elliott et al. 2019). Warming temperatures, sea-level rise, and droughts accelerate estuarine salinization.

With increasing sea-level rise across a range of climate scenarios (RCP2.6 to RCP8.5) in the 21st century, salt marshes and mangroves will have limited capacity to expand laterally and build vertically, depending on tidal characteristics, sediment availability, organic matter accumulation, salinization, and temperature levels affecting their productivity (Bindoff et al. 2019). Vertical accretion of salt marshes and mangroves depends on sediment accumulation and organic matter buildup. Delivery of clay, silt, and sand by tidal action and storms and the buildup of roots, rhizomes, and other sources of organic matter are critical to the successful accretion of the salt marsh platform. Upland lateral expansion by coastal marshes in response to rising sea-levels and inundation, in turn, depends on the successful transgression of the marshes. Upland migration will be constrained by coastal development and infrastructure (i.e., houses, roadways, and other structural features), causing coastal squeeze and subsequent drowning of the marshes by rising sea-levels and flooding estuarine waters. Salt marsh submergence is projected to eliminate 40–95% of New England salt marshes by 2100 (Valiela et al. 2018).

Coastal wetlands are known as blue carbon ecosystems because they are important agents in carbon sequestration. As such, they serve as vectors in climate change impact mitigation. Vegetated coastal ecosystems account for almost 50% of the total carbon burial in marine sediments, even though they occupy only <2% of the total ocean area (Duarte et al. 2005). The loss of coastal wetland habitats decreases its effectiveness in climate change impact mitigation and adaptation. Moreover, the destruction of coastal wetlands re-releases CO_2 from carbon pools in marsh soils to the atmosphere, adding to the atmospheric CO_2 pool (Pendleton et al. 2012; Windom-Myers et al. 2019).

Seagrasses are under increasing threat from human activities. Orth et al. (2006) linked multiple anthropogenic drivers to seagrass declines around the world, including sediment and nutrient runoff, physical disturbance, invasive species, disease, commercial fishing practices, aquaculture, overgrazing, algal blooms, and rising temperatures due to climate change. They noted that the scale of seagrass decline ranges from square meters to hundreds of square kilometers. Significant decreases of *Zostera marina* (eelgrass) are occurring locally in some temperate estuaries as a result of higher mean water temperatures exceeding its threshold of thermal tolerance. Eutrophication and high turbidity are two other factors causing declines in abundance and distribution of *Z. marina* in temperate estuaries (Larkum et al. 2006; Orth et al. 2006; Kennish and Fertig 2012; Fertig et al. 2014; Kennish et al. 2016), as are increasing storminess and winds (Bjork et al. 2008). Temperature is also a major factor limiting the range expansion of *Z. marina* (Hoegh-Guldberg et al. 2018). It is likely that the range of *Z. marina* and other seagrass species will expand poleward with increasing temperatures during the 21st century, while their southern boundaries will likewise shift northward as well. Concerns about the decreasing abundance of seagrass species and shifts in their geographic distribution have led to greater management efforts to monitor, restore, and protect them (Larkum et al. 2006; Orth et al. 2006).

Over the past half-century, the range of tropical mangroves has similarly shifted poleward due to increasing temperatures, encroaching into subtropical salt marshes (Saintilan et al. 2019). Poleward shifts in the distribution of kelps are also predicted this century (Wong et al. 2014). Interactive and cumulative effects of nutrient enrichment and other anthropogenic non-climatic drivers are increasing changes in the distribution, structure, and function of mangroves and kelps in areas within their geographic ranges.

Bioclimatic ecological models indicate significant geographic shifts in marine taxa before 2050. Climate-driven biotic invasions are altering the structure of estuarine biotic communities through species extinctions and competition. Non-native invasive species are a particular concern because they can readily outcompete resident fauna and flora, especially in those systems already stressed by pollution and other human vectors, hastening local species extinctions. Global patterns of marine biodiversity projected out to 2050 reveal high numbers of local species extinctions expected in subpolar regions, the equator, and in enclosed water masses. In addition, biomodels also predict 60% species turnover by 2050 as biogeographic range shifts increase with the opening of Arctic corridors due to sea-ice melting, fostering the exchange of Atlantic and Pacific taxa (Frid and Caswell 2017). As biotic community structure changes due to species shifts and extinctions, ecosystem services in affected water bodies will change as well. For example, climate-driven losses of recreationally and commercially important finfish and shellfish will impact the economy of local coastal communities.

In conclusion, it is necessary to assess both anthropogenic climatic and non-climatic drivers of change in estuaries to characterize overall impacts. This is so because of the potential synergistic interaction of these drivers, which exacerbate natural forcing factors that impact these coastal ecosystems. As noted above, it is often difficult to separate out the impacts of anthropogenic climatic and non-climatic drivers, thereby confounding efforts to accurately assess the impacts and to effectively develop management strategies for their resolution. Thus, individual estuaries must be thoroughly investigated as climate change impacts increase through time to understand more clearly habitat and biotic community responses and the mitigation and resilience efforts necessary to restore and sustain them (Kennish 2021, 2022).

1.6 ECOLOGICAL IMPACTS OF CLIMATE CHANGE

Continued warming of estuaries, increasing storm intensity, and variable precipitation and system hydrology (e.g., vertical stratification, mixing, currents, and tidal ranges) during the 21st century due to climate change will greatly affect organism abundance, distribution, diversity, reproduction, phenology, and production, thereby altering biotic community structure and function. Greater hydrological complexity will occur with increasing flux of freshwater discharges interacting with tidal currents and variable winds. Increasing freshwater, nutrient, and organic matter inputs will stimulate primary production and occurrence of algal blooms, contributing to deoxygenation and eutrophication of estuarine water bodies. A notable response of estuarine and marine organisms to rising temperatures will be an increase in species range shifts as the temperatures approach or exceed species' thermal tolerances. Estuarine species will increasingly shift to waters with more favorable environmental conditions.

Many marine organisms are currently exhibiting a poleward expansion of their geographic ranges with rising temperatures (Beaugrand and Reid 2003; Parmesan and Yohe 2003; Bianchi and Allison 2009; Pinsky and Fogarty 2012; Pinsky et al. 2013, 2019; Poloczansak et al. 2013; Frid and Caswell 2017). Poleward migration of subtropical and tropical organisms between estuaries has been well documented (Hallett et al. 2018). As their distributions shift poleward in response to warming marine waters, many species are accessing and utilizing different estuarine systems, altering migration patterns, reproduction, seasonal activities, and species interactions. These changes, consistent with the poleward migration of oceanic biota, are affecting the species composition and biodiversity of estuarine and coastal marine ecosystems. Shifting range limits may be most conspicuous for planktonic and nektonic species, but is also evident among benthic fauna and flora, including those in vegetated coastal habitats. For example, Helmuth et al. (2006) documented shifting range limits for intertidal species of up to 50 km per decade in the North Atlantic and North Pacific.

Fujii (2012) indicated that the ecological effects of climate change can be particularly acute on the high stocks of macrobenthic invertebrates inhabiting extensive areas of bare intertidal mudflats and sandflats characterizing many European estuaries. Rising temperatures affect the behavior of benthic organisms, as well as their reproduction, growth, and survivorship. Altered environmental cues due to climate change affect spawning and larval dynamics, such as the duration of planktonic larval stages, time of settlement, and metamorphosis, which impact recruitment in the benthos. Aside from the direct effects of warming temperatures on intertidal benthic communities, shifts in sediment supply, composition, and grain size mediated by climatic drivers impact benthic communities in these highly productive habitats. Marked changes in abundance and distribution of benthic forage species in response to climate change also impact fish, shorebirds, and other consumer species that depend on these organisms as a source of food (McLusky and Elliott 2004). The abundance, distribution, and diversity of intertidal benthic organisms in soft sediments and on rocky shores continue to change globally with ongoing warming conditions (Wong et al. 2014).

The distribution of commercially and recreationally important species is changing with rising temperatures as well. For example, the heat-intolerant winter flounder (*Pleuronectes americanus*), a recreationally important fish which occurs in coastal waters of the western north Atlantic, is now found in greater numbers in estuaries north of New Jersey (USA) as the species shifts progressively northward in response to regional warming conditions. Similarly, the southern boundary of the heat-intolerant surf clam (*Spisula solidissima*), a commercially important shellfish species, has shifted northward along the Mid-Atlantic coast of the USA (Kennedy et al. 2002).

Changing temperature regimes are causing an economic impact on fisheries and aquaculture in estuaries (Weatherdon et al. 2016). Recreational and commercial fishery yields are affected by the shifting geographic distribution of fish species in response to the increasing ocean and estuarine temperatures, particularly evident with the poleward expansion of temperate species. Predator and prey species are also shifting geographically with increasing climate change. A similar geographic shift of shellfish species is evident as well, albeit at more variable rates. There is a significant decline in the abundance of fish species in some estuaries and a significant increase in others depending on the location of the water body, the local climate conditions, and the thermal preferences of the species. Growth rates of some fish species are decreasing as well. Frid and Caswell (2017) noted that models predict a 20% reduction in the body size of fish by 2050 under high-emission CO_2 scenarios and deoxygenated conditions. Effective assessment of these changes requires careful tracking of fish species distributions and the effects that shifting species ranges have on recreational and commercial fisheries.

Increasing nutrient inputs and eutrophication linked to climate change are leading to more intense and long-lasting algal blooms and hypoxia, threatening water quality and the sustainability of balanced indigenous biotic communities (Paerl and Huisman 2009; Howarth et al. 2011; Paerl et al. 2011; Paerl and Paul 2012; Havens and Paerl 2015; Kennish 2016; Paerl 2017). More non-native species invasions are occurring in estuaries with the warming of climate systems, which could significantly alter the structure of endemic biotic communities. The frequency of such species invasions is greater in estuarine systems already stressed by pollution and other direct anthropogenic drivers of change (Frid and Caswell 2017). Essential estuarine habitats, such as salt marshes, mangroves, and seagrasses, are also impacted by non-native species invasions, which could result in fundamental changes in the biotic structure of these ecosystems.

The abundance of microbial pathogens increases at higher estuarine water temperatures (Robins et al. 2016). Elevated pathogenic microorganism concentrations (bacteria, viruses, protozoa, and helminths) pose significant human health risks, with declining water quality closely coupled to intensifying enteric pathogens. Humans swimming in contaminated estuarine waters or consuming contaminated seafood products are at greater risk of debilitating diseases, such as typhoid, dysentery, and hepatitis. Food provisioning and tourism can also be compromised as a result. Since 1980, pathogenic organisms have increased in coastal waters with rising water temperatures, deoxygenation, and eutrophication (Bindoff et al. 2019). The interaction of climatic and non-climatic anthropogenic drivers is exacerbating these water quality impacts.

Greater vertical stratification in estuaries due to increased freshwater runoff and higher water temperatures inhibit vertical mixing and reduce water column nutrient distributions, thereby affecting primary production, algal bloom formation, dissolved oxygen concentrations, and nutrient cycling. Changing circulation modulates larval dispersal. The distribution of juvenile fauna is also affected (Newton 2008).

Changes in temperature, salinity, dissolved oxygen, and nutrient levels in estuaries can lead to major changes in biogeochemical processes, primary production, and biotic community structure and function. Seasonal duration of phytoplankton and benthic algal primary production may be protracted by temperature increases in estuarine ecosystems (Cloern and Jassby 2008). Eutrophic and deoxygenated conditions cause significant stress on biotic communities, the loss of biomass, and occasionally mass mortality of organisms in these water bodies (Kennish 2016, 2017; Frid and Caswell 2017). Eutrophication, coupled with accelerating nutrient and organic matter delivery to coastal areas, is an escalating problem in many regions (Kennish 2016, 2017). In some cases, essential habitat (e.g., seagrass) has been severely degraded or lost, not only because of greater nutrient loads but also because of rising temperatures that delimit spatial distribution, especially at species range boundaries where water temperatures approach species thermal tolerance limits (Larkum et al. 2006; Orth et al. 2006). Many estuarine and marine organisms are greatly stressed at their range boundaries (James et al. 2013).

Increasing atmospheric and oceanic temperatures projected for the 21st century will facilitate the occurrence of higher-intensity tropical cyclones. These storms will be particularly detrimental to shallow estuarine and coastal habitats, with storm surges inundating and damaging estuarine shorelines and adjoining salt marsh and mangrove habitats. In addition, seagrass beds will be impacted by erosion and sediment burial during the passage of these storms. The dramatic impacts of tropical cyclones on estuarine and coastal environments have been well-chronicled in the recent scientific literature (Paerl et al. 2018, 2019).

Rising sea-levels this century will gradually shift saline intrusion and turbidity maxima landward in estuaries resulting in an array of biotic responses. Higher-intensity storms linked to climate change will roil bottom sediments, increase suspended solids, and attenuate light transmission in the water column, thereby adversely affecting benthic algal and seagrass populations, albeit ephemerally. In addition, the reproductive success of estuarine biota will be affected, leading to decreased abundance of many species (Robins et al. 2016). Depending on salinity tolerances, species will shift distribution in estuaries, with marine forms adapting to higher salinity conditions farther upestuary.

Increasing sea-level, inundation, and loss of habitat threaten the sustainability of coastal wetlands that serve as important feeding, reproduction, and nursery grounds for estuarine and marine organisms, many of recreational and commercial importance, and that act as effective filters of nutrients, chemical contaminants, microbial agents, and other substances. Extreme weather events linked to climate change alter sediment deposition-erosion balance and hasten the submergence of low-lying wetlands habitat. The loss of this habitat adversely affects biotic communities in estuarine open waters as well. Where coastal marshes are precluded from migrating landward in the face of rising sea-levels due to coastal development, roadways, and other human structures, they will be eventually drowned and lost due to coastal squeeze.

In unobstructed areas, coastal wetlands have the capacity to migrate landward with rising sea-levels and inundation, maintaining their viability. The Bruun Rule indicates that in these areas the coastal shoreline will migrate landward about 100 times the vertical sea-level rise (Bruun 1962, 1988). Numerical inundation models, habitat sustainability models (e.g., Sea-Level Affecting Marshes Model – SLAMM and Marsh Equivalent Model – MEM), and ecological landscape simulation models are being applied to assess and predict coastal wetland habitat loss and conversion due to sea-level rise and inundation.

Increasing inputs of CO_2 in coastal wetlands due to climate change appears to increase the production of salt marshes, mangroves, and seagrasses due to a fertilization effect of CO_2 and greater photosynthesis (Wu et al. 2008; Hendricks et al. 2010; McKee et al. 2012; Wong et al. 2014). However, this increasing production does not effectively compensate for the magnitude of coastal wetland habitat loss due to climate change–driven sea-level rise, inundation, and submergence, which also directly impact numerous organisms inhabiting these valuable environments. In contrast, rising CO_2 levels and declining pH in the sea are significantly impacting biotic resources via acidification, particularly the loss of shell-bearing organisms.

Beaches, dunes, and barriers are under increasing threat of sea-level rise and erosion because these low-lying landforms are highly susceptible to storm surges, wave impacts, and erosion. Enríquez et al. (2019) concluded that sea-level rise is the major driver of the projected impacts on beach-dune habitats that will lead to a ~25% increase in the sediment volume eroded by the end of the century due to storm waves. Thus, it will become increasingly more difficult for these landforms to maintain their position with ongoing climate change through the 21st century. The loss of the beach-dune area would have a significant impact on nesting birds and other fauna (Burger and Gochfeld 2016).

1.7 MANAGEMENT STRATEGIES

Mitigation and adaptation plans are being developed and implemented to address major climate change impacts on estuaries and coastal marine ecosystems. While modeling indicates that sea-level rise and inundation will have a marked impact on coastal ecosystems during the 21st century, mitigation measures would greatly limit the adverse effects. The long-term goal is to improve the sustainability and resilience of coastal environments that are subject to increasing threats from climate change. Many management strategies are focusing on the sustainability of coastal wetlands. Salt marshes, mangroves, and seagrasses are under increasing impacts of climate change and an array of direct anthropogenic drivers (Orth et al. 2006; Saintilan et al. 2014; Valiela et al. 2018). About 25–50% of these habitats have been lost worldwide due to these major drivers (Barbier et al. 2011; Duarte et al. 2013; Kirwan and Megonigal 2013).

Salt marsh, mangrove, and seagrass systems, as well as macroalgae, store nearly 50% of the total organic carbon buried in marine sediments (Duarte et al. 2013). Hence, protecting and conserving these estuarine vegetated habitats are vital for preserving the services they provide as sinks for blue carbon capture and mitigation of climate change effects (Emmett-Mattox and Simpson 2019). To this end, ecological engineering is gaining favor as a viable method of facilitating coastal adaptation, while concurrently increasing ecosystem connectivity. Ecological engineering is an integrative approach that uses combined adaptive strategies to protect against habitat degradation and loss. For example, the planting of salt marsh grasses behind living shorelines with offshore oyster reefs acting as submerged breakwaters provide positive interaction that generates synergies to enhance habitat restoration and ecosystem recovery (Cheong et al. 2013). Living shorelines use natural habitat elements to protect shorelines and thereby improve the adaptation of wetlands and other coastal habitats. They serve as a viable climate adaptation strategy to conserve coastal resilience in recoverable areas (Bilkovic et al. 2019). Deteriorating conditions of coastal wetlands are leading to more aggressive management intervention programs that include restoration initiatives to promote wetlands creation and enhance coastal vegetated habitat. While ecological engineering approaches for wetlands creation are deemed to be less costly than traditional coastal engineering approaches to protect shoreline areas from inundation, coastal managers still often select hard adaptation options and on-land mitigation measures, such as bulkheads, flood walls, rock revetments, and levees. These structures typically destroy the connectivity of estuarine and coastal environments and seriously alter ecosystem function.

Thin-layer sediment placement (also termed thin-layer sediment application, thin-layer sediment deposition, or thin-layer sediment nourishment) on coastal marsh surfaces is a preferred method used to restore and maintain marsh elevation in subsiding marsh systems impacted by rising sea-levels and/or sediment deficiency. To enhance marsh vertical accretion, high-pressure spray dredging has been used to deliver thin-layer placement of dredged material on marsh surfaces to increase elevation. The thickness of the sprayed layer of sediment (usually amounting to ~1–10 cm) must be thin enough to ensure the survival of salt marsh vegetation. A thick layer of applied sediment can significantly reduce plant survival. In addition, efforts must stabilize the targeted area via vegetative colonization to avoid erosion of the recently deposited sediment (Forda et al. 1999). High-pressure sediment spraying on marsh surfaces is generally limited to an area within ~100 m of spray equipment located at a water body source. A recent innovative approach to enhance vertical accretion of marsh surfaces involves the semi-continuous supply of mud to a shallow tidal channel habitat, with natural processes (tidal action) then dispersing the sediment to nearby marsh surfaces and intertidal flats where it accumulates (Baptist et al. 2019).

1.8 CONCLUSIONS

Climate change is having an increasing impact on estuarine and coastal marine environments worldwide. The upper ocean is a major sink for heat generated on earth via greenhouse gas emissions (mainly CO_2), with sea surface temperatures increasing by ~1°C since 1900. The heat content of the world's oceans has increased most significantly in the upper 2000–3000 m. From the 1950s to the 1980s, water temperatures in the Southern Ocean increased by 0.17°C at mid-depths (700–1100 m) as reported by Scripps Institution of Oceanography in 2002. Between 1955 and 1995, water temperatures for the combined Atlantic, Pacific, and Indian Oceans increased by 0.06°C in the upper 3000 m and

0.31°C in the upper 300 m as reported by NOAA in 2000. Increasing water temperatures have significant implications for biological, chemical, and physical processes in estuarine and coastal marine ecosystems.

Climate change affects estuaries in a myriad of ways, most notably by increasing water temperature, sea-level, tropical cyclone intensity, storm surge, precipitation, and freshwater flux, as well as by altering salinity levels, modulating biogeochemical and circulation processes, and accelerating shoreline erosion. Warming ocean waters, changing density, shifting currents and water masses, and other factors coupled with climate change are altering the abundance, distribution, diversity, reproduction, phenology, species interactions, and food web dynamics of estuarine and coastal marine biotic communities. Climate change–driven biotic invasions and extinctions are on the rise. Fishery yields are declining in some regions. Rising sea-levels mainly attributable to the thermal expansion of the oceans and melting of ice sheets are responsible for the increasing loss of essential coastal habitat (e.g., salt marshes, seagrasses, and mangroves) and an array of diminishing ecosystem services to coastal communities. For example, global mean sea-level rise, amounting to 0.15–0.25 m between 1901 and 2018 and projected to be up to 0.5 m by 2050, is reducing the resilience and sustainability of many coastal wetlands and other essential estuarine and coastal marine habitats that provide a protective buffer for natural and developed communities from extreme weather events, inundation, and flooding. Greater precipitation and nutrient inputs to estuaries in some regions due to climate change are increasing eutrophication, coastal hypoxia, and acidification.

There are numerous anthropogenic non-climatic drivers of change in estuaries that can interact synergistically with climatic drivers to create more hazardous conditions than those attributed to climate change alone. Many of these non-climatic drivers of change are linked to human development and activities in coastal watersheds. Anthropogenic non-climatic drivers can be organized into 12 major categories including: (1) habitat loss and alteration (lagoon construction, shoreline hardening, and land reclamation); (2) watershed impervious cover; (3) enrichment (nutrients, organic carbon, and thermal loading); (4) sewage and pathogenic inputs; (5) chemical contaminants; (6) human-induced sediment/particulate inputs; (7) dredging and dredged-material disposal; (8) human-altered hydrological regimes; (9) invasive/introduced species; (10) overfishing and intensive aquaculture; (11) coastal subsidence; and (12) floatables/plastics/debris.

The sustainability of coastal wetlands and other essential estuarine and coastal marine habitats is increasingly threatened by climate change. About 25–50% of these habitats have been lost worldwide due to these major drivers of change. The deterioration of coastal wetlands is a major concern because they serve as important spawning, nursery, and feeding grounds for numerous organisms, including recreationally and commercially important estuarine and marine species. In addition, they filter contaminants derived from land areas, store large concentrations of carbon, and provide a protective buffer for upland coastal communities against rising sea-levels, storm surges, wave action, erosion, inundation, and flooding.

Sea-level rise also increases the steepness of rocky intertidal habitats, causing a substantial loss of the habitat area and potential loss of biodiversity, species interactions, and ecological function. To effectively characterize overall impacts, it is necessary to assess both anthropogenic climatic and non-climatic drivers of change in a given estuary. These drivers may interact synergistically, antagonistically, or additively to cause significant ecological change.

Continued warming of estuarine water bodies, increasing storm intensity, variable precipitation, and altered system hydrology will exacerbate impacts on estuarine biotic community structure and function. Local changes in precipitation and resulting shifts in freshwater flows are difficult to predict because of temporal and spatial variability in forcing factors and morphodynamic differences in estuaries. For example, it is difficult to project regional and local precipitation changes, the magnitude and frequency of tropical cyclones and coastal storms, and the location of major storm surge events with fluxes in climate change. More data must be analyzed on precipitation and freshwater runoff at local and regional scales.

Shifting geographic distribution of organisms, species invasions, greater pathogen activity, and altered hydrology will affect recreational and commercial fisheries and pose an increasing threat to human health. Changing estuarine ecosystem conditions could impact coastal tourism as well. More accurate quantification and prediction of estuarine ecosystem impacts due to climate change are needed to improve understanding of the factors responsible for the ecosystem changes and to develop effective management responses.

Management strategies are being formulated to increase the sustainability of estuarine and coastal marine environments in the face of climate change. A major goal is to increase the resilience of natural and built communities to rising sea-levels and coastal storms. In addition, improved monitoring, modeling, and adaptive management are needed. A concerted effort is necessary from multiple sectors of society to successfully implement the adaptation and resilience measures necessary to improve the conditions of coastal communities impacted by climate change.

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