Climate Change and Geology

Climate Change and Geology:

A Critical Review

By

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Cambridge Scholars Publishing

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This book first published 2026

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-6488-2
ISBN (Ebook): 978-1-0364-6489-9

To the silent sufferers of climate change…

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PREFACE

Over four decades of professional involvement in the field of geology and hydrogeology has seen silent changes in the surrounding environment due to human activities. This has necessitated writing a hand book on 'climate change and Geology' which would serve the Environmental scientists, Geologists, Mining Engineers and graduate students.

All original Sources are acknowledged wherever are appropriate. References have been given at the end of most of the chapters.

My efforts would be successful if this book comes in handy to those for whom it is written.

P. K. Deb.

ACKNOWLEDGEMENTS

The author deeply acknowledges the help of the authors of the books and papers named in the references.

Computerization and secretarial work of the manuscript has been done by Soumyadipta Deb and Biswajit Paul whose contributions have been deeply acknowledged.

Lastly, without the constant support and encouragement of my family members especially my wife Sikha Deb and son Suryadipta Deb this book could not have been written. My heartfelt deep acknowledgement goes to them.

P. K. Deb.

CHAPTER I

INTRODUCTION

Climate change refers to the long-term warming of the planet due to an increase in average global temperatures. This phenomenon is primarily caused by human activities that release greenhouse gases, such as Carbon dioxide and methane into the atmosphere leading to a trap of heat and a rise in temperature.

Key Aspects of climate change:

a) Causes: Climate change is primarily caused by human activities such as burning fossil fuels (coal, oil and gas), deforestation, and land-use changes.
b) Effects: Climate change has various impacts, including rising sea levels, more frequent and severe weather events (heatwave droughts, floods) and changes in precipitation patterns.
c) Consequences: Climate change affects ecosystems, biodiversity, human health economies, and societies worldwide.

Addressing climate change

a) Mitigation: Reducing greenhouse gas emissions through sustainable practices, renewable energy sources, and energy efficiency.
b) Adaptation: Adapting to the impacts of climate change by implementing measures to reduce vulnerability and increase resilience.

Climate change Mitigation strategies

1. Transition to renewable energy: shift from fossil fuels to renewable energy sources like solar, wind and hydroelectric power.
2. Energy efficiency: Improve energy efficiency in buildings, transportation, and industry.
3. Sustainable land use: Implement sustainable agriculture practices, reforestation, and conservation efforts.

Climate change Adaptation strategies

1. Climate-resilient infrastructure: Design and build infrastructure that can withstand the impacts of climate change.
2. Climate-smart agriculture: Implement agricultural practices that are resilient to climate change.
3. Early warning systems: Develop and implement early warning systems for extreme weather events.

Global Response to climate change

1. Paris Agreement: An international agreement to limit global warming to well below 2^0C and pursue efforts to limit it to 1.5^0C
2. Sustainable Development Goals (SDGs): The SDGS aim to address climate change and its impacts while promoting sustainable development.

Climate change and geology are closely linked. Geology plays a crucial role in understanding climate change and climate change impacts geological processes.

Geological Perspective on climate change

1. Past climate records: Geologists study past climate (Paleoclimate) records such as sediment cores, ice cores and fossil records, to understand natural climate variability and the impact of human activities.
2. Carbon cycle: Geologists investigate the carbon cycle including the movement of carbon between the atmosphere, oceans, land and rocks to understand how human activities affect the climate.
3. Geological processes: Climate processes such as weathering and erosion, sea-level rise, glacier dynamics and landslides.

Geological Impacts of climate change

1. Sea-level rise: Rising sea levels lead to coastal erosion, flooding, and saltwater intrusion into fresh water sources.
2. Changes in groundwater: climate change affects groundwater recharge, quality and availability impacting human consumption, agriculture and ecosystems.

3. Increased natural hazards: Climate change contributes to more frequent and intense natural hazards, e.g. landslides, floods and droughts.

Geological contributions to climate change Mitigation

1. Carbon sequestration: Geologists explore ways to capture and store CO_2 in geological formations, reducing atmospheric CO_2 levels.
2. Geothermal energy: Geologists investigate geothermal resources which can provide renewable energy and reduce greenhouse gas emissions.
3. Climate-resilient infrastructure: Geologists help design and build climate- resilient infrastructure, such as sea walls, levels, foundations, to protect communities from climate-related hazards.

In the following few chapters, climate change and its impacts on geology and hydrogeology have been discussed in detail.

Climate change and geology are two closely interconnected fields that help us understand the Earth's past, present, and future. While climate change refers to long-term shifts and alterations in temperature, weather patterns, and atmospheric conditions, geology is the scientific study of the Earth’s physical structure, materials, history, and the processes that shape it. The relationship between these two disciplines offers critical insights into how the Earth’s climate has evolved over millions of years and how it continues to change today.

In this book, we will explore the fundamentals of climate change and geology, their interconnection, and how geological studies help scientists predict and understand contemporary and future climate changes.

What is Climate Change?

Climate change refers to significant and lasting changes in the Earth's climate system. This includes shifts in temperature, precipitation patterns, wind patterns, and other elements of the climate system over periods ranging from decades to millions of years. While climate variability is natural, the term “climate change” today often refers to the rapid changes in climate attributed largely to human activities, particularly since the Industrial Revolution.

Causes of Climate Change

There are two primary categories of causes:

1. **Natural Causes:**

   - **volcanic activity:** Large volcanic eruptions release ash and gases like sulfur dioxide, which can cool the Earth temporarily.
   - **Solar Variations**: Changes in the sun's output can influence Earth's climate.
   - **Orbital Changes (Milankovitch Cycles)**: Variations in Earth's orbit and tilt affect the distribution of solar energy received, causing glacial and interglacial periods.

2. **Anthropogenic (Human-Induced) Causes:**

   - **Burning of Fossil Fuels**: Coal, oil, and gas combustion release large amounts of carbon dioxide (CO_2) into the atmosphere.
   - **Deforestation**: Reduces the Earth's ability to absorb CO_2.
   - **Industrial Processes and Agriculture**: Release greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O).
   - **Urbanization**: Changes land use and contributes to localized warming (urban heat islands).

Effects of Climate Change

The consequences of climate change are wide-ranging and serious:

- Rising global temperatures (global warming)
- Melting ice caps and glaciers, leading to sea-level rise
- More frequent and severe weather events, such as hurricanes, droughts, and floods
- Disruption of ecosystems and loss of biodiversity
- Ocean acidification affecting marine life
- Impacts on agriculture, water resources, and human health

What is Geology?

Geology is the scientific study of the Earth's structure, substances, history, and the processes that have shaped it over billions of years. It involves studying rocks, minerals, fossil records, and the dynamic processes such as plate tectonics, erosion, sedimentation, and volcanism.

Subfields of Geology

Some of the major branches include:

- **Physical Geology**: Focuses on Earth's materials and processes.
- **Historical Geology**: Studies Earth's history and the development of its surface over time.
- **Petrology**: Examines the origin, composition, and structure of rocks.
- **Paleontology**: Studies fossils to understand past life and environments.
- **Geochemistry and Geophysics**: Use chemical and physical principles to study Earth's composition and internal processes.
- **Hydrogeology**: Focuses on the distribution and movement of groundwater.
- **Environmental Geology**: Applies geological knowledge to solve environmental problems.

Geologists use various tools such as rock samples, satellite imagery, seismic data, and computer models to study the Earth's history and predict future changes.

The Interconnection Between Climate Change and Geology

The fields of climate change and geology are intrinsically linked. Geological records provide crucial evidence of past climate changes, which help scientists understand the natural variability of Earth's climate and distinguish it from human-induced changes.

Geological Evidence of Past Climate

Geologists study various natural archives to reconstruct Earth's climatic history:

- **Ice Cores**: Extracted from polar ice sheets, these contain trapped air bubbles that provide information on past atmospheric composition and temperatures.

- **Sediment Cores**: Layers of sediment from lakes, oceans, and floodplains contain pollen, microorganisms, and chemical signatures indicating past climates.
- **Tree Rings**: The width and density of tree rings can reflect historical climate conditions.
- **Corals**: Growth patterns and chemical compositions of coral reefs can provide data on ocean temperatures and chemistry.
- **Fossil Records**: The distribution of plant and animal fossils reveals how species adapted or went extinct in response to climate changes.
- **Glacial Deposits and Moraines**: Physical evidence of past glaciations shows how ice sheets advanced and retreated over time.

Geological Time Scales and Climate

Geology operates on vast time scales, often millions or billions of years. Climate change studies benefit from this perspective because:

- Earth has experienced several major climatic shifts, such as ice ages and warm periods.
- Geological records reveal that CO_2 levels, sea levels, and global temperatures have fluctuated dramatically in Earth's history.
- The current rate of climate change is much faster than most past natural changes, raising concerns about ecosystems' and human societies' ability to adapt.

How Geology Informs Modern Climate Science

Modern climate science relies heavily on geological data to:

- **Calibrate Climate Models**: Historical data help validate the accuracy of computer models predicting future climate scenarios.
- **Identify Thresholds and Tipping Points**: Geological records reveal how abrupt changes in the past led to rapid shifts in climate.
- **Understand Sea-Level Changes**: Ancient shorelines and marine sediments inform projections of future sea-level rise.
- **Track Carbon Cycles**: The long-term carbon cycle, involving volcanic emissions, rock weathering, and sedimentation, influences atmospheric CO_2 levels.
- **Assess Natural Hazards**: Geological studies help predict risks such as landslides, earthquakes, and tsunamis that can be exacerbated by climate change.

Human Impact and the Geological Perspective

The current era is often referred to as the **Anthropocene**, a term used to describe a new geological epoch characterized by significant human impact on the Earth's systems. Human activities have altered the atmosphere, biosphere, and geosphere in ways that may leave a lasting geological signature:

- Rapid increase in greenhouse gases
- Extensive deforestation and land use changes
- Massive species extinctions
- Alteration of sediment flows through damming and mining
- Accumulation of plastics and other pollutants

Geologists are studying how these changes may be recorded in the rock record for millions of years to come.

CHAPTER II

PALEOCLIMATE AND EVOLUTION OF OXYGEN

Our present-day study concerns the history of the earth's atmosphere; not so much what it is now but how it got here, why this is and what may have been the intermediate steps. As will be seen this question has significant bearing on the initiation and evolution of life on earth.

One of the most interesting facts about the earth's atmosphere is the relatively large content of oxygen (about 21%), a condition unique among the planets of our solar system, presenting an interesting paradox. Life could not have been generated in the beginning with the present quantity of oxygen in the atmosphere- yet we cannot live and breathe without it. Most modern forms of life even many plants are highly dependent upon oxygen and in most cases amount of it for their existence. This means that oxygen in the atmosphere must have been stable in its concentration for a considerable time. Yet the very origin of life on earth would have been frustrated if oxygen had been abundant at that time; the amino acids and other vital but vulnerable material needed for incorporation in the incipient organisms would have been promptly oxidized.

It is very amazing how a stable atmosphere came into being with the present amount of oxygen. By the principle of Hutton of uniformitarianism this event can be explained. This explains geological and evolutionary variety by the slow changes we observe under the condition encountered today. On this view all developments have occurred at almost imperceptible rates compared with human events and concepts of time without the need to postulate at any time significant changes in the environment. But a modern interpretation of the geological record can show sudden bursts of evolutionary activity that are hard to explain unless we allow for decisive changes in the environment. Thus, we can observe that multi-cellular forms of life in the sea came into being only at the opening of the Palaeozoic 60 million years ago. Plant life on dryland has existed only about 420 million (preceded for a few million years by some fossil spores) and animal life on land perhaps about as long. The only evidence of any life before the Palaeozoic consists of certain bacteria and other very primitive organisms.

The birth of the earth earth's atmosphere was a secondary phenomenon arising after the earth's formation from the escape of gases from its rocks usually by localised heating, melting and volcanic action. As the primeval atmosphere appeared it would be dominated by hydrogen, water vapour and carbon dioxide and subsequently modified by gradual escape of the lighter gases (hydrogen and helium) and by the absorption and precipitation of carbon dioxide (CO2) in carbonates as the ocean become widespread.

At present there are about 500 volcanoes classified as active around the world and about 400 are situated in the Pacific ring. It is estimated that slightly less than cubic mile a year of solids is being added to the continents at the current rate of activity. Multiplying this number by the lifespan of the earth one has a figure of about 3000 million cubic miles which is very close to the total volume of the continents.

Accompanying the solid effluent, the volume of volcano gases is considerable. The largest single content is water vapour which can be quite as high as 97% by volume.The largest single content is water vapour which can be as high as 97% by volume. This is mixed with varying amounts of nitrogen, carbon dioxide, hydrogen, sulphur dioxide and chlorine plus much smaller quantities of hydrogen sulphible, carbon monoxide, methane, ammonia and others. All these volcanic vapours and gases have been bound in the rock to be released sometimes explosively in the throat of the volcanoes.

The water vapour gases released over 3000 to 4000 million years are thought to be more than sufficient to account for the volume of the nitrogen and other continents of the present atmosphere, excepting only oxygen. But this exception is very important. They are no free oxygen produced by volcanic activity. Volcanic temperatures and the presence of iron, Sulphur and other materials in chemically reduced states lead to violent chemical reactions that ensure that all oxygen comes out in combined form.

Therefore, oxygen was virtually absent from of primitive atmosphere. This view is confirmed in other ways. Ancient sediments formed by erosion in those early days are known to be only partially oxidized, suggesting an atmosphere low in oxygen. Recently scientists concluded that the early atmosphere must have been chemically reducing in character (i.e. dominated by hydrogen) The origin of life itself appears to forbid the existence of much oxygen at the beginning.

The free oxygen must have been derived mainly from the breakup of water molecules into hydrogen and oxygen. This can occur via one of two routes: - by direct photo- dissociation of water vapour exposed to ultraviolet light and by the indirect process that occurs during photosynthesis on green plants on a primitive earth without life, lonely the first alternative appears to be feasible.

Of the product of photo-dissociation the hydrogen is light enough to escape rather quickly from the atmosphere, nor would the nascent oxygen formed by photo-dissociation stay around long in the primitive atmosphere where it was produced at the surface it would react very quickly with partially oxidised rocks and materials. In the atmosphere some of the oxygen forms ozone reactive molecules containing three atoms of oxygen. Ozone itself react at a high rate with surface rocks. In a primitive atmosphere oxygen is used up at a definable rate in surface oxidation and possibly by reconstitution of water vapour at certain levels in the atmosphere.

Following this evolutionary explosion Marine photosynthesis increased the total to a much higher rate further accelerating the build-up of oxygen in the atmosphere. As oxygen built up, living process could take place at shallower depths until oxygen had reached a level of about 10% of the present atmospheric concentration. Then life could finally exist at or near the surface of the water.

The geological evidence shows such explosion of life on land occurred about the late Silurian Period, i.e. 400-to-420-million-year ago. Then very quickly, by the late Silurian Period, many forms of both plants and animals had moved ashore and before long (early Devonian Period; 380 million years ago) great forests had appeared. As dense plant life spread over most of the land surface, it added to its own protection form ultraviolet light by the rapid build-up of oxygen by its photosynthetic action. With the accompanying increase in the thickness of the protective ozone more sensitive forms of life pre-existing in the water have projected their evolutionary counterparts on land including the amphibians and insects.

The oxygen content of the atmosphere may in facts have built up to level exceeding our present atmospheric content by the time of the carboniferous. This reasoning suggests that for the past 300 million years or so both Oxygen and carbon dioxide might have fluctuated about the present levels in a series of saw- toothed oscillations dropping suddenly to perhaps the 10% level and again rebuilding slowly.

From a perusal of above, it may be seen that oxygen had been built up in our atmosphere in a hard-earned way. Therefore, this should be preserved in our atmosphere However, human activity in the present day have affected the global atmosphere initiating unwanted climate-change.

Understanding Earth's past climate and the evolution of oxygen in its atmosphere is crucial to comprehending the complex interplay of geological, biological, and atmospheric processes that have shaped our