Climate Dynamics over the Indian Subcontinent

Climate Dynamics over the Indian Subcontinent:

Geological Perspectives

Edited by

Neloy Khare

Cambridge Scholars
Publishing

Climate Dynamics over the Indian Subcontinent: Geological Perspectives

Edited by Neloy Khare

This book first published 2025

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: 978-1-0364-4386-3
ISBN (Ebook): 978-1-0364-4387-0

CONTENTS

FOREWORD

India secured seventh position in the recently released Climate Change Performance Index (CCPI) 2024, underscoring its notable role and contribution to the ongoing global efforts to mitigate climate change. The report also emphasises India's reliance on coal, oil, and gas to meet its energy needs despite efforts to promote renewable energy. This reliance contributes significantly to GHG emissions and severe air pollution in cities. In the ongoing global warming scenario, India is expected to face many significant challenges related to climate change, such as Water Scarcity. Changing rainfall patterns and melting glaciers threaten India's water security. According to NITI Aayog, best estimates indicate that India's water demand will exceed supply by a factor of two by 2030. Climate change affects crop patterns, reducing yields and food security. Increased temperatures and extreme weather events like floods and droughts disrupt farming. According to a 2019 study, extreme weather events cause annual crop losses of about 0.25% of India's GDP. Similarly, Coastal regions, including major cities like Mumbai and Kolkata, face threats from rising sea levels. This endangers infrastructure, habitats, and the livelihoods of millions. According to reports, it is estimated that India could lose about 1,500 square kilometres of land by 2050 due to erosion caused by rising seas. Due to vehicular emissions, industrial pollution, and crop burning, India struggles with severe air quality issues. Climate change exacerbates this problem, impacting public health and ecosystems. According to a 2022 report, India's average PM2.5 concentration was 53.3 micrograms per cubic meter (μg/m3). This is more than ten times the World Health Organization's (WHO) recommended annual guideline level of 5 μg/m3. The Urban Heat Island Effect exacerbates temperatures in cities, leading to an increased frequency and intensity of heat waves. This elevates the risk of heat-related illnesses and fatalities, especially among vulnerable populations living in densely populated urban areas. To mitigate the severe impact of climate change, the Government of India has taken various initiatives like National Action Plan on Climate Change (NAPCC), the National Solar Mission, the National Mission for Enhanced Energy Efficiency, the National Mission on Sustainable Habitat, the National Water Mission, National Mission for Sustaining the Himalayan Ecosystem, National Mission for A Green India, National Mission for Sustainable Agriculture, National Mission on Strategic

Knowledge for Climate Change, Nationally Determined Contributions (NDC), National Adaptation Fund on Climate Change (NAFCC), State Action Plan on Climate Change (SAPCC), and National Adaptation Fund on Climate Change (NAFCC).

We need to prepare the best climate scenarios over the Indian sub-continent by better understanding the past climatic conditions and the dynamics of climate change. Such vital signals of paleoclimatic conditions are archived in a diversified manner in nature, and they are usually reconstructed by utilising various well-established proxies of climatic conditions. It is paramount that such past climate data be collated, evaluated and discussed in detail to enable the climate modellers to use these inputs in their models to help generate improved climate scenarios. The present book titled "Climate Dynamics over the Indian Subcontinent: Geological Perspectives" is poised to bring all such information and shreds of evidence in one place in nine chapters. An overview of geological paleoclimatic indicators and their geological proxies has been presented by Verma et al., coupled with a detailed account of multi-proxy records of climate change over the Indian Subcontinent by Dar et al. On the other hand, Jeshma et al. have put forth the distribution of foraminifera and their ecological conditions in the Anchuthengu Estuary, Thiruvananthapuram, on the southwest coast of India. Banerji decoded the conundrum of Indian monsoon variability and its global linkage during the Meghalayan Stage (4.2 ka to Present). Similarly, Organic carbon and carbonate fluctuations in the south-eastern Arabian Sea past 130 ka for Productivity implications have been recorded by Neelavanna and Hussain. On the contrary, a decline of stromatolites at the base of the Cambrian-A case study from the Tal Group stromatolite, Lesser Himalaya, India, has been reported by Sharma et al. The book also covers pollution through the ages through a chapter by Singh et al. on Arsenic contamination in groundwater in parts of Middle Ganga Plain, Darbhanga district, Bihar. Sabale gleaned Archaeological evidence of climate change: A potential source to understand the past climate trends. The book's last chapter deals with the Paleoseismic studies from Andaman and Nicobar Islands. Dalli and Javed have thoroughly reviewed it.

To help reduce the severeness of global warming and the adversity of climate change, we must invest in research and development of genetically modified or selectively bred climate-resilient crop varieties tailored to withstand extreme weather conditions, ensuring food security despite changing climate patterns. Similarly, we must construct vertical forests within urban spaces to enhance green cover and biodiversity while mitigating the urban heat island effect. These structures consist of multiple levels of vegetation on building exteriors, offering ecological benefits and improving air quality, besides many other vital steps in this direction.

I compliment and congratulate the Editor for being thoughtful in addressing the issue of how climate has changed in the geological past in the present book. This book's collated data and insights are crucial for preparing futuristic models and scenarios of climate conditions over the Indian subcontinent.

Prof. Mahendra Pratap Singh
Former Pro Vice-Chancellor
University of Lucknow
September, 2024
Lucknow

PREFACE

Climate change describes global warming, the ongoing increase in global average temperature and its effects on Earth's climate system. It also includes previous long-term changes to Earth's climate. The current rise in global average temperature is primarily caused by humans burning fossil fuels. Fossil fuel use, deforestation, and agricultural and industrial practices add to greenhouse gases, notably carbon dioxide and methane. Greenhouse gases increase Earth's heat after it warms from sunlight. More significant amounts of these gases trap heat in Earth's lower atmosphere, causing global warming.

Climate change has an increasingly significant impact on the environment. Deserts are expanding, while heat waves and wildfires are becoming more common. Amplified warming in the Arctic has contributed to thawing permafrost, retreating glaciers, and declining sea ice. Higher temperatures are also causing more intense storms, droughts, and other weather extremes—rapid environmental change in mountains and coral reefs forcing many species to relocate or become extinct. Even if efforts to minimise future warming are successful, some effects will continue for centuries. These include ocean heating, ocean acidification and sea level rise.

Climate change threatens people with increased flooding, extreme heat, food and water scarcity, disease, and economic loss. Human migration and conflict can also be a result. The World Health Organization (WHO) calls climate change the greatest threat to global health in the 21st century. Societies and ecosystems will experience more severe risks without action to limit warming. Adapting to climate change through efforts like flood control measures or drought-resistant crops partially reduces climate change risks, although some limits to adaptation have already been reached.

It necessitates a firm scenario of climate change, especially in tropical countries like India, and to prepare any predictive model and futuristic scenarios, a thorough understanding of climate change dynamics and science in space and time is of paramount importance. These past climate conditions could be reconstructed through various proxies duly preserved in various geological archives.

With the above intentions, collating important insights into how the climate has changed in India was essential. Accordingly, the book "Climate Dynamics over the Indian Subcontinent: Geological Perspectives" has been brought out.

The book is composed of a total of nine chapters covering varied facets of past climate changes. The book begins with an overview of geological paleoclimatic indicators and their geological proxies by Verma et al. It is well known that palaeoclimatology describes the climate of the past, and its study is quite distinct from the current environment as it is primarily based on clues preserved in the rock record rather than instrumental climatic data. Fossils, ice cores, sedimentary layers, pale soils and sediments are the primary geological materials yielding proxy data for paleoclimatic investigation. The Earth's rock record provides ample evidence, revealing that its climate has not been uniform throughout its history and has witnessed several episodes of global warming and cooling associated with increasing and decreasing concentrations of greenhouse gases in the atmosphere. Further, it is inferred that all episodes of past climate change were caused by the natural processes responsible for the increasing or decreasing greenhouse gas concentration. However, the current increase in greenhouse gases is mainly caused by anthropogenic activities. Finally, it is concluded that change in climate by any means, whether natural or anthropogenic, usually proves more harmful than beneficial.

To further augment our understanding, comprehension of past climate is essential for developing models to help understand the present and predict the future climate. In the Indian subcontinent, the hunt for understanding past climate change has become more assertive in recent decades, and researchers are analysing various proxies for quantifying the variable response of the Earth system to past climate changes. As an essential component of the climate, more information has been revealed about the birth and the changes in the monsoon systems. In their chapter, Dar et al.present a comprehensive review of the proxies used for paleoclimatic reconstruction in the Indian subcontinent. The details of the Earth's climate through geological ages and the climatic changes right from the odyssey of the Indian plate from the southern hemisphere to its current location are presented in this chapter. The subcontinent's climate during the Quaternary and Holocene are explained in detail. However, given its complex topography and varying climatic conditions observed across its length and breadth, the subcontinent has been divided into numerous broad zones for better comprehension of the regional climatic variations. Similarly, Jeshma et al. emphasised the importance of understanding response in modern times before using the same proxy. They submitted that International coastal water bodies are subjected to large-scale threats and influences from numerous anthropogenic activities. Coastal ecosystems are commonly highly populated with high biodiversity and are influenced by a high anthropic pressure that has adverse effects on the ecosystem and living organisms within. Benthic foraminifera have been widely used as an environmental bioindicator to assess environmental quality, as different ecological characteristics like salinity and temperature fluctuations, nutrient abundance, oxygen concentration, and anthropogenic pollution control them. The development and application of foraminifer indices as tools for understanding the overall ecosystem.

Regional ecological assessment and monitoring strategies have provided a valuable tool for carrying out baseline studies and understanding ecological changes in the Anchuthengu Estuary. They collected 20 surface (0-1cm) sediment (grab) samples from 20 pre-monsoon season stations at water depths varying from 1 to 5 m in the Anchuthengu estuary. All the grab samples were analysed to recognise the spatial distribution of benign foraminifer assemblages and their relationship with environmental variables.

All the stations in the lower estuary (stns.1-9) present dominantly sandy silt, and backwaters (stns.10-15) and upper estuarine region (stns.16-20) generally represent a sandy substrate in the Premonsoon season in the entire study area. The substrate of the lower estuary is enriched in $CaCO_{3,}$ wherein high TFN, TLN, and S are observed. At the same time, CaCO3 is significantly reduced in backwaters and estuarine areas, resulting in lowered TFN, TLN and S. The substrate in the study area is accessible from the bottom vegetation, mainly owing to chemical contaminants and the coir retting process; only species of Ammonia are present throughout the study area. At the same time, other dominant taxa of Elphidium, Nonionoides, Pararotalia, and Quinqueloculina occur in the lower estuary. They need to be more present in the backwaters and upper estuarine regions. The persistence of Ammonia throughout the study area suggests the prevalence of stressed environmental conditions.

Their study integrates foraminifera density and diversity with ecological parameters to assess the environmental quality of the study area. The study concludes that the outfall of sewage from adjoining urban clusters and aqua culture contaminants mainly enhances the chemical pollution in the lower estuary (stations.1-9), while the backwaters (stations.10-15) and estuarine region (stations.16-20) undergoing constant anthropogenic activities like retting of coconut husk and substrate reworking are mainly causing pollution, and thus significantly impacting the foraminifera distribution, density, and diversity in the Anchuthengu estuary.

On the contrary, Banerji attempted to decode the conundrum of Indian monsoon variability and its global linkage during the Meghalayan Stage. According to her, the northern Indian Ocean and the Indian subcontinent are influenced by the monsoon-driven climate variability on decadal to multi-millennial timescales. The Indian monsoon dynamics are ascribed to the seasonal reversal of wind systems led by lateral migration of the intertropical convergence zone (ITCZ), driven by the solar insolation, causing the Indian summer monsoon (ISM) and the Northeast monsoon (NEM). Further, the monsoons are also significantly impacted by a high-latitude climate system, such as the North Atlantic climate, in the form of Western Disturbances (WD). The interference of other climate variables and forcing mechanisms on Indian monsoon dynamics leads to severe complexity in understanding climate change. It raises the need to address the past monsoon variability, especially the Meghalayan Stage, which represents the last 4.2 ka of the Holocene Epoch. Her chapter aims to provide an overview of the Indian monsoon variability, explicitly emphasising the ISM and its response towards the globally recognised abrupt climatic events during the last 4.2 ka. The present review revealed that solar forcing, with the occasional influence of volcanic forcing, has been the prime factor in controlling the Indian monsoon system. Nevertheless, it is premature to characterise the processes responsible for monsoon variability during the Meghalayan Stage and, thus, requires extensive qualitative and quantitative proxy-based records to accurately underline the climate variables predominantly influencing the Indian monsoon vis-à-vis the climate system and its teleconnection with global climate patterns.

It is indubitable that the biological productivity of the western Arabian Sea was higher during interglacial periods than during glacial periods. Contrary to fluctuations in southwest monsoon intensity, productivity in the eastern Arabian Sea was higher during glacial than during interglacial. Neelavanna and Hussain., in their chapter, observed that over the past 140 ka, the productivity of the south-eastern Arabian Sea has changed over time. Calcium carbonate ($CaCO_3$), total organic carbon (TOC), total carbon, total nitrogen, and sulphur on the GC-02 were analysed. Calcium carbonate in the southeast Arabian Sea exhibits high values during glacial periods and low values during interglacial periods throughout the core. However, the fluctuations in organic carbon concentration across time are only appreciable during MIS 5. Regional variations in sedimentation rates, dilution, and preservation, which affect the signal of carbonate and carbon production, are thought to cause the different variations in calcium carbonate and organic carbon concentration at the north-eastern and south-eastern Arabian Sea, as well as between glacial and interglacial. On the other hand, Sharma et al. noticed a decline of stromatolites at the base of the Cambrian through their case study from the Tal Group stromatolite, Lesser Himalaya, India. They further stressed that the Lower Cambrian stromatolite Columnaefacta vulgaris is an essential paleobiological element of the lesser Himalayas. It is found in the Basal Chart, a Member of the Deo-Ka-Tibba Formation of the Tal Group in the Mussoorie Syncline, a part of the phosphate unit, exposed in the Durmala area. Its morphological attributes, microstructure, and micro fabric of the Columnae Facts Vulgaris are described. Hypothesis on the decline in the diversity of stromatolites during the Neoproterozoic and their sharp reduction across the Ediacaran-Cambrian is widely debated. Various models exist on the drop of stromatolites. This noticeable decline of stromatolites is attributed to higher algae's competitive pressure and metazoans' advent in the Ediacaran Period. This hypothesis has never been discussed in the Indian context. Stromatolites occurring in the Chert Member of the Lesser Himalaya are considered an appropriate geological sequence to test the theories on the decline of stromatolites across the Ediacaran-Cambrian transition. Details of the morphological studies on Columnae Facts Vulgaris showseffect of the advent of animals in the Ediacaran times (635-538 Ma) on its continuity and formation. Their association with phosphorites and pyrites is discussed to assess the cause of their continuity during the early Cambrian. Repeated glaciations during the Neoproterozoic Era (Cryogenian: Sturtian that lasted between 717 to 660 Ma and Marinoan-650 to 635 Ma; Ediacaran: Gaskiers-579.63 to 579.88 Ma and Baykonurian-547 to 541.5 Ma) are considered to have posed an environmental challenge for the growth of stromatolites. The role of animal fossils, the chemistry of seawater during the precipitation of phosphorite, and the role of the depositional environment in the decline of stromatolites, if any, are discussed. The morphological completeness of Columnae Facts Vulgaris showsthat animals of the Ediacaran Period did not feed on the microbenthicorganisms forming stromatolites. It is, therefore, substantial evidence refuting the exclusive role of animals in the decline of stromatolites in the Lower Cambrian.

Interestingly, Singh et al. She studied the Arsenic contamination in groundwater in parts of the Middle Ganga Plain, Darbhanga district, Bihar, through the Holocene interglacial. In Bihar, the alluvial aquifers within the Quaternary succession along the course of the Ganga River and particularly to its north have a distinctly high arsenic incidence. The study carried out in Darbhanga district, Bihar, falling in the middle Ganga plain during 2019-20 & 2020-21indicates that ~38% of a total of 926 no-water samples tested values above 10ppb (BIS: <10ppb).

Their results revealed that the elevated concentrations of arsenic were confined to the aquifers lying within the depth zone of 80ft to 240ft (24-73m). In contrast, shallower and deeper aquifers appear to be less or non-contaminated. With the median principal drainage river, Ganga acting as a delimiting receptacle to the influx of sediments through drainages emanating from the extra peninsular region into the foreland basin, the predominance of Arsenic to the north of Ganga supports an extra peninsular source. Because the deeper aquifers are less or non-contaminated, the role of underlying lithology or basement rocks, if any, appears minimal. To an extent, the pockets of contamination are aligned along the banks of significant drainages or even within the vestiges of the pale channel, which formed the active channel during earlier times.

Analytical study and earlier bibliography support the model that the area's primary provenance contributing to arsenic is the rocks exposed in the extra-peninsular region, particularly the serpentinised ophiolites of the Indus-Tsangpo Suture zone. Siwalik could be the secondary source, which in turn has contributed Arsenic to the foreland basin through the network of river systems, including the River Baghmati, draining the study area.

The secondary detrital sources may have become active after the creation of the hydrological divide, i.e., the Himalayas, during the Holocene, and the primary migration could have been accentuated during the Himalayan orogeny.

The problem has an evident implication for the health of the local habitats dependent on groundwater for drinking and domestic needs. The topographic expression, locales of incidence, and symptomatic arsenic manifestation in human beings in and around such pockets, along with reported increased incidence of life-threatening diseases like cancer, indicate the role of water contaminants like arsenic. In these habitations, cancer types such as Gall bladder and breast cancer were distinctly reported along with surficial skin manifestations, cardiovascular, neurological and gastrointestinal disorders, hypertension, loss of appetite, breathlessness, loss of energy, etc. The disease burden in these particular habitations has increased in recent years, which may pose serious problems for the exposed population. Historical evidence of climate change is a potential source for understanding past climate trends because each river develops a typical type of topography according to its reach. Each flowing channel shapes the earth's surface through the erosion, transportation, and deposition of sediments. This is because of weathering and sediment erosion from source areas and sediment deposition in low-lying areas; streams modify the earth's surface. The old sediments deposited during the Quaternary era are immensely important from an archaeological perspective because human development occurred in this period. Therefore, most of the contemporary cultural deposit is deposited in these sediments. Also, such sediment is rich in flora and fauna, which helps reconstruct the paleoenvironment of areas concerning human development. In the present context, the details of the paleoenvironment and man-land observed in the Upper Reaches of the Sina are studied by taking the Quaternary trenches or excavations at suitable cultural settlement localities in parts of the south Ahmed Nagar district of Maharashtra. The book ends with a review of prehistoric, historical and recent earthquakes in the Himalayas by Dhali and Malik. They further elaborated that the Himalayan arc, spanning 2400 km, has experienced several surface-rupturing earthquakes documented through historical and paleoseismological records. Significant seismic events have occurred during the AD 1555 and AD 1905 rupture in the NW segment, the AD 1344, 1505, and 1803 ruptures of the Central segment, and the AD 1100, 1255, 1934, and 1950 ruptures of the NE segment, among others. These events, with rupture lengths ranging from 200 to 800 km, suggest the occurrence of both great-magnitude earthquakes (8.0Mw8.7) and large-magnitude earthquakes (7.5≥Mw≤8.0). The limitations of the ^{14}C ages may lead to overestimating events, potentially grouping multiple earthquakes as single events. Notably, the NW, Central, and NE segments have ruptured in both the $14/15^{th}$ and $19/20^{th}$ centuries. The average surface rupture during great magnitude earthquakes is approximately 400 km, while large magnitude earthquakes typically exhibit ruptures around 200 km. This pattern supports the concept of a significant magnitude earthquake often following a large magnitude event in the Himalayan arc. The present book is hoped to be a ready reference for anyone interested in understanding climate, its changing pattern in the geological past, and new insights into the changing climate over the Indian subcontinent. It is important to policymakers, economic planners, and scientific institutions.

Neloy Khare
September, 2024
New Delhi

ACKNOWLEDGEMENTS

Kind support and help received from all contributing authors are gratefully acknowledged. Without their valuable inputs on various facets of the past climate changes reconstructed based on multiple proxies over the Indian sub-continent, the book would not have been possible. Various learned experts who have reviewed different Chapters are sincerely acknowledged for their timely, essential and critical reviews.

I sincerely thank the Ministry of Earth Sciences, Government of India, New Delhi (India) for various inputs, support and encouragement. Dr M. Ravichandran, Secretary, Ministry of Earth Sciences, and Government of India and Dr Arbind Mitra, former Secretary, Office of the Principal Scientific Advisor to the Prime Minister, Government of India, New Delhi, have always been a source of inspiration and are acknowledged for their kind support. Shri. D. Senthil Pandian, Joint Secretary to Government of India at Ministry of Earth Sciences, New Delhi (India), Dr Prem Chand Pandey, former Director, National Centre for Polar and Ocean Research, Goa (India) and Dr K.J. Ramesh, former Director General, India Meteorological Department (IMD), New Delhi (India) have always been supportive as true well-wisher and are deeply acknowledged for providing many valuable suggestions at various stages of the preparation of this book. This book has received blessings from eminent Climate experts of the country, namely Prof. Anil Kumar Gupta from the Indian Institute of Technology, Kharagpur (India), Prof Devesh Kumar Sinha, University of Delhi, Delhi and Dr Rajiv Nigam, former Deputy Director, National Institute of Oceanography, Goa (India).

My wife, Dr Rajni Khare, and my sons, Flight Lieutenant (Dr) Akshat Khare and Ashmit Khare, have unconditionally supported me enormously during various stages of this book. Dr Upasana. S. Banerjee and Dr Sidharth Dey of the Ministry of Earth Sciences, New Delhi, have helped immensely in formatting this book's text and figures and bringing them to their present form. Publishers have done a commendable job and are sincerely acknowledged.

Neloy Khare
September, 2024
New Delhi

CONTRIBUTORS

Arjun Singh Rathore
Department of Geology, G. G. M. Science College, Jammu, Jammu Tawi, 180001, India

Abhinav Srivastava
Mahavir Cancer Sansthan & Research Centre, Patna, Bihar, 801505, India

Akhouri Bishwapriya
Geological Survey of India, SU: Bihar, Patna, Bihar, 800020, India

Apurva Kumar Singh
Geological Survey of India, SU: Bihar, Patna, Bihar, 800020, India

Arun Kumar
Mahavir Cancer Sansthan & Research Centre, Patna, Bihar, 800001, India

Ashok Kumar Ghosh
Mahavir Cancer Sansthan & Research Centre, Patna, Bihar, 800001, India

Ashu Khosla
Department of Geology, Panjab University, Sector-14, Chandigarh, 160014, India

Irfan Rashid
Department of Botany, University of Kashmir, Srinagar, 190006, India

Javed N. Malik
Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, 208016, India

Jehangeer Ahmad Mir
Department of Earth Sciences, University of Kashmir, Srinagar, 190006, India

Jeshma P
Department of Geology, University of Madras, School of Earth and Atmospheric Sciences, Guindy campus, Chennai, 600005, India

Kannaiyan Neelavanna
Applied Research Centre for Environment & Marine Studies, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia

M. Prashanth
Geology Discipline Group, School of Sciences, Indira Gandhi National Open University, New Delhi, 110068, India

Mitthu Dhali
Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, 208016, India

Mukund Sharma
IIAST, Integral University, Kursi Road, Lucknow–226026, India

Omkar Verma
Geology Discipline Group, School of Sciences, Indira Gandhi National Open University, New Delhi-110068, India

P. D. Sabale
Department of Archaeology, Deccan College Deemed University, Pune, 110007, India

Reyaz Ahmad Dar
Department of Earth Sciences, University of Kashmir, Srinagar, 190006, India

S.M. Hussain
Department of Geology, University of Madras, Chennai, 600005, India

Shreya Singh
Geological Survey of India, SU: Bihar, Patna, Bihar, 800020, India

Suresh Gandhi M
Department of Geology, University of Madras, School of Earth and Atmospheric Sciences, Guindy campus, Chennai, 600005, India

Tharun R
Department of Geology, University of Calicut, Christ College, Irinjalakuda, Thrissur, 673635, India

Upasana Swaroop Banerji
National Centre for Earth Science Studies (NCESS), Thiruvananthapuram, Kerala, 695011, India

Waseem Qader
Department of Earth Sciences, University of Kashmir, Srinagar, 190006, India

Yogmaya Shukla
Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow, U. P., 226007, India

About the Editor

Dr Neloy Khare is an Adviser/Scientist G to the Government of India at MoES. He has a distinctive acumen in administration and quality science and research, and his areas of expertise cover a large spectrum of geographically distinct locations like the Antarctic, Arctic, Southern Ocean, Bay of Bengal, Arabian Sea, Indian Ocean, etc. Dr Khare has almost 30 years of experience in the field of paleoclimatic research using paleobiology/Paleontology) /teaching/science management/administration/coordination for scientific programmes (including the Indian Polar Programme), etc. Having completed his doctorate (PhD) in tropical marine regions and Doctor of Science (DSc) on Southern High latitude marine regions towards environmental/climatic implications using various proxies, including foraminifera (micro-fossil), have made significant contributions in the field of palaeoclimatology of Southern high latitude regions (Antarctic and Southern Ocean) using Micropaleontology as a tool. These studies, coupled with his paleoclimatic reconstructions from the tropical areas, helped understand causal linkages and teleconnections between the processes in Southern high latitudes and climate variability occurring in the tropical regions. Dr Khare has been conferred Honorary and Adjunct Professor by many Indian Universities. He has an imposing list of publications to his credit. The Government of India and many professional bodies have given him many prestigious Awards for his humble scientific contributions to Past climate changes/Oceanography / Polar Science, and Southern Oceanography. The most coveted award is the Rajiv Gandhi National Award -2013, conferred by the Honourable President of India. Others include the ISCA YOUNG SCIENTIST AWARD, BOYSCAST FELLOWSHIP, CIES FRENCH FELLOWSHIP, KRISHNAN GOLD MEDAL, BEST SCIENTIST AWARD, EMINENT SCIENTIST AWARD, ISCA Platinum Jubilee Lecture, IGU Fellowship and Rajbhasha Gaurav Puraskar-2023, among many. Dr Khare has made tremendous efforts to popularise ocean and polar science nationwide by delivering many invited lectures and radio talks and publishing popular science articles. Many books authored/edited on thematic topics and published by reputed International Publishers are testimony to his commitment to popularising science among the masses.

Dr Khare sailed in the Arctic Ocean as part of "Science PUB" in 2008 during the International Polar Year campaign for scientific exploration and gained the prestigious distinction of being the first Indian to sail in the Arctic Ocean.

CHAPTER 1

AN OVERVIEW OF GEOLOGICAL PALEOCLIMATIC INDICATORS AND THEIR PROXIES

OMKAR VERMA, ASHU KHOSLA
AND M. PRASHANTH

Introduction

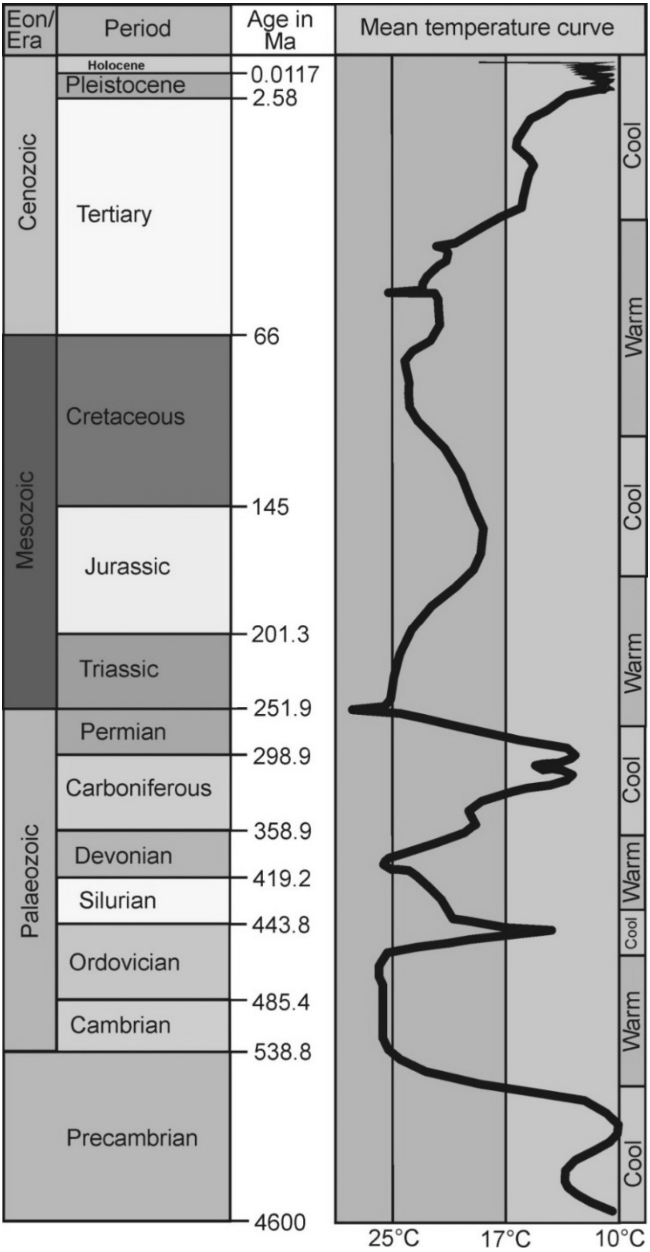
The latest climate assessment report of the United Nations' Intergovernmental Panel on Climate Change (IPCC) says that the modern climate is changing, and people worldwide feel it differently (IPCC, 2022). While compiling recent information on climate change, the IPCC noted that present global warming is occurring due to a continuous increase in greenhouse gas concentration. Common effects of climate change include melting of glaciers, rising sea levels, oceanic and atmospheric warming, ocean acidification, shifting vegetation zones, shrinking Arctic and Antarctic ice sheets, collapsing ice shelves, water scarcity, catastrophic storms, severe droughts, intense flooding, extreme rainfall, wildfires, and biodiversity loss (Cronin, 2010; IPPC, 2022). The current climate change seriously threatens the health of the world and the well-being of humans. Climate scientists have been making projections of future climate change and their effects on abiotic and biotic systems of the Earth using climate data from the previous 40 years (Braconnot et al., 2012; Verma, 2021; IPCC, 2022). It is widely acknowledged that knowledge of the modern or present-day climate, which is based on data that is more or less a century old and was collected using modern instruments, does not sufficiently explain how the climate system functions or how it will behave in the future under the scenario of current climate change (Jansen et al., 2007; Shaltami et al., 2020). Since the beginning of the Earth, around 4600 million years ago, the climate system has undergone several phases of change in the forms of warming and cooling (Ruddiman, 2008; Cronin, 2010; Bradley, 2015; Verma, 2021).

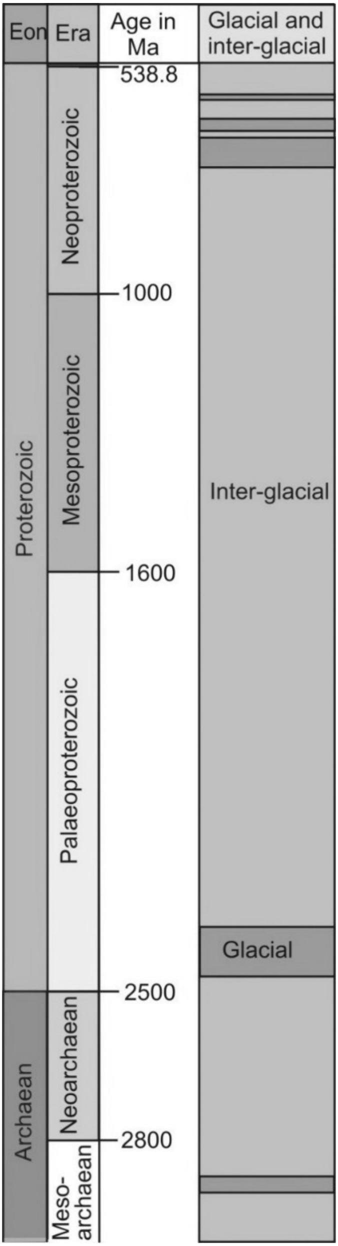
Understanding the present climate system is usually obtained by studying its components (atmosphere, lithosphere, cryosphere, hydrosphere, and biosphere). However, the knowledge of the Earth's natural climatic variation over thousands, millions and even billions of years reveals how the climate system functions and affects the abiotic and biotic components of the Earth. Thus, knowledge of the past climate is essential to understand the modern climate system and how it will respond in the future (Cronin, 2010; Bradley, 2015; Verma, 2021; Verma et al., 2022). Many rock and fossil record proxies are available for research on the paleoclimate. An overview of the geological evidence used to recreate paleoclimate is provided in this chapter.

Paleoclimate

The term palaeoclimatology refers to the climate of the past, and its origin is closely related to the climatic studies of ice ages (Bradley, 2015; Bhandari, 2018; Verma, 2021). It is the science of past climate and uses proxy data recovered from rock records before the period of instrumental data. This aspect dramatically differs from the current or recent climate, which involves the study of instrumental climatic data (Bradley, 2015). Researchers employ natural environmental evidence or proxies on the planet's surface, consisting of sediments, sedimentary layers, fossils, ice cores, and radiocarbon to reconstruct the paleoclimate. Paleoclimatic data deals with interpreting long-term earth climate variations caused by the natural changes in the atmosphere's carbon dioxide (CO_2) content (Crowley & Berner, 2001).

Climate change is neither an uncommon nor a recent phenomenon. Indeed, it is a natural process, and since Earth's creation, there have been several cycles of climate change (Fig.1). Let us get acquainted with the geologic time scale before talking about the Earth's past climate. Time, which spans the entire Earth, is split into specific geologic time units: s, era, period, epoch (Fig.1), and age, much as our time is divided into years, months, weeks, days, hours, minutes, and seconds. By dating rocks using radioactive techniques, it is possible to ascertain the length of a particular time unit on the scale. The genesis or extinction of certain species is a typical example of a sudden biotic event that marks the boundary between two-time units.


Eon/Era
Period
Age in Ma
Mean temperature curve
Cenozoic
Mesozoic
Palaeozoic
Holocene
Pleistocene
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Precambrian
0.0117
2.58
66
145
201.3
251.9
298.9
358.9
419.2
443.8
485.4
538.8
4600
Cool
Warm
Cool
Warm
Cool
Warm
Cool
Warm
Cool
25°C
17°C
10°C
(a)



(b)

Fig. 1. Geological time scale showing (a) Global mean temperature curve (modified after http://www.scotese.com/climate.htm; https://stratigraphy.org/ICSchart/ChronostratChart2022-02.pdf) and (b) Precambrian time scale showing glacial and inter-glacial stages (after Godderis et al., 2020). Ma stands for a million years ago.

Concise History of Earth's Climate Through the Ages

The Earth's rock record has preserved several clues of the ancient climate, revealing that the Earth's climate has been unique throughout its history. Fossils, ice cores, sedimentary layers, paleosols, and sediments are primary geological materials that yield proxy data for paleoclimatic investigation. The analysis of the proxy data also shows that solar activity, tectonic plate movements, volcanic eruptions, weathering processes, and variations in greenhouse gases and temperatures frequently changed the Earth's climate in the past. Earth's former temperature was also influenced by changes in oceanic circulation patterns, periodic changes in Earth's orbit around the Sun, extra-terrestrial (meteorite) impacts, and biological evolution. It is widely documented that the Chicxulub meteorite impact at the Cretaceous-Palaeogene (66 million years ago) boundary caused severe global climate effects that led to the extinction of dinosaurs (land-ruling reptiles) and allowing mammals to diversify and expand in the whole Earth during the Cenozoic (Alvarez et al., 1980; Verma & Khosla, 2019). The eruptions of the Siberian and Deccan traps at the Permian-Triassic boundary and Cretaceous-Palaeogene boundary extensively contributed to global climate change in the Earth's history and the mass extinctions at these boundary intervals. A vast emission of CO_2 was released during the volcanic eruptions of the Siberian and Deccan traps, which significantly altered the global climate by increasing temperature. It should be emphasised that non-glacial (infra- and inter-glacial) and glacial periods are broadly used to identify the planet's past climate. Let us talk briefly about the Precambrian and Phanerozoic climates.

Climate during Precambrian Time

The Precambrian constitutes more than 88% of Earth's history, starting from its birth, dated ca. 4600 million years ago and lasting until 539 million years ago (Godderis et al., 2020). The Precambrian time is divided into one informal unit (Hadean) and two formal units: Archaean (4000 to 2500 million years ago) and Proterozoic (2500 to 539 million years ago) eons. The informal would encompass the first 600 million years of Earth's history and has no known rock record. According to U/Pb dating, the oldest rock on Earth is dated as 4 billion years old based on zircon crystals recovered from the Acasta gneisses (Slave Province), Canada (Godderis et al., 2020).

The climate on Earth was warm, and concentrations of greenhouse gases, including CO_2, methane, and water vapour, were very high during the

Precambrian times, ranging from 4600 to 541 million years ago. Methane levels were above 1000 ppm, while CO_2 concentrations were more than 18 times higher than they are now. In the early atmosphere, oxygen was not present. However, the formation of banded-iron deposits from 3000 to 1800 million years ago indicates that little oxygen was present in the oceanic environment. The Earth's temperature dropped after millions of years of planet formation, and the water vapour in the early atmosphere generated rain. As a result, the world was endowed with fundamental necessities, including soil, water, and air, for the beginning of life. Earth's early past differs significantly from its later periods. The crust was likely much warmer than it is now between 4600 and 3900 million years ago. Significant cosmic debris impacts may have destroyed early ecosystems by creating globally deadly conditions that also caused water loss due to evaporation during these occurrences. The Earth's surface may have warmed to 1200°C due to enormous amounts of heat being released during the development of the Earth's iron-rich core due to gravitational sinking.

The earliest life forms, including cyanobacteria, appeared on the Earth's surface some 3500 million years ago. These bacteria could produce their food by harnessing the sun's radiation as a source of energy and producing oxygen as a by-product of photosynthesis. Because of this, the atmosphere had enough oxygen roughly 600 million years ago, enabling the emergence of multicelled creatures. The Earth's Precambrian history has records of both the glacial and non-glacial periods (Fig. 1b). Evidence from sedimentary rocks left behind by glaciers indicates that the Earth was extremely cold, perhaps even close to the freezing point, during the Precambrian period (Ruddiman, 2018). The Proterozoic eon, ranging from 2500 to 539 million years ago, representing late Precambrian times, had a typically cold climate with widespread glaciations. The accumulation of oxygen in the Earth's atmosphere was one of the most significant Proterozoic events (Godderis et al., 2020). There have been four ice ages recorded in the Precambrian period: the first one occurred in the Archaean eon about 2500 million years ago, and three others occurred between 900 and 600 million years ago in the Proterozoic eon (Barry & Chorley, 2010).

Climate during Phanerozoic Time

The Phanerozoic eon began with an increase in temperature and humidity. Since then, there have been four cycles of glaciers and hot, tropical oceans on Earth. Some creatures adapt to climatic changes and survive. When the climate changes too much, other species become extinct. On a Phanerozoic scale, the overall pattern is one of high CO_2 (4000+ ppm) during the early Palaeozoic, a fall to present-day levels by the Pennsylvanian (ca. 320 million years ago), a rise to high values (1000-3000 ppm) throughout the Mesozoic, and finally, a decline to the present. The last 539 million years of Earth's existence, or about 12% of its history, are accounted for by the Phanerozoic times. During the Phanerozoic, the main events in the evolution of life included the fast diversification of multicellular organisms that first appeared in the Cambrian, the colonisation of continental surfaces by living organisms in the Ordovician, and the appearance of the first hominids around 8 million years before present (Godderis et al., 2020).

The CO_2 content varied substantially during the Phanerozoic eon, falling from 6000 ppm to its current levels. The carbon cycle significantly influenced the Phanerozoic climate, leading to variations in multicelled creatures and land plants (Beerling & Berner, 2005). During the Phanerozoic, it has been observed that the environment frequently fluctuated between icehouse (glacial and non-glacial) and greenhouse conditions (Fig. 1a), with temperatures being greatly influenced by natural processes involving the breaking and reunification of landmasses as well as meteorite impacts. A phenomenon known as mass extinction occurs when a significant number of species or groups of creatures on the surface of the globe suddenly and permanently vanish. The Phanerozoic life history suffered from five mass extinctions, including the End Ordovician, End Devonian, Permian/Triassic, End Triassic, and Cretaceous/Paleogene boundary. The widespread changes to the previous climate are directly responsible for these catastrophic extinctions. Three significant ice ages were known from the Ordovician, Carboniferous-Permian and Late Cenozoic times (Barry & Chorley, 2010).

Geological Proxies of Paleoclimate

Climate scientists can access data from a century ago to examine the modern climate. Can you believe this century-old data is enough to know the environment of the 4600-million-year-old Earth? Without a doubt, the answer is no. To reconstruct the Earth's past climate, Paleoclimatologists use proxy data preserved in geological material that yields information on the climate variability of the Earth's past. Earth has witnessed numerous short- and long-term climatic variations in its history, thus leaving a wealth of climatic proxies or natural archives recorded in the geological material. The most common categories of geological climatic archives include sedimentary lithologies, glacial features, fossils, ice cores, and cave deposits.

Sedimentary Lithologies

The sedimentary lithologies include sedimentary rock types. Sedimentary rocks are formed by the slow deposition processes of minerals and sediments at the surface of the Earth and within the water bodies. These rocks can be classified as terrigenous, organic, chemical, and volcanogenic; each is formed in a distinctive environment and, thus, yields significant paleoclimatic information. Many common climatically sensitive sedimentary rock types serve as geological climatic archives.

For example, sedimentary rocks such as sandstone, limestone or laterite give valuable paleoclimatic information. Sandstone is a classic rock formed in various environments. Sandstone formed by the lithification of desert dunes yields well-developed large-scale cross-bedding structures and provides valuable information about the desert and clastic direction. Highly mature sandstone lacking feldspars and containing glauconite indicates a warm and humid paleoclimate. Low mature sandstone with unstable weathering components indicates a cold and humid paleoclimate, and sandstone formed in an arid paleoclimate is typically enriched in feldspars (Shvanov, 1987; Maslov, 2003).

Limestone is a non-clastic (carbonate) rock and is a good indicator of an arid paleoclimate. Its coral-rich variety indicates a tropical ocean with warm water and paleotemperatures ranging from 21° to 29°C. Evaporates are non-clastic rocks consisting of rock salt (halite and gypsum) formed by evaporation of surface water and valuable indicators of polaroid to low latitudes having an arid paleoclimate. They are usually formed when evaporation rates go beyond the water supply and, thus, are considered the best indicators of a warmer temperature (Boggs, 2012). The sedimentary rocks containing coal deposits are typical indicators of a humid tropical climate.

Calcretes refer to the terrestrial accumulation of calcium carbonate that ranges from brown to red, rich in iron, aluminium, and manganese, and formed near the surface by evaporation of groundwater. Its presence indicates sparse rainfall, average temperature of 18°C and humid to semi-arid climatic conditions. The varves are lacustrine deposits yielding alternate layers of coarse and fine-grained sediments and are the best indicators of past climate. The coarse-grained sediments layer deposits when the sediment supply is high and fine-grained when the sediment supply is low (Fig. 0.2). Therefore, alternating coarse and fine-grained