Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Energy and mass balances related to climate change and remediation

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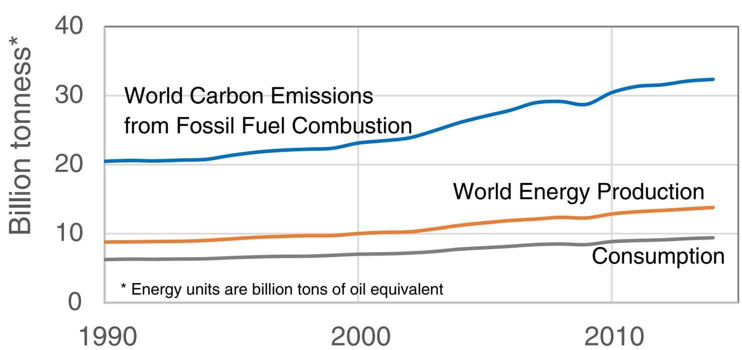
HIGHLIGHTS

- A historical development of one-parameter climate models is reviewed and developed.
- A basic explanation of the greenhouse gas effect is provided.
- The relative quantity of carbon in various environmental reservoirs and fluxes is reviewed.
- Various carbon remediation strategies are prioritized based on the relative carbon mass fluxes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 October 2016
Received in revised form 14 December 2016
Accepted 14 December 2016
Available online xxxx

Editor: Jay Gan

Keywords:
Climate model
Carbon capture and storage
Carbon utilization

ABSTRACT

The goal of this paper is to provide a forum for a broad interdisciplinary group of scientists and engineers to see how concepts of climate change, energy, and carbon remediation strategies are related to quite basic scientific principles. A secondary goal is to show relationships between general concepts in traditional science and engineering fields and to show how they are relevant to broader environmental concepts. This paper revisits Fourier's early mathematical derivation of the average temperature of the Earth from first principles, i.e. an energy balance common to chemical and environmental engineering. The work then uses the concept of mass balance to critically discuss various carbon remediation strategies. The work is of interest to traditional scientists/engineers, but also it is potentially useful as an educational document in advanced undergraduate science or engineering classes.

Published by Elsevier B.V.

Contents

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http://dx.doi.org/10.1016/j.scitotenv.2016.12.101
0048-9697/Published by Elsevier B.V.

Please cite this article as: Lueking, A.D., Cole, M.W., Energy and mass balances related to climate change and remediation, Sci Total Environ (2016), http://dx.doi.org/10.1016/j.scitotenv.2016.12.101

1. Introduction

From artists to engineers, how does an instructor best prepare students for issues they will face related to climate change, energy supply, and the nexus of these two issues? Future public policy decisions may well be in the hands of those without a strong scientific background. Meanwhile, as many science and engineering undergraduates are developing the technical background to tackle these challenges, they may miss out on many aspects of a broader education that will put future solutions in context. To "engineer a sustainable future", our undergraduates will need a broad contextual understanding of energy usage, energy supply, carbon dioxide emissions, and environmental ramifications of technology. Yet, topics regarding energy and the environment are much broader than are typically covered in disciplinary science and engineering courses, and although these topics are suitable for electives, the scientific concepts of many electives may be diluted to accommodate a broader audience. Meanwhile, technical papers are often so highly specialized that they may be nearly incomprehensible to those outside the immediate field, at least without a significant investment of time to understand the background literature.

Over the past three years, we have written a textbook, Science of Earth, Climate and Energy (Cole et al., 2016), which is targeted to a general (non-scientific) audience. In undertaking such a task, i.e. writing such a very broad overview that introduces the underlying scientific concepts that govern these processes on a level accessible to a non-scientifically minded citizen, the authors often found in their discussions that many of the "basic" concepts should not be taken as "assumed basic knowledge" to all authors. This is perhaps surprising, given that the authors of this book come from quite closely related disciplines (i.e. physics and chemical engineering), and even had collaborated on a number of scientific papers. If such a small subset of scientists occasionally found difficulty in communicating in each other's "basic language", surely the same could likely be said for a larger subset of scientists from even more divergent fields. Moreover, in asking colleagues to review the book draft, and/or discussing basic tenets that came to light in its writing, the authors often received comments from "expert" colleagues indicating that they had learned something new, or seen something from a new perspective. Surely such dialogue on such an important topic has merit beyond the narrow community of educators that would be teaching from a general education textbook. The purpose of this paper is to repurpose the basic premises found within this general education textbook to a broader technical community, including scientists and engineers that are expert within their individual disciplines, but perhaps have become too focused to see the broader applicability of their disciplinary science. The paper has the additional purpose of serving as an introductory manuscript for advanced undergraduates to learn how issues of energy and the environment are grounded in basic fundamental principles. Too often, in an effort to communicate difficult concepts to the general public, some of these basic tenets may become lost and not at all transparent to disciplinary scientists and engineers.

Anthropogenic climate change is a politically charged subject, as it has considerable implications regarding how we use energy, which in turn, affects every facet of our society and economy. Much attention and heated debate have been drawn to the so-called "hockey stick" graph (Mann et al., 1998; Mann, 2012), which, when published in 1998, showed a long-term "global warming" phenomenon. Indeed, the seven warmest years on record are all recent: 1998, 2005, 2009, 2010, 2013, 2014 and 2015; the present year, 2016, thus far, exceeds all records. The hockey stick graph is but one aspect of much more detailed reports of the Intergovernmental Panel on Climate Change (IPCC) which was established by the United Nations in 1988 to study climate change. However, the hockey stick graph is perhaps the one piece of information that is distilled from these reports to communicate a complex topic to the general public, including policy makers, the media, and even scientists in other fields. Although it serves this purpose, the hockey stick graph presents an observational relationship without a detailed mechanistic understanding of the phenomenon. In some of these same public policy forums, it is mentioned that the science of climate change is 'settled', in that there exists an overwhelming consensus among scientists that human activities are responsible for

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