Chemical Oceanography

Element Fluxes in the Sea

Chemical Oceanography: Element Fluxes in the Sea focuses on the use of chemical distributions to understand mechanisms of physical, chemical, biological, and geological processes in the ocean. After an introduction describing observed chemical concentrations, chapters focus on using chemical tracers to determine fluxes on a variety of timescales. Long-term chemical cycles are dominated by exchanges between seawater and land, sediments, and underwater volcanoes. Biological and ocean mixing processes dominate internal chemical cycles that respond to changes on hundred- to thousand-year timescales. Stable and radioactive isotopes trace the fluxes of nutrients and carbon to quantify the rates and mechanisms of chemical cycles. Anthropogenic influences – which have grown to be of the same magnitude as some natural cycles – are a specific focus throughout the book. Discussion boxes and quantitative problems help instructors to deepen student learning. Appendices enhance the book's utility as a reference text for students and researchers.

Steven R. Emerson has been a professor of Oceanography at the University of Washington for about 40 years. He taught Chemical Oceanography for most of this period while being the major advisor to 12 Ph.D. students and an equal number of post-docs. His research focuses on fluxes at the air–sea interface and the sediment–ocean interface. He is a fellow of the American Geophysical Union and the Geochemical Society.

Roberta C. Hamme is an associate professor in the School of Earth and Ocean Sciences at the University of Victoria, and holds a Canada Research Chair in Ocean Carbon Dynamics. She has taught upper-level undergraduate Chemical Oceanography since 2007. Her research focuses on understanding and quantifying the natural mechanisms that transport carbon from the surface ocean to the deep. Her main tools are measurements of dissolved gases, both bioactive gases like oxygen and inert gases such as neon, argon, and krypton.

"*Chemical Oceanography: Element Fluxes in the Sea* is completely updated from the previous version. The new version cites up-to-date, peer-reviewed literature, and includes compelling figures, discussion boxes, and problems at the end of each chapter. In addition, the links to MATLAB® and Python® toolboxes are a great resource. In my opinion, this is the best chemical oceanography textbook currently available for both undergraduate and graduate-level courses."

Annie Bourbonnais, University of South Carolina

"The choice of contents for a chemical oceanography textbook is, to some extent, a Rorschach test of the authors' view of the field. In their focus on element fluxes affected by life in the oceans, Emerson and Hamme seek to navigate the narrow channel between attention to detail – a hallmark of quantitative ocean science – and the desire to share the fabulous panorama that is the field as a whole."

Andrew Dickson, Scripps Institution of Oceanography

"In their outstanding and exceptionally well-structured textbook, Emerson and Hamme transform the way we think about chemical oceanography. While the distribution of chemical tracers in the ocean still provides the foundation of their textbook, they organize it around the biogeochemical transformations that govern these distributions. A particular focus is the question of how fast these processes operate and how we can measure these rates. To this end, they introduce many modern techniques involving various isotope systems and transient tracers in a way no other textbook has achieved so far. This is a must-read for any student, postdoc, and researcher in the field, especially in these rapidly changing times."

Nicolas Gruber, ETH Zürich

"A readable, comprehensive, authoritative account, by two distinguished chemical oceanographers, of what we know about chemical processes in the oceans, and how we have learned it. The book features deep descriptions of the oceanic cycles of oxygen, nitrogen, and especially carbon. *Chemical Oceanography* will be valuable to Earth scientists as a guide to topics in chemical oceanography, to specialists as a source of detailed information, and to students as a textbook chock full of stimulating problems and provocative topics for discussion."

Michael Bender, Princeton University

"This new book is a comprehensive and modern treatment of a broad range of marine chemistry topics. The thoughtful, well-written text and clear illustrations are a valuable resource for professors, and provide a strong foundation in the subject for advanced undergraduate and graduate students."

Abigail Renegar, Nova Southeastern University

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Preface

The field of Chemical Oceanography is evolving from surveys of chemical distributions toward a focus on deriving element fluxes in the sea. By evaluating fluxes, ocean scientists glean an understanding of mechanisms that underlie circulation, biological processes, air–sea exchange, and interactions between seawater and solids on land and in the ocean basins. Because of the imprint each process leaves on the chemistry of the sea, chemical oceanography in many ways unites the various disciplines of oceanography. As anthropogenic influences on element fluxes grow stronger so must oceanographers' understanding of processes that control them, so that humanity's impact can be predicted and informed decisions can be made about managing the ocean environment to maintain a livable planet.

This book, *Chemical Oceanography: Element Fluxes in the Sea*, is both a text for teaching the subject at the level of senior undergraduates and graduate students and an aid to chemical oceanography researchers. We were inspired to write this successor to *Chemical Oceanography and the Marine Carbon Cycle* by Emerson and Hedges (2008, Cambridge University Press) to better align with the development of our teaching strategies. This new book is more than a second edition to the earlier work. In particular, we have incorporated new materials for teaching. These include Discussion Boxes throughout each chapter, designed to facilitate in-class, small-group student discussions of the material and Problems intended to solidify key concepts using quantitative approaches. These have grown out of our courses for graduate students at University of Washington and primarily undergraduates at University of Victoria. We have also developed an extensive appendix section to provide a go-to reference for key constants.

For this new text, we have reordered and streamlined topics following the way we have found most natural to teach them and to bring greater focus to the interactions between processes and the element fluxes they control. We begin the book with a background on chemical concentrations in the ocean and introductory physical and biological aspects of oceanography that influence chemical distributions (Chapter 1). This chapter sets up some of the key questions we return to throughout the book. After this introduction, long-term geological processes that control the concentrations of major ions and gases are discussed in Chapter 2. The next two chapters (3 and 4) deal with shorter-term fluxes controlled by biological processes in the upper ocean and thermocline – the impact of life on the ocean and how it is quantified. This leads naturally to Chapter 5 on the carbonate system, which combines equilibrium chemical concepts with the impact of life and circulation on ocean carbon. This chapter provides the background necessary for a detailed discussion of the global carbon cycle and the fate of fossil fuel CO_2, with which

we conclude the text (Chapter 8). Chapters 6 and 7, on the way from the carbonate system to the carbon cycle, demonstrate applications of stable and radioactive isotopes as tracers of chemical fluxes. This new text contains fewer chapters than the earlier Emerson and Hedges (2008). We have incorporated parts of the earlier book into the new text, and the publisher has agreed to make three of the earlier chapters that are not in the new book freely available online.

As an aid to teaching and research we provide the following material online at the Cambridge University Press website (www.cambridge.org/emerson-hamme): (a) all figures as they appear here, (b) computer code (MATLAB and Python) for determining constants presented in the appendices, and (c) pdf copies of chapters from Emerson and Hedges (2008) that do not appear in this book (Chapters 3, 8, and 9: Thermodynamics Background, Marine Organic Geochemistry, and Molecular Diffusion and Reaction Rates, respectively).

Acknowledgments

We are both to some extent products of the University of Washington (UW) School of Oceanography in Seattle, either as a professor (Emerson) or as a graduate student (Hamme). We would like to acknowledge the influence of UW colleagues – professors, post-docs, technicians, and students – during the time we were there. Because we were Ph.D. thesis advisor and advisee, we knew our talents well enough to feel secure in undertaking the daunting task of writing a textbook together. We each appreciate the support and encouragement we received from the other when the time invested in the book seemed to encroach too greatly on other responsibilities, and the end seemed far away.

Special acknowledgment goes to the late UW Professor John Hedges, who was a co-author of the predecessor to this book (*Chemical Oceanography and the Marine Carbon Cycle*, 2008, by Emerson and Hedges). Many concepts and descriptions that were part of the earlier work were from John, and they remain. This book could not have been completed without the efforts of Michael Peterson, whose hard work produced beautiful figures in record time, and whose knowledge of chemical oceanography and skill in drafting the figures greatly improved the clarity of our explanations.

We are grateful to the students of EOS 312/504 at University of Victoria who experienced early versions of most of the discussion boxes and quantitative problems in this book. Their reactions to these were invaluable. Several colleagues across North America either "test drove" the text in their own courses on this subject or helped to edit some of the chapters. This feedback has been important to the final product and is greatly appreciated. Parts of this book were written on short sabbaticals by Emerson to the writing-friendly environments of the Whiteley Center at Friday Harbor Laboratory of the University of Washington, and Clare Hall College of Cambridge University in Cambridge, England. We would like to thank the editors at Cambridge University Press for their skill in presenting the book. Matt Lloyd, in particular, helped us to solve problems, from the concept at the beginning to the final product.

Finally, we would like to thank our families for their generosity in giving us the time we devoted to creating this textbook, which was sometimes stolen from our personal lives. Steve Emerson would like to thank his wife Julie for her support and love during this project. Roberta Hamme thanks her husband Jody for both his love and his suggestions on physical oceanography, as well as their children, Cordelia and Felix, for enlivening every day.