Climate Change and a Sustainable Earth

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By

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FOREWORD

The challenges to human enterprise on this planet of climate change and sustainability are now so pervasive and imminent that it is everybody's business to know and do something about it. Understanding what we are actively doing to ourselves, and our planet is a prerequisite to responsible citizenship. This textbook by two impressive scholars, Dr. John J. Qu and Dr. Raymond Motha, intends to fill this need.

It is no small task to provide such a textbook. It encompasses a multiplicity of disciplines, from basic science to applied social, political, and economic science, and yet it must be written in a way that is accessible to any undergraduate. Living organisms and the distortion of the great global cycles of carbon, nitrogen, and more can no longer be ignored and left to be the concerns of future generations. Just to lay out the subject matter is daunting but so is presenting it in a way that is eminently teachable. Professors Qu and Motha, who are extremely distinguished scholars and masterful in the classroom, have both managed to do just that.

For far too long climate change has been offered through a physical science lens—this is essential to understanding the challenge (e.g., the role of greenhouse gases in trapping radiant heat). It is, however, insufficient in itself because humans are living organisms that have collectively disturbed the basic equilibrium of this planet's ecology.

At the heart of this textbook is the lesson that our planet does not work solely as a physical system, but rather as a linked biological and physical system. This has always been true, beginning with the origin of life with blue-green bacteria oxygenating the atmosphere and making higher life-forms possible. It is even truer today, with a multiplicity of living systems, from oceans to rainforests and even human-modified ones like agroecosystems, all affecting the environment locally and globally.

The fundamental perceptual problem is that individual actions that may not seem remarkable in themselves can have major impacts when multiplied by the near eight billion people alive today.

The 17 United Nations Sustainable Development Goals (SDGs) address sustainability collectively, but it is worrisome that the three goals representing the environment per se (one regarding the climate and two on biodiversity: life on land, and life in water) still tend to play second fiddle to the others. It needs to be recognized that these three SDGs are not just critical elements of the Earth system that need protection, but that they contain within them opportunities to address the sustainability challenge beyond restoring the baseline conditions. Notably, human creativity has the capacity to devise biological solutions and opportunities that can enhance human well-being without exacerbating the global sustainability challenge.

This is a lot to cover in a single textbook, but it is all interlinked and essential to foster the importance of climate and sustainability of Earth. Writing this textbook was no simple task. May the students of today learn from it and, in their life trajectories, act upon it so that a future edition will encompass some of their solutions.

Dr. Thomas E. Lovejoy (08/22/1941-12/25/2021)
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Member of the National Academy of Sciences, USA

Authors' Note: We are truly saddened by the passing of Dr. Lovejoy on 25 December 2021. Dr. Lovejoy was a world-renowned expert in the field of environmental science. In fact, he has been referred to as "the Father of Biodiversity". He provided inspiration, encouragement, and support to the authors of this book. We are gratefully indebted to this compassionate scientist.

PREFACE

Climate change is one of the great challenges for natural resources and human habitability on Planet Earth. According to the World Meteorological Organization (WMO), climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) entitled "Climate Change 2021: The Physical Science Basis" was released on 9 August 2021. The IPCC AR6 report is based on the latest physical understanding of the Earth's climate system and explains the current state of the world's climate. It also addresses future climate possibilities and suggests that we need to take urgent climate action to tackle climate change emergencies and to reduce greenhouse gas emissions to ensure a sustainable Earth. Measures of climate change include extreme changes in temperature, precipitation, and wind patterns among others. Climate change can be associated with human-induced changes caused by fossil fuel burning and aerosol pollution, or by alterations of the Earth's landscape, such as transforming carbon-storing forests into farmland or urbanized centers. Climate change can also occur due to natural causes such as alternating cold periods of ice ages and warm interglacial periods. Climate change influences the Earth system, and its impacts on natural resources are among the greatest challenges that threaten our sustainable Earth. The Earth system can adapt to the challenges and consequences of anthropogenic and natural changes in the atmosphere, hydrosphere, biosphere, and cryosphere provided that a coordinated effort focuses on solutions to environmental degradation, loss of biodiversity, and resource sustainability. A multidisciplinary approach that combines the principles of changing climate with the specialized fields of the water-energy-food-health (WEFH) nexus is needed to examine how the Earth operates as an interconnected, integrated system. This textbook focuses on the understanding of basic scientific principles of climate change, their interactions with the Earth system, and the impacts and consequences on the nexus of Earth sustainability. The aim is to help provide insight into the development of long-term strategies to cope with the resulting environmental, societal, and economic impacts by utilizing innovative technologies for future sustainability.

There are numerous textbooks and reference books that provide extensive details of climate change and their impact on different sectors, such as water and food security. However, there are very few books that focus on causes and effects of climate change on the sustainable Earth. The impacts of climate change on the Earth's interlinked natural resources and human health concerns are crucial to a sustainable future. This textbook provides students, researchers and decision makers with a thorough introduction to the challenges and opportunities of the climate and Earth sustainability nexus. This textbook examines climate change issues affecting the Earth system from a holistic perspective. Each component will be reviewed to gain insight and understanding of causes and effects. The unique and unintended consequences on socio-economic sectors of society will be discussed. The synergistic opportunities and strategies can then be highlighted to help address natural resource security and sustainable development for the Earth system. The book reviews the physical foundations of climate change and aims to present a scientific discussion of climate change impacts on natural resource security, ecosystem preservation and sustainable development. It does not present arguments for or against socio-political interpretations. The goal is to present a factual set of scientific information for students to better understand the issues and to help them make their own decisions on potential courses of action. Portions of this manuscript have been taught to graduate and undergraduate students studying a range of course curricula for their degree programs.

During the preparation of this textbook, we use some important data and information from the IPCC, WMO, the Food and Agriculture Organization (FAO), UN Environment Programme (UNEP) of the United Nations, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), the Environmental Protection Agency (EPA), and the European Space Agency (ESA), and many more. To acknowledge their contributions, we list their webpages and QR (Quick Response) codes in the textbook. We hope that students and readers can obtain the newest data and information on climate change and sustainable development from this textbook.

This book is intended to broaden the academic program of studies for a wide range of students due to the multidisciplinary nature of climate change impacts on society. This book can be used as a textbook for introduction level courses of college graduate, undergraduate and high school basic science programs. This textbook can be offered as a course at liberal arts colleges, technical institutes and universities, and international organizations,

such as WMO, FAO, UNEP and other international institutions that offer educational programs for a wide range of specialists. It can also be offered and tailored for both online learning programs and specialized training modules through technical institutes. The contents of this textbook deal with past, current and future scientific evidence and facts, and provide ideas and considerations for future analysis of climate change impacts. The organizational structure of this textbook focuses on the Earth system approach to climate change. This approach will expand in coverage and detail in the future as new and more comprehensive scientific information evolves. This textbook is tailored generally to students who are enrolled in a range of multidisciplinary science programs, such as atmospheric and environmental science, biology and ecosystems, hydrological, energy and agricultural sciences, and natural resource management. It can also be an elective for students in liberal arts, socioeconomics, and educational course programs to enhance their knowledge base. This textbook is intended to broaden the academic program of studies for a wide range of students because of the multidisciplinary nature of climate change impacts on society. Climate change issues are in the public news frequently. We believe that there is a greater need to provide academic program courses to a wide student audience with the aim of enhancing knowledge of the issues, exposing students to the challenges that face them, and promoting greater opportunities to meet these challenges.

We are very grateful to colleagues, staff and family who have provided invaluable support in the preparation of this book. Our publisher, Adam Rummens and Cambridge Scholars Publishing have offered invaluable guidance throughout this endeavor, allowing us to concentrate on the manuscript preparations. We are grateful to Thomas Lovejoy, world-renowned scholar and University professor, and the Institute for a Sustainable Earth (ISE) team including Leah Nichols and Judit Ungvari for their encouragement and support for writing this manuscript. We wish to thank Zhiliang Zhu and Xianjun Hao for their scientific and technical advice, suggestions, and feedback on the manuscript that enhanced the quality of the publication. We are thankful to Carolyn Qu and Wendy Sun, who designed some important figures for the textbook. We are also thankful to the faculty, staff, and graduate students including Szandra Peter and Bradley Gay at the Department of Geography and Geoinformation Science (GGS), College of Science, George Mason University for assistance in draft preparation. We want to express our appreciation to James Baron, Matthew Ty Miller and YoonJi Kim for their rigorous editorial reviews and revisions that contributed immensely to the final manuscript. We are grateful to Lina Hao and Jenna Cai who provided important comments and suggestions from

high school students' perspective during their summer intern period. Finally, we express our sincere gratitude and appreciation to our families who gave their unending support and patience to us as we prepared the manuscripts for publication.

CHAPTER 1

INTRODUCTION

Learning Objectives:

1. Describe the major objectives and structure of this textbook.
2. Explain climate change and its impact on sustainable Earth.
3. Learn basic principles of climate change.
4. List the major components of the Earth system.
5. Describe the Sustainable Development Goals (SDGs).
6. Learn about climate change and its impact on natural resource security.
7. Explain the water–energy–food–health (WEFH) nexus.
8. Identify the climate risks and their impacts on sustainable Earth.

1.1 Introduction

Climate change and its impacts on natural resources are among the greatest challenges that threaten Earth. This textbook focuses on the understanding of basic scientific principles of climate change to help develop long-term strategies to cope with the resulting broader environmental, societal, and economic impacts. A multidisciplinary approach combines the principles of changing climate with the specialized fields of water, energy, food, and human health (WEFH). The WEFH nexus plays a key role in how the Earth operates as an interconnected, integrated system. The Earth system can adapt to the challenges and consequences of anthropogenic and natural changes in the atmosphere, hydrosphere, biosphere, and cryosphere provided that a coordinated effort focuses on solutions to environmental degradation, loss of biodiversity, and resource sustainability. The goal of this textbook is to take a holistic approach to the examination of climate change issues that affect the Earth system. Each component will be reviewed to gain insight and understanding of causes and effects. The synergistic opportunities and strategies can then be highlighted to help address natural resource security and sustainable development for the Earth system.

Why is this book important? Life exists on the Earth system, which is unique in our solar system. Life may exist elsewhere in our galaxy of solar systems or in our universe; however, the fact is clear that there are some simple basic reasons why Earth supports life. Water in all three states (i.e., liquid, solid, and gas) is abundant on Earth, which is a necessity of life. While all planets receive light in a unique orientation as they rotate around the Sun, the Earth spins on its axis that allows each side of the planet to receive a favorable amount of daily sunlight that is utilized effectively to support plant life. The Earth's atmosphere is vital to life. The protective ozone layer at high altitudes of the stratosphere absorbs most of the harmful ultraviolet radiation emitted from the Sun but allows the beneficial sunlight to sustain life on Earth. The Earth's atmosphere is composed of the right combination of breathable gases. Most notably, oxygen is required for life. It is present in the atmosphere as well as in water, and plant life on Earth is a source of additional oxygen that is released to the atmosphere. Finally, Earth has favorable climate conditions suitable to sustain life. While climate extremes have normally occurred throughout Earth's history, nature has found a way to provide a return to a more normal equilibrium over the course of Earth's evolution. In recent decades, climate extremes and climate change have become more pronounced and have raised significant concerns among the scientific community. In fact, ongoing heat waves, droughts, and other extreme climate events around the world are causing significant water shortages, electrical power generation problems, crop failure, and loss of human life. The causes and effects of many of these climate anomalies will be discussed in this book. What is becoming increasingly evident is that there needs to be a holistic approach to the understanding of both the problem and the solution to the problem. This book hopes to direct attention to this approach.

The textbook is divided into four main sections. The first section is a review of the fundamentals of climate and its changing state. This includes the basic concepts involved in climate observations, trends, extreme events, and climate change indicators. It also examines the physical principles and global teleconnections that define the climate problem. The purpose of this section is to highlight important themes related to local, regional, and global impacts of climate change on the Earth system. The second section reviews the Earth system and its components. Each of these spheres has both common and unique features that are vulnerable to climate change. The third section then delves into climate change impacts on the sustainability of natural resources and human health, which is vulnerable to resource availability and utilization. Climate change has significant consequences on the WEFH sectors of society. The crucial aspects of sustainability under

changing climate conditions are discussed in this section. These sectors of society can be seen as interconnected through climate and resource sustainability when viewed from a holistic, or nexus, approach. Finally, this book examines the future challenges and opportunities that satellite applications and innovative technologies, such as artificial intelligence and machine learning, offer to mitigate the impact of climate change on the Earth system and to develop adaptation strategies for a sustainable future.

Climate change has significant influences on natural resources such as water, food, and energy. It also affects the health, safety, and welfare of human society. Together, the pressures of climate change on the security of the WEFH nexus create serious concern for the sustainability of our Earth. Figure 1.1 illustrates the nexus concept of global climate change, the Earth system, and the WEFH nexus.

In Figure 1.1, climate change is shown as the core of the problem that planet Earth must deal with. That is not to say there are no other issues posing serious threats to the planet. However, this text focuses on the specific issue of the impacts of climate change on the Earth system. Thus, the first ring in Figure 1.1 illustrates the five spheres that make up the Earth system, namely the atmosphere, hydrosphere, cryosphere, biosphere, and geosphere. The problems posed by climate change directly affect the first four spheres on a wide range of temporal and spatial scales. Climate change does impact the geosphere as well, but the effects of the Earth's climate on this sphere generally evolve over long periods of time and are beyond the scope of this book. Thus, the focus will be on the atmosphere, hydrosphere, cryosphere, and biosphere. Why these four spheres are important is represented by the next outer ring, i.e., WEFH. Earth could not sustain life without these four vital elements. Changing climate poses additional threats to the secure and stable elements that have helped global society evolve and strive for higher standards of living over thousands of years. However, the growing global population with its demands for higher quality of living, industrialization, urbanization, and dwindling natural resources, along with natural and anthropogenic causes of climate change, have raised critical concerns about the future of human society on Earth, as depicted by the outer ring on Figure 1.1 of forces enhancing pressures on the Earth system.

Scientists estimate that the planet will warm by 2°C by 2050 (IPCC, 2021). Many scientists believe that this level of warming is the threshold for dangerous implications for life on this planet. We urgently need a comprehensive understanding of the basic scientific principles behind climate change to develop long-term strategies to cope with the broader

environmental, societal, and economic impacts. This effort must involve a multidisciplinary approach using the principles of atmospheric science, biology, engineering, socioeconomics, and the specialized natural resource fields of hydrology, agriculture, energy, and health, to understand how the Earth operates as an interconnected, integrated system.

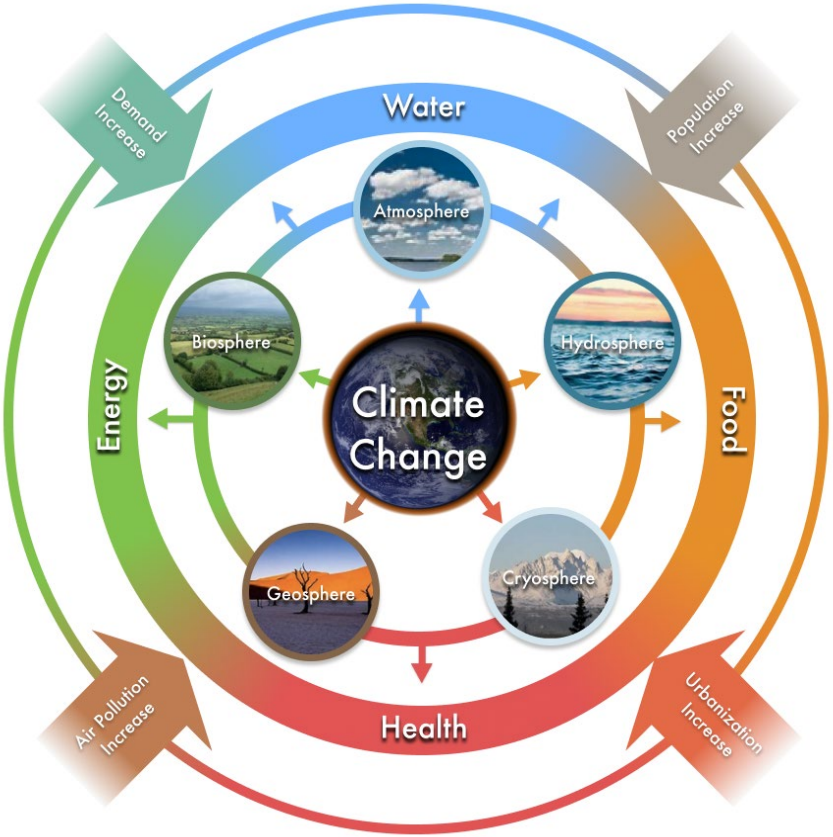

Figure 1.1: A schematic illustration of climate change, the Earth system, and the water–energy–food–health (WEFH) nexus.

1.2 Sustainable Earth

Before reviewing the structure of this textbook, it is also important to note that this overall problem is being addressed by universities, industries, governments, and international organizations around the world. There is growing awareness of the global issues and recognition that societal changes must be addressed to cope with the related problems, with the ultimate goal of sustaining a quality life on Earth. The mobilization of means of implementation, including financial resources, and technology development, transfer and capacity-building, as well as the role of partnerships, are also acknowledged as critical.

In 2015, the United Nations (UN) adopted "The 2030 Agenda for Sustainable Development." At the heart of this blueprint for the planet were 17 Sustainable Development Goals (SDGs), which outline an urgent call to action by all countries in a global partnership. The SDGs provide a to-do list for people and countries to combat the impacts of climate change through a coordinated set of actions during the next 15 years. The SDGs address the needs of people in both developed and developing countries, emphasizing that no one should be left behind. Broad and ambitious in scope, the agenda addresses the three dimensions of sustainable development that include social, economic, and environmental aspects. The 17 SDGs are illustrated in Figure 1.2. A number of these SDGs are directly linked to the topics discussed in this book. There are others that are indirectly linked as well, but the focus of attention will be on following SDGs: #2 (Zero Hunger); #3 (Good Health and Well-Being); #6 (Clean Water and Sanitation); #7 (Affordable and Clean Energy); #13 (Climate Action); #14 (Life Below Water); and #15 (Life on Land).

Figure 1.2: The 17 Sustainable Development Goals (SDGs), adopted by the UN in "The 2030 Agenda for Sustainable Development."

These 7 SDGs are related to climate, natural resources, and human health and well-being. Figure 1.3 summarizes how extreme climate events pose severe risks and have consequential impacts to human society. Most of these topics will be addressed in this textbook.

Figure 1.3: Climate risks and their impacts on sustainable Earth (WMO, 2019).

1.3 Objectives and Structure

The impacts of climate change on the environment, natural resources, and fragile ecosystems are immense, complex, and interrelated. The atmosphere–land–ocean continuum must be fully understood in a holistic manner to gain proper insight into future impacts on the Earth system. An important motivation for this textbook is to focus on the growing set of facts and scientific evidence that form the basis of concern for the current and future impacts of changing climate on the Earth system. This textbook aims to present a scientific discussion of climate change impacts as they relate to natural resource security, ecosystem preservation, and sustainable development, to improve the knowledge base of students. It does not present arguments for or against sociopolitical interpretations. The goal is to present a factual set of scientific information for students to better understand the issues and to help them make their own decisions on potential courses of action. Portions of this manuscript have been taught to graduate-level students studying a range of course curricula for their degree programs. Feedback from course questionnaires has helped to guide the preparations of this manuscript.

The topics of the textbook include a basic review of the fundamental principles of weather and climate that govern the state of the atmosphere, and help explain the drivers of weather extremes, climate variability, and climate change. The physical principles of climate change are introduced to differentiate the distinct differences between its natural and anthropogenic causes. The primary emphasis of this textbook is on focusing attention on a holistic approach to this real and evolving problem of changing climate. The concept of the atmosphere–land–ocean continuum is then introduced to demonstrate the interconnected and integrated components of the Earth system. The distinctions between climate hazards and disasters are reviewed to form the basis of understanding impacts of climate change on society. Climate change is not new. The history of climate change is reviewed, including the evidence of how climate change contributed to the rise and fall of ancient civilizations. This topic brings into clearer focus that changing climate trends and patterns have always been a part of the dynamic state of the Earth system. While historical evidence of climate change has been documented through paleoclimatology, current monitoring, analysis, and prediction tools have greatly enhanced the technological capability to gather and analyze global, regional, and local patterns of change. Satellite-based applications are now employed to further improve our understanding and analysis of changing climate conditions. With this background, climate change impacts on the Earth system can be examined.

The impacts on the natural environment and fragile ecosystems need to be demonstrated, as well as how natural resource sectors of society are vulnerable to changes in climate. This foundation is needed to bring together a more holistic understanding of natural resource management and help to prepare the students to cope with future challenges and opportunities to develop strategies to sustain socioeconomic development. While many of these topics have been discussed in other publications, this textbook focuses entirely on the synergistic approach of climate change on the Earth system.

This textbook includes a comprehensive overview of the specific impacts of climate change on the environment; ecosystems; water, agriculture, and energy sectors; and natural resource management. It focuses on a holistic approach to climate change impacts on the Earth system. From this perspective, it is unique and provides extremely important insight about the history and evolution of climate change into its present-day form, why it is so critical to society, and how to address critical issues for the preservation of the Earth system in the future. The main theme is the interrelated and integrated aspects of climate change impacts on the Earth system. The process is constantly evolving and is dynamic in nature. This textbook highlights the components of climate change's causes and effects on economic sectors of society, and aims to inspire the student with knowledge and insight to further examine the state of the climate and its societal impacts in the future. The book is divided into the following four parts.

Part I: Basic Principles of Climate Change

The intent of this section is to provide a brief overview or summary of important features that lay the foundation of climate support for the Earth system. There are many textbooks and journal articles that delve into the theories, principles, and scientific discoveries that are beyond the scope of this book but offer significant depths of study for interested students. For this book, the emphasis is on key indicators and drivers of essential climate factors that have helped promote and sustain components of the Earth system. Chapter 2 provides an overview of basic observational climate factors that contribute to the overall climate system. Indicators of climate change are reviewed in this chapter to provide the reader with the key factors that offer evidence of potential changes in climate. Chapter 3 reviews the fundamental physical principles of climate change. This chapter provides an important understanding of the underlying causes of climate change that have occurred throughout Earth's history and that have led to the current state of the climate that dominates the Earth today. While the climate and its changing state of flux may manifest themselves at local and regional

levels around the world due to the Earth's unique spatial features, it is important to understand that the cause-and-effect relationships extend to the global scale. Chapter 4 reviews several very important global teleconnections that link an important climate event in one part of the world to consequences of the event elsewhere. These three chapters provide the basics of climate change that impact life on Earth.

Part II: Climate Change and the Earth System

This section reviews how and why climate is an integral factor in the development and survival of the Earth system. There are five main spheres of this system, i.e., the atmosphere, hydrosphere, cryosphere, biosphere, and geosphere. This book will focus attention on the first four spheres that are most directly affected by changing climate conditions. The geosphere generally refers to the solid part of the Earth, consisting of the crust and mantle. While climate does have an impact on the geosphere, the effects generally occur over long periods of time and are beyond the scope of this book. Chapter 5 reviews the important components of the atmosphere that provide the first clues of changing climate on a local, regional, and/or global scale. It is very important to understand the composition of the atmosphere and how changes in the levels of atmospheric gases play a key role in climate change. Chapter 6 examines the importance of the hydrosphere: the waters of the Earth that cover about 70% of its surface. Water is essential to life on Earth, and it plays a fundamental role in changing climate conditions, especially the ocean–atmosphere interactions. Chapter 7 provides an overview of the portion of the Earth that is covered by frozen water: the cryosphere. Water in solid form, including ice, snow cover, ocean and mountain glaciers, and continental ice sheets, comprises an important component of the global climate system. The linkages and feedback processes between climate and the cryosphere are important to understand. Chapter 8 focuses on the biosphere: the regions of the Earth's surface, atmosphere, and hydrosphere that are occupied by life-forms. It is in this sphere that the global ecological system integrates all living organisms and interacts with elements of all other Earth spheres. Chapter 9 summarizes the components of the Earth system, with the aim of introducing the important nexus concept of how these components are interlinked and how they influence human activities.

Part III: Climate Impacts on Earth's Sustainable Resources

Chapter 10 focuses on the impacts that changing climate has on both on oceans and terrestrial water systems. The oceans provide an essential service to human existence by generating oxygen for the air that we breathe, by producing food that we eat, and by storing excess carbon dioxide that we generate. Human existence depends heavily on the terrestrial water supply. Climate change has complex consequences on water supply and demand. Chapter 11 discusses the Earth's array of fossil fuel and renewable energy sources that have sustained human evolution, from nomadic beginnings through agrarian evolution to modern technologically industrialized societies. However, this successful advancement in the quality of human life has had consequences on the Earth system, caused by anthropogenic factors that have influenced Earth's climate. Chapter 12 reviews some of the past and present impacts that changing climate has had on agriculture and identifies the critical climate parameters that have contributed to the success or failure of agriculture. Climate change poses numerous challenges to sustainable agricultural development, but there are opportunities to enhance and promote further development of mitigation and adaptation strategies to meet these challenges. Chapter 13 addresses several important consequences of climate change that affect human health. Changes in precipitation that result in flooding, drought, heat waves, intense hurricanes, storms, sea level rise, and degraded air quality all contribute to human health hazards. Human health is endangered by our food and water sources, the air we breathe, the weather we experience, and our interactions with the natural environment. Chapter 14 shows how WEFH are all inextricably linked. The competition for resources to produce safe drinking water, nutritious food, and efficient energy creates sets of intricate problems for sustainable development and resource security. Nexus interactions are complex and dynamic, but sectoral issues cannot be evaluated in isolation from one another. The challenge of changing climate and the future sustainability of the Earth system requires a proactive synergistic approach to resource management and environmental preservation.

Part IV: Challenges and Opportunities for a Sustainable Earth

Chapter 15 presents a climate nexus view from space. Satellite technology provides an invaluable capability to study the Earth system in a more holistic manner from a more comprehensive spatial perspective. Remotely sensed information enhances the ability to understand and cope with changing climate conditions. Chapter 16 presents an overview of innovative

technologies to manage and inventory large volumes of data that are available to the scientific and technological communities to help meet the common goals that were laid out in the UN's SDGs. There are many challenges and limitations that need to be overcome, but with coordination, cooperation, and collaboration many of these challenges can be met to help fulfill the objective of future sustainable development in a changing climate.

1.4 Summary

Each chapter of this textbook will be introduced by a set of learning objectives. These will provide guidance on the relevant information presented in the chapter to serve as a learning aid. At the end of each chapter, a set of critical thinking questions have been developed to assist in the understanding of the content. By learning about these processes and impacts, the intent is to broaden the understanding of the current issues that pose serious concerns for the state of the Earth system. In doing so, it may bring forward new ideas and innovations that will contribute to the future sustainable development options to preserve the health and well-being of human society.

Key words: climate change, Earth system, global warming, climate risk, SDGs, water–energy–food–health (WEFH) nexus, sustainable Earth.

Critical Thinking Questions:

1. What are the major objectives and structure of this textbook?
2. Why is climate change important and why has it occurred throughout Earth's history?
3. What are the major components of the Earth system and how do they impact climate change?
4. What are the 17 Sustainable Development Goals (SDGs)?
5. How does climate change affect the water–energy–food–health (WEFH) nexus?
6. What are the main causes of climate change?
7. How does climate change impact the Earth's natural resources?
8. What may happen to future sustainable development if climate change is ignored by human society?
9. If the Earth's temperature continues to increase, how could we adapt to it in the future?

Useful Links:

1. **World Meteorological Organization (WMO)**

 https://public.wmo.int/en

2. **Global Climate Observing System (GCOS)**

 https://gcos.wmo.int/en/

3. **United Nations Sustainable Development Goals (SDGs)**

 https://sdgs.un.org/goals

4. **Sustainable Earth**

 https://sustainable-earth.org/

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PART I:

THE BASICS PRINCIPLES OF CLIMATE CHANGE

CHAPTER 2

INDICATORS OF CLIMATE CHANGE AND CLIMATE OBSERVATIONS

Learning Objectives:

1. Explain the significance of climate observation (including past, present, and future).
2. Describe paleoclimatology and its importance to global climate change monitoring.
3. Discuss the major climate change indicators.
4. Explain the current state of the Earth's climate change, including global warming.
5. Describe climate hazards and how they can turn into climate disasters.
6. Describe future technology for climate change observations.
7. Discuss the climate change and extreme natural hazards.

2.1 Introduction

The Earth's climate system is exceedingly complex. To understand the current climate, we need to look at climate conditions in the past and compare the rate of change between the two periods. Although there are no significant climate data records before human history, there are ways to assess past climates using proxy climate data records, such as oceanic deposits, ice cores, tree rings, and other such methods. Throughout history, natural events caused temperature changes to Earth's climate. For example, there were multiple warm intervals and ice ages that occurred, all of which significantly affected the past and current climate. In the past, these changes in temperatures during these epochs have shaped the changes to polar ice caps, continental vegetation, and sea level globally. Other natural factors that affect climate change are plate tectonic movements, ocean circulation, mountain building, land erosion, and land-use changes due to deforestation and desertification. Human activity is also an important factor affecting current climate change. Since the 1800s, human activities in the industrial

sector have ignited rapid changes in carbon dioxide (CO_2) emissions through the burning of fossil fuels. Industrial activities also introduced chlorofluorocarbons (CFCs) into the atmosphere, which contribute greatly to greenhouse effects. During the 20th century, motor vehicles with combustion engines were mass-produced to serve as a global means of transportation but they have become one of the major sources of CO_2 emissions in recent years. Finally, with the increase in global population, the demand for industrial and agricultural land has increased significantly, and many countries have chosen deforestation methods to meet this demand. Tropical forests, such as the Amazon rainforest, have experienced widespread deforestation in recent decades, which has significantly reduced a major carbon sink source. To understand the current climate change status, we need to learn from basic weather and climate observations, as well as from climate data records.

In this chapter, we will be focusing on the (1) historical paleoclimate and past indicators of climate change, (2) current state of climate changes and present indicators, (3) climate hazards and disasters, (4) climate observations, and (5) future technology for climate change observations. Meteorology is the study of weather and climate. Weather can be described as the state of the atmosphere over a short period of time, whereas climate is generally how the atmosphere behaves over relatively longer periods of time. Thus, climate refers to long-term averages of weather. Weather is characterized by short-term (0–36 hours) changes in temperature, humidity, precipitation, cloudiness, wind velocity, and atmospheric pressure. Climate is a description of the long-term (>30 years) patterns of weather in a given area. In the past, climate was generally represented by statistical averages of weather at an observational site or by regional/global statistical compilations. However, since changing climate conditions alter components of the Earth system, including water supplies, agricultural patterns, and ecosystems, climate change has taken on an important role in the planet's sustainability. It is important to review the observational data to understand the current and long-term changes in global or regional climate patterns. This chapter reviews some of the fundamental indicators of climate change, which are measured or derived from different types of observational measurement approaches. From these basic observational climate indicators, the changes underway in most components of the Earth system can be evaluated. These analyses pave the way for the development of innovative technologies, which can be used to monitor climate change, provide mitigation, and adapt strategies for sustainable development.

2.2 Paleoclimate and Indicators

Paleoclimate refers to climate conditions that have existed for billions of years before the dawn of human civilization (Ackerman & Knox, 2015). Paleoclimatology is the study of past climates for which direct measurements were not taken. Scientists have built historical climate data records of Earth's paleoclimates from ancient proxy data. The paleoclimate record combined with global models shows past ice ages and periods even warmer than today. However, the paleoclimate record also reveals that the current climatic warming is occurring much more rapidly than past warming events. Physical, chemical, and biological climate proxy data within the geologic record (in paleoclimate archives) are used for analyzing and correcting with climate or environmental parameters in the modern world, since there were no direct observations from instruments. Figure 2.1 shows the different types of climate proxy data that recorded changes in climate conditions but do not measure temperature or precipitation.

The climate proxy indicators include sediments, ice cores, tree rings, documents, pollen, and long-term instrumental records (Ackerman & Knox, 2015). Scientists combine proxy-based paleoclimate reconstructions with instrumental records (such as thermometer and rain-gauge readings) to expand our understanding of climate variability to times before humans began measuring the climate. These reconstructions of the past climate and environment span all timescales, from year-to-year variations to those that occurred over millions of years. These data help us understand how the Earth's climate system varied both before and after human alteration of the landscape (USGS, 2021).

There are means of analyzing proxy data that offer valuable insight into historical trends, patterns, and changes in climate throughout history. In paleoclimatology, or the study of past climates, physical characteristics of the environment that have been preserved over time provide strong evidence of climate, which can be merged with current and more sophisticated observational measurements.\ Historical documents are often a valuable source when used in collaboration with other proxy data. Figure 2.2 shows global temperature anomalies over 800,000 years based on historical proxy climate data records reconstructed based on glacial ice code records. Temperature anomalies from paleoclimate data are shown by the green line, while the levels of CO_2 are shown by the gray points. In their research on Antarctic climate variability, Jouzel et al. (2007) rebuilt new high-resolution Antarctic climate records, which can be used to understand systematic long-term as well as millennial changes over the past 800,000 years. These