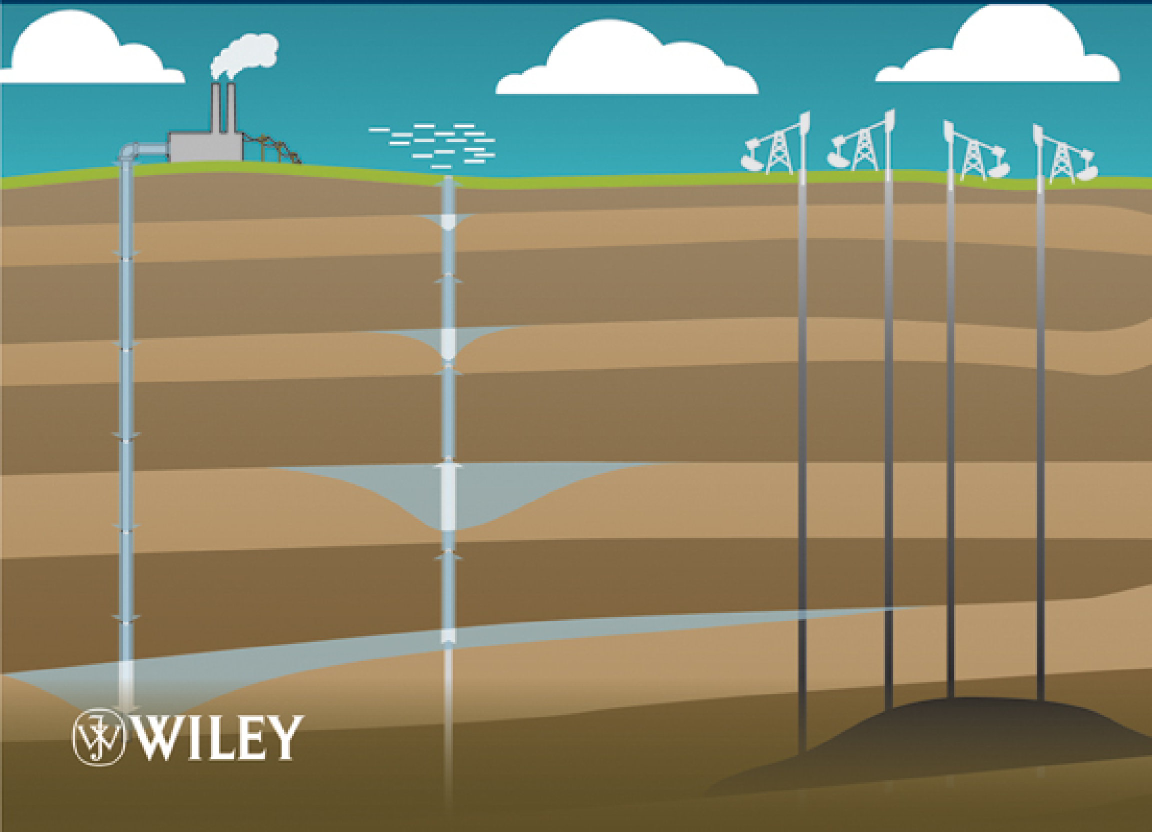
Geological Storage of CO_2

Modeling Approaches for Large-Scale Simulation

Jan M. Nordbotten and *Michael A. Celia*



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Prologue

Injection of carbon dioxide into subsurface formations dates back to the early 1970s. At that time, there was no consideration of the environmental benefit; rather, the purpose was to provide pressure and solubility conditions which would be advantageous for increased oil production. More than a decade later, in the 1980s, injection for the purpose of emission avoidance was first considered. This, together with favorable legislation, led to the first pure CO_2 storage project, off the coast of western Norway in 1996. Since then, carbon storage has gained increasing attention as a carbon mitigation option from academia, industry, environmental organizations, and regulators.

Despite this relatively long history, and the significant current interest, no textbooks exist that cover the fundamentals of carbon storage. As such, students of the subject are forced to assimilate knowledge from a broad range of sources. This situation is unfortunate, in that it hinders the development of dedicated courses for teaching the science and technology of carbon storage, and consequently makes the subject less accessible in general. We hope that this book will begin to remedy this situation.

As the first textbook on the subject of carbon storage, we hope our audience will be broad. However, this is not a general book on carbon mitigation, or even on the overall technology of carbon capture and storage. Rather, we have focused the book on basic concepts needed to understand subsurface storage of CO_2, with a focus on mathematical models used to describe storage operations. We have begun from the basic concepts of flow in porous media, and expanded the discussion to include fairly involved mathematical developments, especially in the later chapters. We have attempted to make the early material accessible to a wide audience, with the successive chapters more oriented toward graduate-level students in the fields of civil and environmental engineering, subsurface physics, petroleum engineering, and applied mathematics. At the same time, we hope that experienced professionals from related fields will find in this book a concise introduction to the particular challenges that separates carbon storage from other subsurface problems. Finally, the regulator will hopefully find in this book descriptions of the key physical processes, of which knowledge is needed in the design and enforcement of meaningful regulation.

This is not a long book. Nevertheless, we attempt to take the reader all the way from the basic concepts of fluid flow in porous formations to considerations involving large-scale simulation. This is a steep journey; however, we are confident that the text will allow the dedicated reader to follow us. The first chapter serves as the motivation for this journey. There, we provide arguments for the role of carbon storage in the global portfolio of carbon emission reduction strategies. We also review the basic features of geology that makes the idea of carbon storage plausible.

Our second and third chapters cover the laws that govern fluid motion in the porous materials that constitute the subsurface. In Chapter 2, we consider flow of a single fluid. In addition to the laws of motion, we review the basic solution strategies for the governing equations, together with the most common simplifications. This approach is mirrored in Chapter 3, where we focus on the flow of multiple fluids in the pore space, with a general focus on two-fluid systems involving supercritical CO_2 and brine. The classical theory in both these chapters is presented while emphasizing the particular aspects most relevant for carbon storage.

Chapter 4 considers changes of scale. In particular, it addresses the fact that our governing equations are developed and parameterized in the laboratory, while the enormous volumetric needs of carbon storage force us to answer questions on scales spanning many kilometers horizontally and decades in time. Bridging the gap between the laboratory and field is therefore a crucial aspect. In this chapter we present a systematic approach to allow equations to be written at large space and time scales while still retaining essential information from smaller scales.

With large-scale equations in hand, the two last chapters discuss solution approaches. Analytical and numerical solution methods for flows contained within a single aquifer are covered in Chapter 5, including practical calculations applied to real-world data. In Chapter 6, additional issues related to the interaction with other aquifers in the vertical sequence, in terms of pressure propagation and fluid migration, are covered. We conclude Chapter 6 with a set of practical calculations, involving leakage across different formations in a vertical sequence, using as realistic data as possible. This allows us to emphasize the important practical quantities that can be calculated from the governing models.

In sum, this book contains what we see as the essentials of carbon storage modeling, with a focus on how systems and solutions can be simplified to provide useful solutions to practical questions. It is the book we wanted to write. We can only hope that it is also the book that the audience wants to read.

We have greatly enjoyed writing this book, and we have also enjoyed the great fortune to be located at two outstanding educational institutions where we have many colleagues interested in the carbon problem. At Princeton, the support of the Carbon Mitigation Initiative (CMI) has been invaluable, and the authors are especially thankful to the co-directors of CMI, Steve Pacala and Rob Socolow. At the University of Bergen, the Center of Integrated Petroleum Research has provided both assistance and a wealth of interested colleagues, most notably our long-time colleagues Magne Espedal and Helge Dahle. We have also been fortunate to work with many other terrific colleagues and students, both from our home institutions and from many other institutions around the world. Very helpful reviews of different versions of the text were provided by Mark Person from the New Mexico Institute of Technology and Mining, Karl Bandilla from Princeton University, Knut-Andreas Lie from SINTEF ICT, and especially Quanlin Zhou from Lawrence Berkeley National Laboratory. We are very much indebted to these reviewers. Finally, much of the writing was done during extended visits to the Ecole Polytechnique Federale de

Lausanne (EPFL), the University of Utrecht, and the University of Barcelona. We thank our very gracious hosts at these institutions—Andrea Rinaldo, Majid Hassanizadeh, and Jesus Carrera—for their help and their understanding as we "hid out" to concentrate on our writing. The result is this book, which we very much hope will help in the efforts to solve the carbon problem.

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Chapter 1

The Carbon Problem

The "carbon problem" refers to the ongoing increase in atmospheric concentrations of the greenhouse gas carbon dioxide (CO_2) observed over the last two centuries. This increase is being driven almost entirely by anthropogenic emissions, with most of the emissions associated with combustion of fossil fuels. If humankind decides, at some point, to reduce significantly the anthropogenic emission rate, new or different technologies will almost certainly play a central role. In this book, we are interested in one specific technology: carbon capture and storage (CCS), wherein the CO_2 produced from the use of fossil fuels is captured at large stationary sources like power plants and is stored somewhere other than the atmosphere. We are specifically interested in the storage part of this operation, and even more specifically, in geological storage, where the captured CO_2 is injected into appropriate geological formations deep underground. Proper analysis of the operations and possible consequences of this kind of injection requires careful mathematical and computational models to predict the system behavior. We focus on such models in this book.

1.1 BACKGROUND

The concentration of CO_2 in the atmosphere is naturally dynamic. Figure 1.1 shows the so-called Keeling curve, named after Charles Keeling, who initiated a program of ongoing measurements of atmospheric CO_2 in the 1950s. These data show annual cycles of variability superimposed on a monotonic increase over the half century of measurements. Atmospheric concentration of CO_2 in the late 1950s was around 315 parts per million (ppm), while today's concentration has grown to about 390 ppm. To put these numbers into historical context, consider the data shown in Figure 1.2. There the Keeling data, measured at Mauna Loa, Hawaii, are combined with data from ice cores to show atmospheric concentration of CO_2 over the last 1000 years. These data show a stable atmospheric concentration of about 280 ppm, which is the concentration to which the atmosphere stabilized at the end of the last ice age. The increase above 280 ppm began with the industrial revolution and has accelerated continuously to the present day. The range of values shown in Figure 1.2, between

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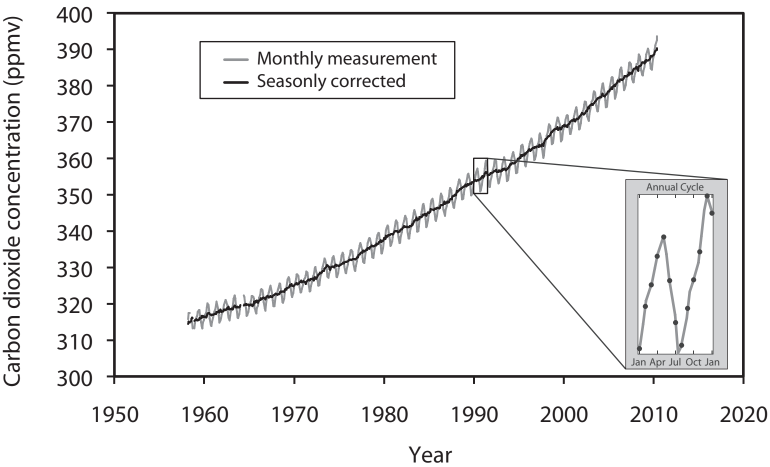

Figure 1.1 Atmospheric carbon dioxide as a function of time, measured at Mauna Loa (modified from wikipedia.org/wiki/Keeling_curve).

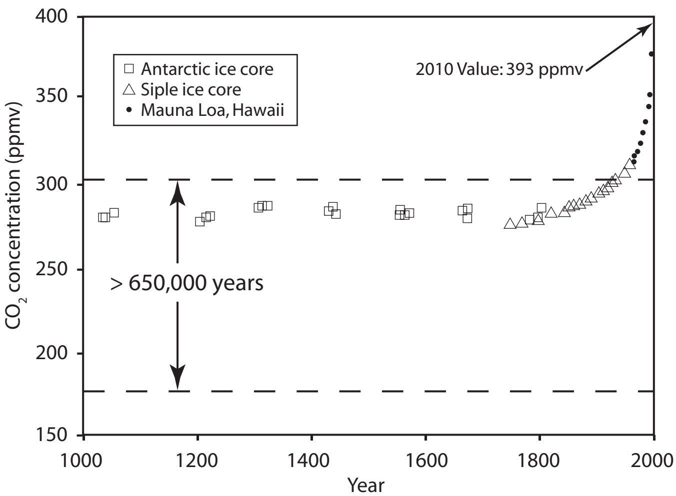

Figure 1.2 Atmospheric carbon dioxide as a function of time, over the past 1000 years. Also shown is the range of CO_2 concentrations measured over the past 650,000 years (modified from http://www.britannica.com/eb/art-69345/Carbon-dioxide-concentrations-in-Earths-atmosphere-plotted-over-the-past).

a low of about 170 ppm and a high of about 300 ppm, indicates the maximum and minimum values of atmospheric CO_2 concentration seen in ice core data over the last 650,000 years. In those ice core records, clear 100,000-year cycles of glacial–interglacial periods can be seen, with corresponding maximum and minimum values of atmospheric CO_2. From these data, we conclude that the current concentration is about 100 ppm above the "natural" equilibrium associated with the current interglacial period. We also conclude that the current value of 390 ppm is larger, by about

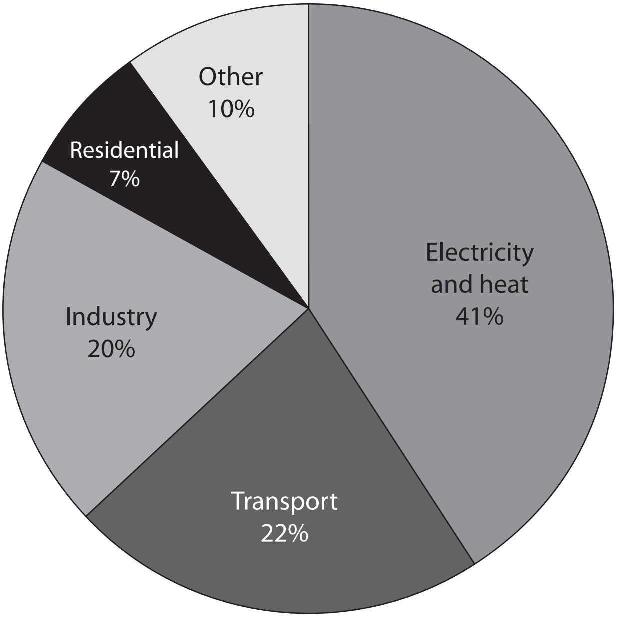

Figure 1.3 Fraction of total fossil fuel emissions by sector. Data from the International Energy Agency (IEA 2010).

30%, than the highest value seen in at least the last 650,000 years. As such, we humans are collectively performing an interesting global-scale experiment to see how the earth system will respond to significant increases of an important greenhouse gas. The consensus expectation is that these increases will lead to dangerous climate change unless they are reduced or reversed.

In order to understand the problem, it is helpful to identify the specific sources of anthropogenic CO_2 associated with combustion of fossil fuels. Figure 1.3 shows global estimates for the different sources of CO_2 emissions, indicating the fraction of total fossil fuel-related emissions coming from each major sector. The dominant source of CO_2 emissions is electricity generation, accounting for approximately 40% of emissions, followed by transportation at slightly more than 20%. A recent estimate for total annual anthropogenic emissions (for calendar year 2008) is between 8 and 9 gigatonnes (Gt) of carbon (where $1\,\mathrm{Gt\,C} = 1 \times 10^{15}\,\mathrm{g}$ of carbon $= 1 \times 10^{9}$ metric tones of carbon). The molecular weight of carbon is 12, while the weight of a CO_2 molecule is 44; therefore, the conversion factor from carbon to CO_2 is 3.67, which means that the global annual anthropogenic emission rate measured in mass of CO_2 is about 30 Gt CO_2/year. In the remainder of this section we will use 8 Gt C/year as the estimated current emission rate.

Given this profile of emissions, it seems logical that any successful strategy for carbon mitigation will involve decarbonization of electricity generation coupled with associated strategies that may include the use of decarbonized electricity in the remaining sectors. For example, one can consider electrification of the transportation sector and modified designs for both residential and commercial buildings to take advantage of carbon-free electricity. Overall, development of effective solutions to the carbon problem constitutes a grand challenge for the early 21st century.