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Climate Changes and Sustainability

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Abstract

Climate change is the phrase used to describe long-term changes in temperatures and weather patterns. Changes in the atmosphere and their interactions with diverse geologic, chemical, biological, and geographic variables are the main contributors to this cyclical adjustment of the Earth's climate. Such changes may be induced purposefully, because of burning fossil fuels, clearing forests, and raising animals, or they may be natural, brought on by significant volcanic eruptions or variations in the sun's activity. By significantly increasing the amount of greenhouse gases already in the atmosphere, this heightens the greenhouse effect and contributes to global warming. This work includes several additional theoretical and practical explanations of sustainable development. The theoretical work encompasses hundreds of researches that identify requirements for how development routes might satisfy sustainable development (SD) criteria using economic theory, complex systems approach, ecological science, and other techniques. The agreements made by the Parties in various nations across the world will consider a wide range of perspectives about what would be considered undesirable effects on the environment, the climate system, sustainability, economic growth, or food production.

Keywords

Earth System, Ancient Climatic Changes, Causes of Climatic Changes, Ecological Risk Assessment, Ecosystem, Abrupt Climate Change of Earth, Sustainability

1. Introduction

The atmosphere is fluid, dynamic and always moving. The physical properties of the body as well as several principles affect its speed and direction of movement, comprising the position and orientation of mountain ranges, ocean currents, chemistry of the atmosphere, solar radiation and vegetation covering the land's surface. All these fundamentals evolved throughout the epoch. Some elements change rapidly, including atmospheric chemistry, surface vegetation, and the way heat is distributed in the seas. Others, such as the positioning and altitude of mountain ranges, as well as the orientation of continents, change over extraordinarily long time periods. As a result, climate, which is dependent on the mobility and physical characteristics of the atmosphere, changes on every possible timeline [1].

Earlier, more significant changes to the planet's climate are included in a broader definition of climate change. Fossil fuel use by humans is the main cause of the present, quicker rise in the average world temperature. Fossil fuel consumption, deforestation, and other industrial and agricultural practices all help to produce greenhouse gases, including methane and CO_2 [2]. A fraction of the heat that the Earth produces after absorbing heat from the sun is captured by greenhouse gases. More of these gases trapping heat in the Earth's lower atmosphere cause global warming.

What makes climate change so crucial? The enormity of climate change's repercussions is unmatched. They include things like changed weather patterns that put the world's food supply in jeopardy and increasing sea levels that raise the possibility of catastrophic disaster. Future adaptation to these consequences will be more difficult and expensive if quick action is not taken today.

In the context of the integrated system of natural processes and characteristics identified as the Earth system, this text discusses the idea of climatic fluctuation and change. The types of climate change evidence are described, along with the main mechanisms that have influenced climate change over Earth's history [3]. Finally, a thorough explanation of climate change is provided over a variety of periods, from typical human life to all geologic time.

The assessment "**Climate Change 2007**: Alleviation of Climate Change" [4] aims to deliver precise, timely information on all socioeconomic policies and technological developments, including workable options to lower greenhouse gas (GHG) outputs. To assist talks on future global emissions reductions, a solid knowledge of future GHG outputs, their sources, potential alleviation techniques, costs, and benefits is crucial.

A two-edged sword is the criteria that have to do with allowing economic progress to occur sustainably. Sustainable development looks to be negatively impacted by projected anthropogenic climate change, and these negative consequences tend to get worse as climate change and GHG concentrations get greater. On the other hand, expensive mitigation efforts can have a negative impact on economic growth. The conundrum that policymakers must overcome is reflected in discussions about the extent of interferences and the correct balance to be struck between climate policy (adaptation and mitigation) and economic development. It is anticipated that the levels and rates of climate change that would place economic growth, food production, ecosystems, or in enough danger to be classified as dangerous will be determined by the evaluation of repercussions, vulnerabilities, and adaptive potentials. The most vulnerable people to damage because of human climate change are frequently those with the least economic and political standing [5]. It is a difficult effort that can only be partially supported by science to define what constitutes harmful interference with the climate system since such definitions always require normative assessments.

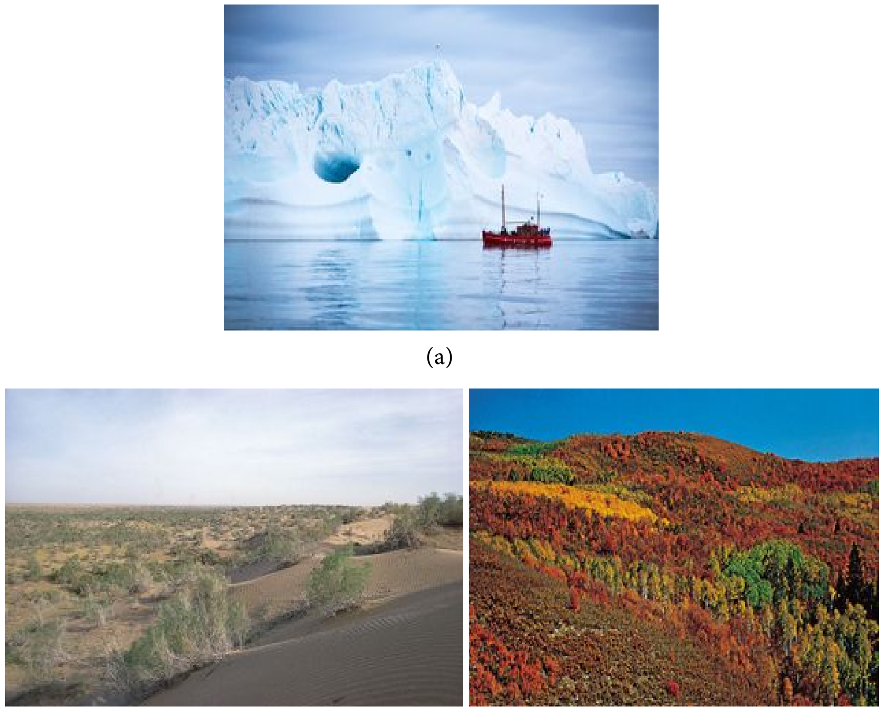
A synthesis of these many viewpoints will be included in the agreements reached between the Parties about what would constitute unacceptable effects on the ecosystems, climate system, sustainability, economic growth, or food production.

2. The System of Earth

The atmosphere is affected and interconnected by land surfaces, vegetation, the seas, and ice masses. They combine to form an interconnected Earth system, in which every element engages in frequent complicated interactions with and influences one another. For instance, climate influences how vegetation is spread across the surface of the Earth (forests are found in humid regions, whereas deserts are found in arid regions) (**Figures 1(a)-(c)**). In addition to modifying the horizontal air flow across the land surface, vegetation also reflects solar energy back into the atmosphere, moves water (and latent heat) from the soil to the atmosphere, and does several other things that have an impact on climate.

The intricate interactions and feedback involving the many parts of the Earth system are still a mystery to Earth and atmospheric scientists. The emergence of the multidisciplinary field known as Earth system science is aiding this endeavor. Earth system science encompasses many different fields, such as ecology (the investigation of the interactions between living organisms and their surroundings), geology (the investigation of earth's surface and subsurface processes), climatology (the study of the atmosphere), glaciology (examining the ice masses on Earth), oceanography (the study of Earth's oceans), and beside the Sociological study (the study of human behavior in its cultural and social features).

To have a thorough grasp of the planet, one must comprehend the evolution of the Earth system and each of its component sections. The pursuit of this information has given rise to the multidisciplinary area of study known as Earth system history, which draws on the research of paleoclimatologists, paleontologists, paleoceanographers, paleoecologists, and other planetary historians. This history is a big and intricate science because various parts of the Earth system evolve at diverse speeds and are significant at altered times. In the past, significant features of the Earth system, such as solar radiation, continental configurations, atmospheric chemistry, ocean currents, and others, have been transformed, according to researchers studying the history of the Earth system. These researchers aren't only interested in recording what has already occurred. Learning about the relative impacts and interactions of different Earth system components is made possible by these investigations. Studies on the past of the Earth system also detail the whole range of phases the system has gone through and those it may encounter in the future.



(a)

(b) (c)

Figure 1. (a) (b) (c) Climate influences how vegetation is spread across the surface of the Earth. (a) Iceberg; (b) Karakum Desert, Turkmenistan; (c) Deciduous trees.

There is no doubt that, within the relatively short timescales of years, decades, and seasons, humans have always been aware of climate change. Droughts, floods, extreme cold spells, and other climatic phenomena are mentioned in the Bible and other ancient writings. However, it wasn't until the early 19th century, when the deep antiquity of Earth was widely acknowledged, that a thorough understanding of nature and the scope of climatic variation evolved. The naturalists of this era, including the Swiss-born naturalist, the English naturalist Charles Darwin, the geologist Louis Agassiz, the Scottish geologist Charles Lyell, the Welsh naturalist Alfred Russel Wallace and the American botanist Asa Grey, learned to recognize biogeographic and geologic indication that could only be explained in the context of past climates that were radically different from the ones that prevail today. In the early 20th century, paleontologists and geologists uncovered proof of large temperature changes happening before the Pleistocene. Despite fossilized coral reefs and coal-swamp plants indicating that tropical climates formerly existed at modern-day high latitudes in both North America and Europe, red beds in now-moist places (such as New England and England) suggested aridity. Since the late 20th century, when cutting-edge methods for dating rocks were developed and combined with geochemical processes and other analytical tools, our understanding of the early Earth system's history has undergone a significant transformation [6].

At the end of 19th century, scientists had started to understand that high-latitude continental glaciers had repeatedly invaded eastern North America and northern

Europe. According to James Croll (Scottish geologist), the Earth's orbit deviates from being fully circular on a regular basis, and this causes the alternating glacial and interglacial ages. Milutin Milankovitch (a Serbian mathematician and astronomer) accepted Croll's divisive theory in the beginning of 20th century. Axial tilt (an adjustment of the Earth's axis' inclination regarding the plane of its orbit around the Sun) and Precession (an alteration in the axis of rotation of the Earth) were also factors, according to Milankovitch, in the mechanism that caused periods of glaciation. It is commonly documented that during Earth's history, orbital oscillation has significantly contributed to climate change [1].

3. Climate Changes across Geologic Times

Over the course of its 4.5-billion-year existence, the Earth system has seen significant changes. These have included several types of climate changes with various processes, intensities, rates, and effects. Many of these historical developments are difficult to understand and contentious, and some have only lately come to light. These modifications have had a tremendous influence on the history of life, some of which fundamentally changed how development proceeded. Since respiration and photosynthesis have significantly altered Earth's atmosphere's chemistry, sediments, and seas, life itself is a causal component in some of these changes [7].

3.1. Cenozoic Climates

The Cenozoic Era has seen a wide spectrum of climate change since the massive extinction that signaled the end of the Cretaceous Period (66 million years ago), with episodes of global cooling and warming happening alternately [8]. During this time, Earth has experienced both extremes of heat and cold. The continents' locations and altitudes, as well as the ocean's channels and bathymetry, have all changed because of tectonic processes. Feedback between the biosphere, atmosphere, cryosphere, lithosphere, and seas in the hydrosphere—all parts of the Earth system—are becoming more and more understood as factors in regional and global climate. Particularly, atmospheric CO_2 concentrations have changed significantly during the Cenozoic for unknown causes; yet this variation must have entailed feedback between the spheres of the Earth [9].

The orbital force is still in operation throughout the Cenozoic, even though when observed over such a long timescale, orbital variations may be perceived as oscillations against a constantly shifting background of lower-frequency climatic trends. The explanations of orbital oscillations have changed as our knowledge of tectonic and biogeochemical processes has increased.

Climate change, which persisted until the early Cenozoic, was present at the time of the meteor impact that happened at the finale of the Cretaceous interval or very near to it. According to the geochemical records of marine sediments, subtropical and tropical fauna and flora were present at high latitudes until at least 40 million years ago, and warm ocean temperatures are predicted. The temperature peaked during the late Paleocene and early Eocene periods between 59.2 and 41.2 million years ago. Approximately 100,000 years ago, there was a brief period known as the Paleocene-Eocene Thermal Maximum (PETM) that saw the Cenozoic's greatest global temperatures. The PETM began abruptly, within a few thousand years, some 56 million years ago. The ecological repercussions were severe, with widespread extinctions in both terrestrial and marine ecosystems, even if the underlying causes are unclear. Sea surface and continental air temperatures increased by more than 5˚C as the PETM began. High-latitude Arctic Ocean surface temperatures may have reached 23˚C, which is equivalent to modern subtropical and warm-temperate waters. After the PETM, the earth's temperature dropped to pre-PETM levels, but over the next few million years, during the Eocene Optimum, it gradually increased to levels that were almost pre-PETM. Around 33.9 million years ago, the Eocene-Oligocene boundary signaled the start of a trend of steady cooling from this temperature high [10]. Paleontological specimens and marine sediments from the continents where plant zones moved equatorward provide excellent records of these migrations. Tectonic motions undoubtedly had a substantial role in the cooling trend, even though the causes are still under investigation. When the marine route between Tasmania and Antarctica eventually became viable, the Drake Passage between Antarctica and South America opened.

A continental ice sheet developed in Antarctica during the Oligocene Epoch and remained there until a significant warming event 27 million years ago [11]. The late Oligocene and early to mid-Miocene epochs (28.4 to 13.8 million years ago) were warm, albeit not as warm as the Eocene [12]. The Antarctic Ice Sheet once again expanded once cooling picked up 15 million years ago, regaining much of the continent. The cooling trend maintained through the late Miocene and into the early Pliocene Epoch 3 million years ago. When the Northern Hemisphere was free of ice during this period, cool-temperate Pliocene flora was found at high latitudes in Greenland and the Arctic Archipelago. The Northern Hemisphere glaciation, which began 3.2 million years ago, was caused by two tectonic events: the closure of the Panama Seaway and the elevation of the Tibetan Plateau, the Andes, and western portions of North America. High northern latitudes benefited from prolonged ice formation due to these tectonic shifts in ocean and atmospheric circulation. This glacier is believed to have formed in the mid-Oligocene, when CO_2 levels were at their lowest [8].

3.2. Phanerozoic Climates

The Phanerozoic Aeon, which spans the whole time complex, has seen a remarkable variety of environmental conditions and changes. Many of these regimes and events are quite old, making it challenging to fully comprehend them. However, because of accurate geological recordings and extensive investigation by researchers, a few eras and transitions are widely documented. Cool ("icehouse") and Warm ("greenhouse") phases of the Earth system alternate, and a cyclical pattern of low-frequency climate change is also evolving. High sea levels, a lack of continental glaciers, and High temperatures, are characteristics of the warm times. The presence of continental ice sheets, low sea levels, and Low temperatures, at least at high latitudes, are signs of cool periods. Higher-frequency oscillations are superimposed on these alternations, with warm intervals inside icehouse phases and cool intervals included within greenhouse phases. For example, glaciers formed for a brief time (between 1 and 10 million years) during the early Silurian and late Ordovician, in the middle of the early Paleozoic greenhouse era. Throughout the early Miocene and late Oligocene epochs of the late Cenozoic cold age, there were warm intervals with glacial retreat [11].

The Earth system has been in an icehouse phase since the creation of the Antarctic ice sheets 30 to 35 million years ago. In the Carboniferous and Permian ages of the late Paleozoic Era, a large icehouse event occurred between 359 million and 252 million years ago. Glacial deposits from this epoch have been discovered throughout much of Africa, South America, the Arabian Peninsula, India, Antarctica, and Australia. All these areas were formerly a component of the Southern Hemisphere's high-latitude supercontinent known as Gondwana. Like the latitude that the Pleistocene ice sheets of the Northern Hemisphere reached, the glaciers on top of Gondwana stretched to at least 45˚S. Even farther equatorial—to 35˚S—were some late Paleozoic glaciers. Cyclothems, which are sedimentary strata that repeat and alternate between sandstone, coal, shale, and limestone, are among the most prominent characteristics of this period. These cyclothems may be caused by the repeated retreats (generating coals and shales) and incursions (creating limestone) of ocean shorelines in response to orbital changes. In these cyclothems are interbedded the vast coal reserves of the Appalachian area of North America, northern Europe, and the American Midwest [13].

The two most prominent warm periods in Earth history were between 252 and 35 million years ago during the Mesozoic and early Cenozoic eras and between 500 and 359 million years ago during the early and mid-Paleozoic eras. The Paleozoic warm age included many greenhouse periods, each with distinct climates, continent placements, and ocean bathymetry. The emergence of terrestrial flora on the continents did not occur until quite late in this time. Both time periods saw significant long-term climatic change and fluctuation; mounting evidence points to a few short glacial occurrences in the middle Mesozoic [14].

An essential field of research is integrating geologic data with models of the Earth system and its constituent parts to understand the mechanisms underpinning icehouse-greenhouse cycles. Phanerozoic climate change has been attributed to two mechanisms. First, tectonic processes altered the bathymetry of the oceans and seas as well as the placements and heights of continents. Second, even though tectonic processes over such long periods of time generally regulated fluctuations in greenhouse gas concentrations, these variations were significant climate drivers.

3.3. Pre-Phanerozoic (Precambrian) Time

Precambrian time, often referred to as pre-Phanerozoic time, has lasted from the Earth's creation for around 88% of that period. Mystery surrounds the pre-Phanerozoic period of Earth system history. Numerous studies are conducted on the pre-Phanerozoic Earth System because it is crucial to understand the beginnings and early development of life on Earth [15]. Additionally, due to the impact of living things at this time, major changes in the chemical composition of the Earth's atmosphere and seas occurred. The study of this era is highly valued by palaeontologists, planetary geologists, geologists, geochemists, microbiologists, and atmospheric scientists. Three subjects that have generated a lot of attention and debate include the "young Sun paradox that is dim," the impact of life on the atmosphere, and the theory that Earth had one or more "snowball" events of global glaciation [16].

3.4. Photosynthesis and Atmospheric Chemistry

The discovery of a novel photosynthetic pathway by cyanobacteria that utilizes water (H_2O) rather than hydrogen sulfide (H_2S) as a reducing agent for CO_2 has had a substantial influence on the geochemistry of the Earth system [17]. In contrast to the less developed H_2S system, the water route produces molecular oxygen (O_2) as a byproduct of photosynthesis, which is more energy efficient. 90% of today's iron ores come from banded-iron formations, or BIFs, which were widely deposited due to the usage of water as a reducing agent in this process. Iron that was dissolved in the ancient seas' oxygen-rich environment was oxidized, precipitating onto the ocean floor. Most of the iron that was dissolved in the oceans was precipitated after millions of years of this oxygen-demanding deposition process. O_2 was able to bond as a dissolved gas in seawater some 2 billion years ago, and eventually escape to the atmosphere [3]. Even if oxygen doesn't fit the definition of a greenhouse gas, it nonetheless has a substantial indirect impact on climate, especially at certain points in the carbon cycle.

3.5. Theorem of the Snowball Earth

Geochemical and sedimentary evidence suggests that Earth experienced up to four large cooling events between 750 million and 580 million years ago. According to geologists, during these occurrences, ice blanketed Earth's oceans and land areas from the poles to the equator. There has been a great deal of research and debate surrounding the "Snowball Earth" theory [18]. This proposition raises two crucial queries. First, how might Earth defrost after becoming frozen? Second, how did life endure times when the entire planet was frozen? Since the planet's primary CO_2 basins (photosynthesis and rock weathering) would have been muted by a freezing Earth, one explanation for the first point is that enormous amounts of CO_2 were released by volcanoes, dramatically warming the planet's surface. The persistence of modern life-forms in deep-sea vents and hot springs, which would have persisted long ago although Earth's surface being frozen, might provide a solution to the second issue [19].

3.6. The Methane Burp Theory

In oceanography and climatology, the Paleocene-Eocene Thermal Maximum (PETM), also known as the gas hydrate dissociation theory, began abruptly 55 million years ago and was marked by the highest global temperatures of the Cenozoic Era (65 million years ago to the present) [20] [21]. According to the idea, the PETM happened when enormous methane hydrate deposits in ocean sediments warmed to the point where substantial volumes of methane were cycled through the ocean and atmosphere. CH_4 was oxidized, producing CO_2. The rise in CO_2 concentration caused an increase in air temperature, which may be like global warming currently seen in the 21st century [22].

The large-scale submarine landslides discovered off the coast of Florida have significantly supported the notion, even though many more comparable landslides would have required to have place for there to be enough methane to generate the PETM.

Chemical reactions were widely used in industrial processes during the 19th century in metallurgy, agriculture, textiles, and many other fields. This led to the development of chemical engineering. An industry dedicated to the mass manufacture of chemicals had been established by 1880 because of the usage of chemicals in manufacturing. The chemical engineer now oversees the construction and maintenance of these industries' plants.

3.7. Unexpected Climatic Changes in Earth History

Since the 1980s, there has been a significant rise in the amount of research on abrupt climate change. This research was prompted by the finding of evidence for earlier substantial fluctuations in global and regional temperatures in the ice core archives of Antarctica and Greenland. From a scientific perspective, these occurrences, which involve abrupt changes in the Earth's climate system's equilibrium state, and which have also been noted in ocean and continental records, are extremely important because they could reveal the mechanisms governing and the sensibility of the climate system. They highlight discontinuities, which happen when little, slow changes to one part of the system can have a significant influence on the entire. These interactions between the many components of the Earth system produce these discontinuities. For instance, the Younger Dryas event caused the sudden cessation of thermohaline circulation in the Atlantic basin due to an increased freshwater input into the North Atlantic Ocean [23]. A major source of worry for society is the possibility of sudden climate change to be so rapid and severe that it would be impossible for the ecological, industrial, economic, and agricultural systems to adapt and cope [24].

The instance of sudden climatic change that has been studied the most is the Younger Dryas period (12,900 - 11,600 years ago). The incident took place when the Earth system transitioned from a glacial to an interglacial state during the most recent deglaciation, a period of increased global warming. Eastern North America and Northern Europe are likely to have dropped by 4˚C to 8˚C during the Younger Dryas, when temperatures in the North Atlantic area plunged substantially. Evidence from the land and the sea suggests that the Younger Dryas had substantial effects in many other parts of the Earth, albeit to a smaller extent. The Younger Dryas ended within a decade, and it did so very swiftly. The thermohaline circulation in the North Atlantic, which currently includes the Gulf Stream, which is crucial for transferring heat from equatorial regions northward, mysteriously stopped functioning during the Younger Dryas. There were certainly other causes at play as well, but the thermohaline circulation shutdown has been linked to a significant freshwater influx from melting glaciers into the North Atlantic [25].

Paleoclimatologists are paying more and more attention to locating and researching more abrupt shifts. It is now understood that the Dansgaard-Oeschger series from the preceding glacial age represents an oscillation between two climate regimes with quick changes [26]. A 200-year cold period occurred in the Northern Hemisphere around 8200 years ago because of the rapid draining of glacial Lake Agassiz into the North Atlantic through the Great and the St. Lawrence Lakes drainage. A dramatic drop in hemlock populations in New England woods was one of the ecological effects of this phenomenon, which has been called a smaller version of the Younger Dryas. 5200 years ago, lakes and bogs in eastern North America saw a sharp decline in water levels, pointing to a previous comparable shift. In temperate regions, it has been found in peatland, tree-ring, and lake-level samples as well as ice cores from tropical glaciers at elevated altitudes [27].

There is proof that dramatic climatic changes occurred before the Pleistocene. A brief temperature maximum has been noted around the Paleocene-Eocene boundary (56 million years ago), while evidence of rapid cooling episodes has been discovered close to the Oligocene and Miocene (33.9 million years ago) and Oligocene and Eocene (23 million years ago) epoch borders. Global climatic, ecological, and biogeochemical effects result from all three of these occurrences. Geochemical studies show that the huge increase in atmospheric CO_2 levels during the warm event at the Paleocene-Eocene boundary was caused by the enormous outgassing and oxidation of methane hydrates from the ocean floor. Methane is trapped by the chemical structure of a substance known as methane hydrates within an ice lattice. Like the Pleistocene, a brief period of positive feedback between the seas, ice sheets, atmosphere, and biosphere appear to have caused the two cooling episodes.

In the past, humans and other animals have endured a great number of climate shifts, demonstrating how adaptive people are. When climate changes are gradual and largely predictable, adaptation is simplest and least destructive, whether it is biological (as in the case of other animals) or ethnic (for human beings) [7]. Rapid changes are more disruptive, risky, and harder to adjust to. Acute changes, especially unanticipated climatic surprises, cause a sever hazard to the ecosystems and the populations of other species. Humanity may be able to adapt to these changes, but only at great cost in terms of disruptions to the economy, the environment, agriculture, human health, and other aspects of life. The sensitivity and natural variability of the Earth system may be understood by considering past climate change. This information also highlights the risks associated with altering the Earth's system through greenhouse gas emissions and changes to local and global land cover.

4. Climate Change Brought by Humans

Climate change and variation have played a significant role throughout human history, from its first manifestation around two million years ago to the emergence and spread of the present human being initiating 150,000 years ago [28]. Even though there have been almost two full cycles of glaciation and interglacial activity for the contemporary human species, their rapid population growth, cultural diversity, and ecological dominance only began during the most recent glacial-interglacial transition and intensified throughout the furthermost recent glacial-interglacial time. In contrast to Homo erectus, an extinct species that may have been the ancestor of modern humans, which emerged during a colder period in the Pleistocene Epoch and survived both the transitional era and numerous glacial-interglacial cycles, the emergence of the first bipedal apes took place during a time of climate transition and change. Therefore, it is possible to assert that the development of mankind and all its many cultures and civilizations is directly related to climatic change [29].

4.1. The Most Recent Glacial Epoch and Its Interglacial Predecessor

Earth was in an interglacial phase 125,000 years ago, like the one we are in today, with glacial ice isolated to elevated altitudes and latitudes. The system of Earth did, however, experience a full glacial-interglacial cycle over the previous 125,000 years, just one of numerous events that took place during the last million years. About 120,000 years ago, the most recent cooling and ice era started. Large ice sheets formed and remained across most of northern Eurasia and Canada [30].

The Earth's system cycled between two phases after the advent of glacial conditions: one with growing glaciers and extremely low temperatures, and another with temperatures that were somewhat warmer but still much below those of today. These Dansgaard-Oeschger (DO) cycles took place around every 1500 years, as shown by records found in ice cores and marine sediments. A lower-frequency cycle known as the Bond cycle, which happens every 1400 - 2200 years, is superimposed over the DO cycle pattern [31]. Every Heinrich event is distinguished by a short cold and dry phase that is followed by a short warming phase. Each Heinrich event during the cold phase of a (DO) cycle is characterized by abnormally low temperatures [32]. Huge iceberg fleets were discharged into the North Atlantic during each Heinrich episode, carrying boulders that the glaciers had collected far out to sea. Rock shards delivered by icebergs provide obvious strata in marine sediments that identify Heinrich episodes [33].

Paleoclimatologists and Earth system scientists are closely studying the quick and abrupt shifts that occurred during the DO and Bond cycles to better understand the underlying causes of such extreme climate swings. These cycles currently seem to be the result of interactions between the oceans, continental rivers, ice sheets, and atmosphere that alter thermohaline rotation, the pattern of ocean currents that is primarily influenced by changes in water salinity, temperature, and density rather than airstreams.

4.2. The Most Recent Glacial Maximum (LGM)

Over the last 25,000 years, there have been several dramatic changes to the Earth system. Informally referred to as the most recent glacial era, the Most Recent Glacial Maximum (LGM) peaked 21,500 years ago. The Scandinavian Ice Sheet in Europe spanned Scandinavia, the British Isles, north-central Siberia, and northern Europe. The Cordilleran Ice Sheet encompassed much of western Canada, as well as northern Montana, Idaho, Washington, and in the United States. The Laurentide Ice Sheet dominated the northern section of North America at the time, and it extended as far south as Ohio, Cincinnati, Des Moines, Iowa, and New York City. There are several montane glaciers in other areas, even at low latitudes in South America and Africa. Global sea level was 125 meters lower than it is presently because of the long-term net transfer of water from the oceans to the ice sheets [34]. In unglaciated areas, the temperature was around 5˚C lower than it is now. Numerous plant and animal species from the Northern Hemisphere once lived in regions far further south than their current series. One thousand kilometers south of their current distribution limitations in the Great Lakes area of North America, for instance, white spruce and jack pine trees have been seen thriving in northern Georgia [35].

4.3. The Last Deglaciation

About 20,000 years ago, the continental ice sheets initially began to melt. Submerged fossil coral reefs may be drilled into and date to clearly show how the sea level rose when the glacier receded. In the past 15,000 years ago, the melting has been the fastest. For instance, by 10,000 years ago the southern border of the Laurentide Ice Sheet in North America was located north of the St. Lawrence and the Great Lakes regions, and by 6000 years ago it had completely disappeared [36].

The Younger Dryas climatic interval, which occurred between 12,900 and

11,600 years ago, was the most notable brief cold episode that interrupted the rising trend [23]. There are no present locations where the seasonal patterns of warmth and wetness that persisted through the deglaciation epoch in numerous areas, including much of Northern America, do. For instance, temperatures were far more continental in the center of North America than they are now (depicted by hot summers and harsh winters). Paleontological research also reveals assemblages of species of plants, insects, and vertebrates that do not exist anywhere today. Boreal and temperate zone species coincided in Russia and central North America throughout this deglaciation despite their current distance from one another. The most likely causes of these unique climatic circumstances are the long-lasting ice sheets in the Northern Hemisphere, which changed air circulation patterns, and the peculiar orbital pattern, which enhanced summer insolation and lowered winter insolation there.

4.4. Agriculture Development and Climate Change

In western Asia, between 11,000 and 9500 years ago, goats and sheep were first herded, while the first domesticated plants including barley, lentils, wheat, and rye were cultivated around 9000 years ago. This stage of technical development took place after the last glacial era, when the climate was transitioning. According to some experts, although the fast swings in resource availability caused by climate change put pressure on hunter-gatherer-forager communities, it also created opportunity since new plant and animal resources began to emerge [37] [38].

4.5. Pleistocene Glacial and Interglacial Cycles

In the previous 450,000 years, there have only been five glacial periods, with the most recent reaching its peak 21,500 years ago. The cyclical alternation of the Earth system's glacial and interglacial regimes during the Pleistocene era, which lasted for more than two million years, is what defines it. Throughout this period, there were longer and more severe glacial episodes, with a particularly quick transition occurring between 600,000 and 900,000 years ago. The Holocene Epoch, which began 11,700 years ago and is still in effect now, is the most recent interglacial era on Earth [11].

However, estimations of the breadth and length of the distinct interglacial and glacial times are most accurately provided by oxygen isotopes found in ocean sediments. Landforms and Glacial deposits are evidence of the Pleistocene continental glaciations on the environment. These statistics provide both an indirect measurement of the amount of global ice and a direct measurement of sea level. The lighter oxygen isotope ^{16}O causes water molecules to evaporate more quickly than the heavier oxygen isotope ^{18}O. When paired with ^{16}O, high ^{18}O concentrations throughout glacial epochs suggest a net movement of water from the oceans to the ice sheets. Several intermediate glacial states, which were colder than interglacials but warmer than glacial maxima, existed for around 80% of the past 500,000 years. Significant glaciers were present throughout most of Canada and likely even blanketed Scandinavia during these interglacial periods. These transitional states fluctuated in climate on a millennium-scale, and they were not stable. The Earth system cycled between interglacial and glacial phases throughout the Pleistocene and Holocene, with neither an average nor normal state for the climate [39] (**Figure 2**).

In the end, changes in the Earth's orbit have produced the system's cycle between the glacial and interglacial regimes. Since orbital force alone cannot explain all this variance, Earth system scientists are focusing their attention on the interactions and feedback between the many components of the Earth system. A continental ice sheet's early formation, for instance, raises the albedo in a certain area of the Earth, which reduces the amount of sunlight that is absorbed by the surface and causes additional cooling. Similar changes in albedo and latent heat transmission through evapotranspiration result in changes in terrestrial vegetation, such as the transformation of forests into tundra. Because of their enormous leaf area, forests, especially those in temperate and tropical climates, transpire large amounts of water vapor and latent heat. Much smaller tundra plants with tiny leaves that only generate a tiny fraction of the water vapor that forests do assist to avoid water loss.

The discovery in ice core records that atmospheric concentrations of two potent greenhouse gases, CO_2 and CH_4, increased during interglacials and decreased during previous glacial eras serves as an important example of feedback mechanisms in the Earth system [40]. The cooling that is now taking place during the transition to a glacial phase would be hastened and made worse if greenhouse gas concentrations were to fall. When a glacial period ends, the opposite happens. There is still a lot of study being done on the glacial carbon sink. Understanding the intricate relationships between the circulation and chemistry of the oceans, the ecology of terrestrial and marine organisms, the chemistry and circulation of the atmosphere and the dynamics of ice sheets, is necessary to comprehend glacial-interglacial carbon cycles [41].

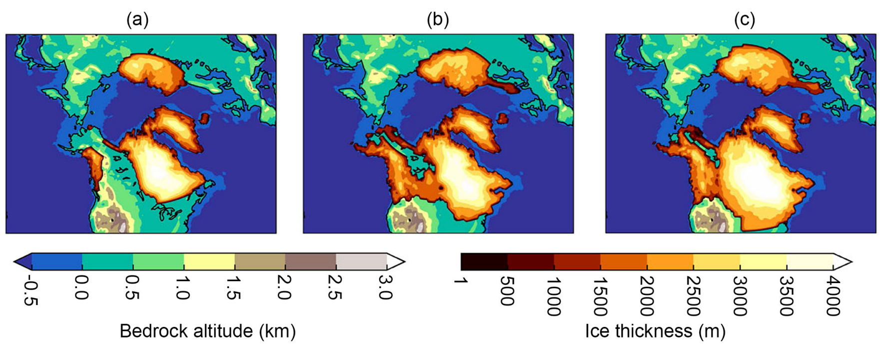


Figure 2. Simulated North American ice sheet distribution. Simulated North American ice sheet distribution for each glacial maximum, (a): A typical glacial maximum; (b): A large glacial maximum under a constant CO_2 (230 ppm); (c) Last glacial maximum with realistic variations in atmospheric CO_2 [39].

4.6. The Last Great Cooling

A general cooling trend in the Earth system over the past 50 million years resulted in the formation of persistent ice sheets in the Northern Hemisphere roughly 2.75 million years ago. The global temperature steadily decreased as the ice sheets waxed and waned, causing more severe glaciations and colder interglacial periods. The frequency of the glacial-interglacial cycles changed beginning 900,000 years ago. Since that time, the Earth system has seen more cold periods than usual, and the glacial maximum has been spaced by 100,000 years. The 100,000-year cycle is obscured by smaller oscillations, whereas the 41,000-year periodicity has remained [36].

The two components of the Earth's orbital geometry that ultimately drive the 23,000-year and 41,000-year cycles, respectively, are the equinoctial precession and the axial-tilt cycles [42]. The eccentricity, the third element that determines how the Earth orbits the sun, fluctuates on a 100,000-year cycle. The origin of the periodicity visible in the Earth's eccentricity is of enormous relevance in contemporary paleoclimate study.

5. Evidence for Climate Change

All historical disciplines have the same issue: as they delve further into the past, they become increasingly dependent on sporadic and circumstantial evidence. The past of the Earth system is no different. For the most part, there are excellent instrumental records from the last century, but the 19th century saw a decline in the number of records. Court and church records, diaries, Ship logs, tax registers, and other historical sources can also be utilized. These sources can include details on droughts, sea ice, frosts, the timing of floods, monsoons, and other meteorological characteristics in strictly geographic settings [43].

By coincidence, the natural world shows several signals of climate change. Climate has an influence on the quantity and geographic distribution of animal and plant species, the chemistry of the lakes and seas, the development of ice in frozen provinces, and the deposition and erosion of materials. Coral and tree growth are both impacted by climate.

The state of the climate is being monitored by networks of sensors in space, on the surface of the Earth, and below and above the ocean's surface. Instrumental recordings and other archives provide evidence of the climatic changes that have occurred during the last two - three hundred years, particularly since the early 1900s. Researchers who are interested in climatic changes prior to the observational record are using natural archives—biologic or geologic processes that retain some aspect of past climate—more often. These incredibly varied natural archives include sedimentary and geochemical markers of former ocean and continental conditions, land surface features indicating previous climates, fossil records of ancient animal and plant dispersals, and fossil archives of continental conditions and past ocean.

6. Causes of Climate Change

Documenting instances of climatic variability and historical climate change is far simpler than figuring out the fundamental causes of these phenomena. Numerous variables that work across timeframes extending from hours to millions of years have an impact on the climate. The Earth system is only one of several external elements that affect climate change. Others are present inside the system of the Earth, but they are not enveloped by the atmosphere. The interactions between the atmosphere and other planetary system components are among those that are referred to as feedback within the Earth system. However, it is becoming more widely acknowledged that these elements contribute significantly to climate variance.

6.1. Greenhouse Gases

The greenhouse effect may result from greenhouse gas molecules absorbing infrared radiation (net heat energy) released from the Earth's surface and reflecting it back to the surface. The energy balance of the Earth system is significantly impacted by the three most important greenhouse gases, water vapor, CO_2, and CH_4, despite their relatively tiny proportion in the total amount of atmospheric gases (**Figure 3**). Across the course of Earth's history, greenhouse gas concentrations have fluctuated greatly, and these fluctuations have resulted in significant climatic shifts across a variety of periods.

6.2. Solar Changeability

The Sun's luminosity, or brightness, has been steadily increasing since its formation. Since the Sun supplies the energy required for air circulation and serves as an input for the Earth's heat budget, this phenomenon influences the planet's temperature (**Figure 4**). The dim young Sun paradox is caused by low solar illumination during Precambrian period [44].

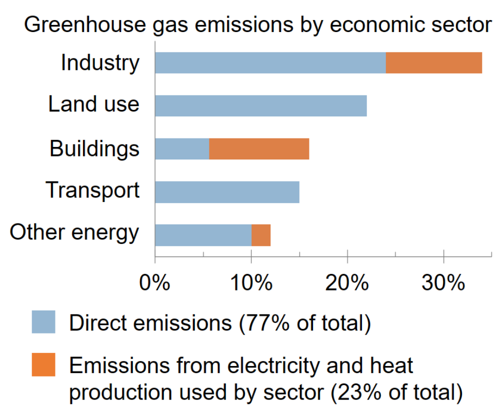


Figure 3. Industry accounts for the largest portion of world emissions when both direct and indirect emissions are considered. Information from the IPCC as of 2007.

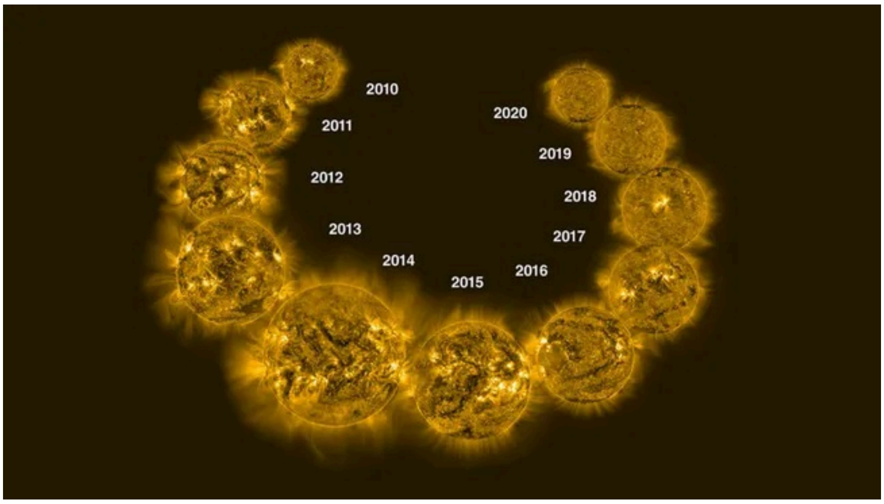


Figure 4. The telescope on board Europe's PROBA2 spacecraft observed the solar cycle between 2010 and 2020. (Image credit: NOAA/JPL-Caltech/NOAA/Dan Seaton/European Space Agency). 2022-Daisy Dobrijevic.

The Sun's energy fluctuates over relatively short durations due to solar storms and other disturbances, but fluctuations in solar activity, particularly the frequency of sunspots, have also been seen over decadal to millennial timelines and are anticipated to occur over longer timescales as well.

6.3. Volcanic Activity

At various timescales, volcanic activity can have a variety of effects on the climate. Large amounts of SO_2 and other aerosols can be released during a single volcanic eruption, which reduces the transparency of the atmosphere and, therefore, the quantity of solar energy that reaches the troposphere and the Earth's surface (**Figure 5**). Observable effects on the circulation and heat budgets of the atmosphere were caused by the 1991 eruption of Mount Pinatubo in the Philippines as a recent example [45]. Because the next year (1816), known as "the year without a summer," witnessed unusually frigid spring and summer temperatures throughout most of the world, the Mount Tambora eruption on the island of Sumbawa in 1815 had more substantial repercussions.

CO_2 is released into the atmosphere and seas by volcanoes and other associated processes including ocean rifting and subduction. However, the production of this greenhouse gas can have significant consequences across geologic timeframes. Variations in the CO_2 emitted by volcanoes and ocean rifts over millions of years can alter the chemistry of the atmosphere.

6.4. Tectonic Activity

During intervals of one to tens of millions of years, tectonic movements of the Earth's crust have had a substantial influence on the climate (**Figure 6**). These processes have changed the ocean's bathymetry as well as the shape, position, size, and height of the continental masses. Changes in topography and bathymetry have also had a significant impact on how the atmosphere and oceans circulate. For instance, the Cenozoic Era's elevation of the Tibetan Plateau, which also had an influence on air circulation patterns, the climate of much of the rest of Asia, and surrounding areas, led to the formation of the South Asian monsoon [46].

Tectonic activity also has an impact on CO_2 concentrations and the chemistry of the atmosphere. Vents and volcanoes produce CO_2 in subduction and rift zones. Throughout Earth's history, variations in the pace of rift zone expansion and the level of volcanic activity near plate borders have affected atmospheric CO_2 concentrations. Even rock weathering caused by chemicals is a large CO_2 sink. "Carbon sinks" are any processes that chemically transform CO_2 into organic or inorganic carbon molecules to remove carbon dioxide from the environment. CO_2 and water combine to form carbonic acid, a reactant in the dissolution of silicates and other minerals. The bulk, height, and exposure of bedrock affect weathering rates. All these characteristics may increase due to tectonic elevation, which would result in more weathering and CO_2 absorption. For instance, the atmospheric CO_2 level may have been significantly reduced because of the increasing Tibetan Plateau being chemically weathered during a time of global cold in the late Cenozoic Era [46].

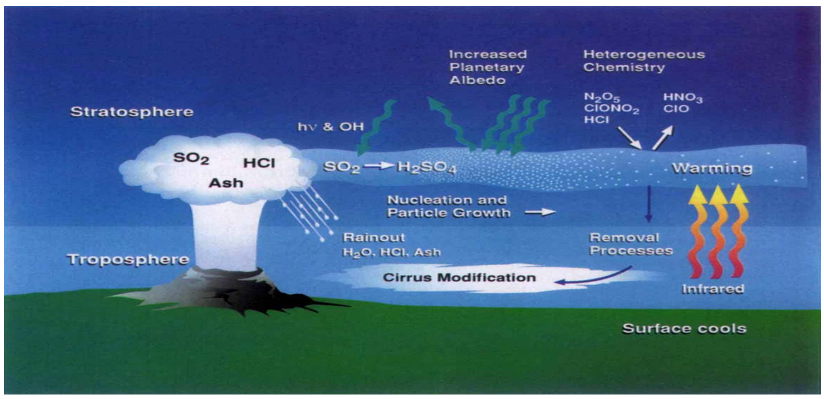


Figure 5. According to McCormick *et al.*, [45].

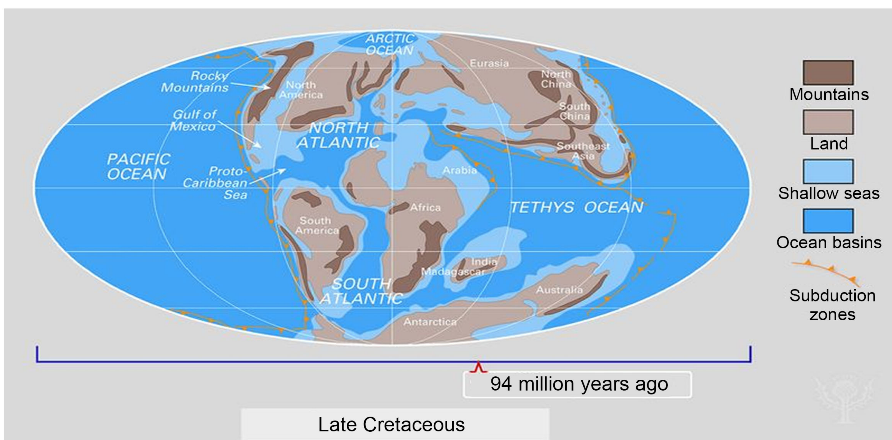


Figure 6. From 650 million years ago to 250 million years in the future, observe how Earth's continents have changed.

6.5. Deviations of Orbital

The gravitational pull of the other planets in the solar system has predictable effects on the orbital geometry of Earth (**Figure 7**). Three key aspects of the Earth's orbit are cyclically, or repeatedly, influenced [47]. The periodicities of the Earth's eccentric, almost elliptical to circular orbit around the Sun range from 100,000 to 413,000 years. Seasonal climates on Earth are mostly caused by the Earth's axis tilting away from the plane of the planet's rotation around the Sun by 22.1˚ to 24.5˚. A 41,000-year cycle governs this fluctuation. The Earth's axis of rotation waves alters its direction regarding the Sun as the orientation of the Earth's orbital ellipse progressively shifts. The third cyclic alteration to the Earth's orbital geometry is caused by these two events taken together. The positions of Earth during the solstices and equinoxes vary throughout a 26,000-year cycle caused by these two processes, known as the precession of the equinoxes. Perihelion occurs close to the December solstice, 9000 years after the Earth was closest to the Sun [48].

The latitudinal and seasonal distribution of solar energy is altered by these orbital motions, which has an impact on several climate-related variables. The timing of glacial-interglacial and monsoonal trends is greatly influenced by orbital fluctuations. Many of the Phanerozoic's climate shifts can be attributed to their impacts. For instance, during the Pennsylvanian Subperiod (323.2 to 298.9 million years ago), the cyclothems, which are interbedded marine, river, and coal layers, appear to indicate Milankovitch-driven changes in mean sea level.

6.6. Human Activities

The effects of human activity on the climate have come to light because of global climate change becoming an environmental issue. Deforestation and fossil fuel burning have received most of the attention as the main causes of CO_2 emissions [49]. Additional greenhouse gases are emitted because of human activity, such as chlorofluorocarbons (from industrial sources) and methane (from landfills, cattle, rice farming, and other sources). The paleoclimate data from ice cores, coral, and tree rings show a consistent warming trend over the whole 20th century and the first decade of the 21st century [50]. The twentieth century was the warmest of the previous ten centuries thanks to the decade from 2011 to 2020, which was the warmest decade since the advent of modern instrumental record keeping. Many climate scientists see this emerging pattern as unmistakable evidence of human-induced climate change brought by the emission of greenhouse gases.

Agriculture, reforestation, and deforestation are examples of a second form of human activity that is changing vegetation and contributing to the change of climate. It is becoming clear that human influences on plant cover can have local, regional, and even global consequences on climate due to changes in the transport of sensible and latent heat to the atmosphere and the distribution of energy across the climate system. An important, relatively new subject of research is examining how these factors have affected historical and present climate change.

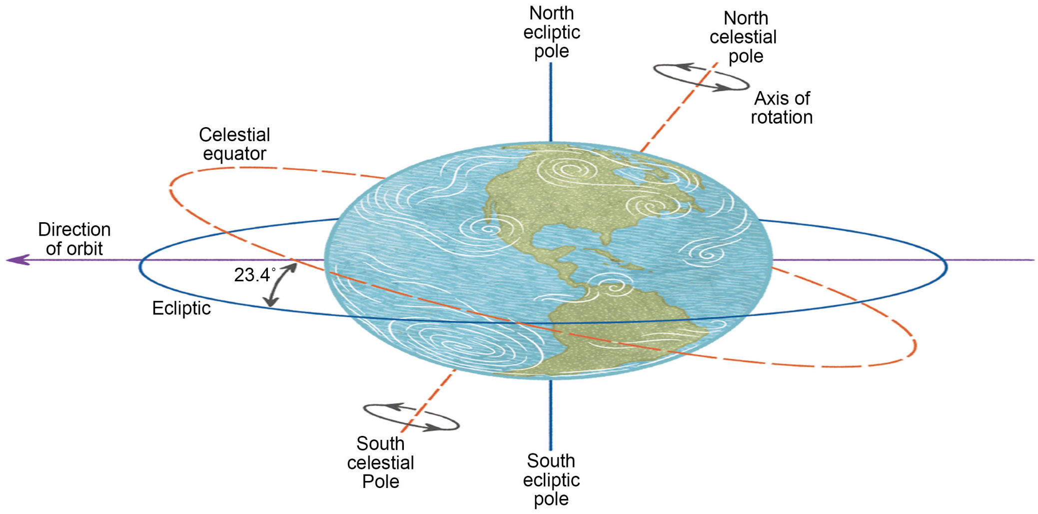


Figure 7. Three key aspects of the Earth's orbit are cyclically, or repeatedly, influenced [47].

6.7. Feedback

The function of exchanges and feedback among the many elements of the Earth system is perhaps the subject of climate variability that has received the most attention from researchers and debaters. Different parts of the feedback function at various rates and over various timeframes. The atmosphere has a direct or indirect impact on several variables, such as terrestrial vegetation, ocean temperatures, ice sheets, sea ice, ocean motion, greenhouse gas concentrations and weathering rates. All these elements, nevertheless, also filter back into the atmosphere, which has a huge impact on it. For example, the types and densities of vegetation influence the Earth's surface's albedo which influences the overall radiation budget at local to regional scales (**Figure 8**). Like this, vegetation promotes direct soil evaporation, direct plant stomatal transpiration, and both direct and indirect pathways for the transportation of water molecules from soil to atmosphere. Vegetation's control on latent heat flow can affect the climate on a local to global scale. Vegetation changes, which are partly impacted by climate, may thus influence the climate system. The amount of vegetation also affects the quantities of greenhouse gases. While live plants are a significant basin for atmospheric CO_2, when these plants burn in wildfires or decompose, they become producers of the gas. Understanding previous climate changes and projecting future ones depend critically on feedback between the many parts of the Earth system [51].

7. Within the Lifetime of a Person, Climate Change

All humans experience climatic fluctuation and change over the course of their lifespan, regardless of where they are on the earth. The most well-known and predictable occurrences are the seasonal cycles, which cause people to change their outdoor activities, thermostat settings, clothing, and farming practices. The yearly fluctuations in fuel costs, agricultural production, road maintenance

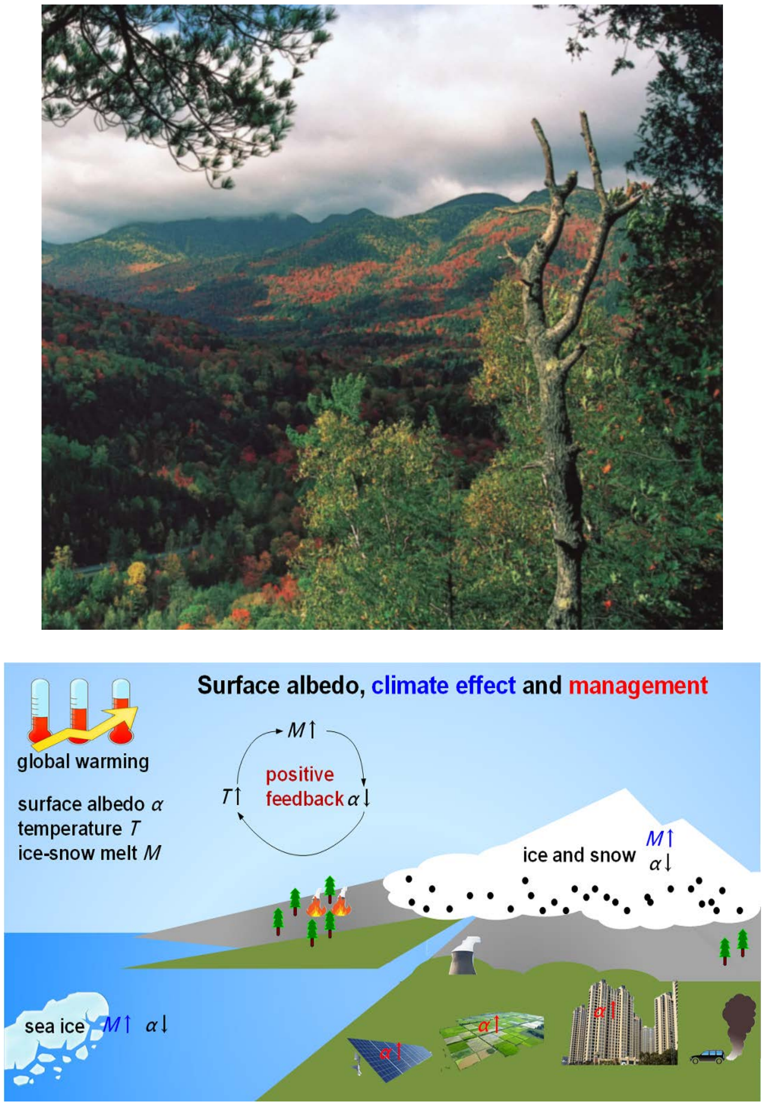


Figure 8. Vegetation influences the Earth's surface's albedo [51].

budgets, and the risk of wildfires are all influenced by this interannual climatic volatility. Floods brought on by a single year of precipitation can be lethal, as was the situation for the majority of Bangladesh in the summer of 1998, and they can also be completely devastating economically, as it was in the summer of 1993 for the upper Mississippi River drainage basin. Wildfires, hurricanes, heat waves, violent storms, and other climate-related disasters can also cause similar harm and deaths [51].

Longer timescales, like decades, may also see climate fluctuation and change. Numerous years of drought, flooding, or other extreme weather occur in certain places. Planning and human activities are made more difficult by the decadal change in the climate. Multiyear droughts, like the Dust Bowl droughts that hit North America's midcontinent in the 1930s, might, for instance, interrupt water supplies, result in agricultural failures, and generate economic and social upheaval. Long-lasting droughts, like the Sahel drought that struck northern

Africa in the 1970s and 1980s, can even cause widespread starvation [51].

7.1. Seasonal Change

Everywhere on Earth suffers seasonal climate change, albeit in certain tropical areas the change may not be particularly apparent. This cyclical oscillation is due to seasonal fluctuations in the quantity of solar energy reaching the Earth's surface and atmosphere. The Earth travels an elliptical path around the Sun, getting 91 million miles closer at the winter solstice in the Northern Hemisphere and 94 million miles further during the summer solstice. Additionally, the Earth's rotational axis is inclined (23.5˚) regarding its orbit. As a result, during its winter and summer seasons, each hemisphere has a tilt that moves it away from the Sun. More solar energy is absorbed by the hemisphere that is now facing the Sun than by a hemisphere that is tilted away from the Sun. The Northern Hemisphere receives less solar energy in the winter than it does in the summer, despite the Sun being closer near the winter solstice. The tilt also causes the Southern Hemisphere to enjoy summer while the Northern Hemisphere is during winter.

Solar radiation controls Earth's climate system, and seasonal variations in climate are ultimately caused by variations in Earth's orbit. Oceanic and atmospheric circulation are affected by seasonal fluctuations in the energy that the Sun makes accessible. The flow of energy from atmospheric and oceanic circulation is substantially responsible for the seasonal climatic variations that occur at any point on Earth's surface [52]. Storm tracks and pressure centers change in location and intensity due to variations in surface heating that occur between summer and winter. Seasonal fluctuations in cloudiness are also influenced by these heating differences.

Climate and atmospheric circulation are also influenced by the cryosphere's (glaciers, sea ice, and snowfields) and biosphere's (particularly vegetation) seasonal reactions. As deciduous trees enter their winter hibernation, their leaves fall, increasing the Earth's surface's albedo (reflectivity), which might result in more regional and local refrigeration. Similarly, snow buildup raises the albedo of terrestrial surfaces and frequently intensifies the impacts of winter.

7.2. Interannual Variation

A wide range of variables and interactions between Earth system components are to blame for interannual climatic fluctuations, which include droughts, floods, and other occurrences. The 19th century fisherman in northern Peru were the first to refer to the yearly migration of warm equatorial seas southward around Christmas as El Niño [53]. Subsequently, scientists in Peru found that while the thermal anomalies lasted for a minimum of a year, more substantial shifts occurred at intervals of many years and were associated with catastrophic recurrent floods along the normally dry coat (**Figure 9**). The name's initial yearly meaning was supplanted by that of the abnormal occurrence in the 20th century as the increasingly rare instances attracted global notice.

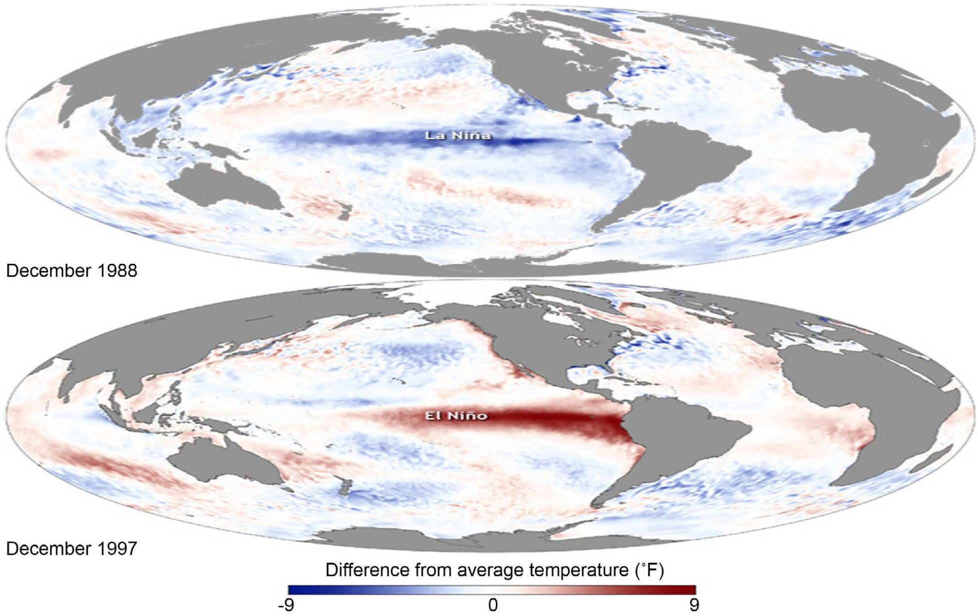


Figure 9. El Nio-Southern Oscillation (ENSO) fluctuation (El Niño) [53].

In oceanography and climatology, every few years, there is an unusual event known as El Nio that causes unusually warm water temperatures along South America's tropical west coast. This event, which occurs from Ecuador to Chile, is connected to adverse effects on local fisheries, agriculture, and weather as well as far-off climatic abnormalities in the equatorial Pacific and, sometimes, North America and Asia. Each El Nio event is primarily identified, evaluated, and forecast using the Oceanic Nio Index (ONI), a measurement of the east-central Pacific Ocean's deviation from the average sea surface temperature [54]. Increases in sea surface temperature of more than 0.5˚C for at least five consecutives, overlapping three-month seasons are indicative of an El Nio event [55]. The El Nio-Southern Oscillation (ENSO) fluctuation, which is a regular adjustment of oceanic circulation and atmospheric patterns in the tropical Pacific area, is mostly to blame for these oscillations. Although the tropical Pacific is where ENSO's main climatic impacts are focused, its flowing influences frequently affect the center of Asia and Europe, the polar regions, and the region around the Atlantic Ocean. These effects, commonly referred to as teleconnections, arise because variations in low-latitude atmospheric circulation patterns in the Pacific area impact atmospheric circulation in upstream and neighboring systems. As a result, storm tracks and the typical locations of ridges and troughs of atmospheric pressure—areas of high and low pressure—are altered [56].

For instance, El Nio events take place when the tropical Pacific's easterly trade winds weaken or change course. This keeps the deep, cold seas off the west coast of South America from rising, while also warming the eastern Pacific and reestablishing the air pressure imbalance in the western Pacific. As a result, surface air is travelling eastward from Australia and Indonesia to the central Pacific and the Americas. The traditionally moist areas of Indonesia and northern Australia experience serious drought, while the generally Peru dry coast, has heavy rains and flash floods. Extreme El Nio episodes cause the Indian Ocean region's monsoon to fail, which causes a severe drought in East Africa and India [56]. Westerlies and storm tracks are redirected towards the Equator, resulting in stormy, rainy winter weather in California and the dry Southwest of the United States, while the Pacific Northwest's typically wet winter conditions become drier and warmer. Drought also occurs because of the westerlies' displacement in northern China, northeastern Brazil, and parts of Venezuela. El Nio events typically happen every two to seven years, based on reef corals, tree rings, and long-term records of ENSO departure from historical recorded records. The occurrence and severity of these episodes, however, change throughout time [57].

Another example of an interannual oscillation that has a major impact on the climate of the Earth system and the Northern Hemisphere is the North Atlantic Oscillation (NAO) [58]. The pressure gradient, or difference in air pressure, between the Icelandic low, which is often located between Iceland and Greenland, and the subtropical high, which is typically positioned between Gibraltar and the Azores, is what causes this phenomenon. When the pressure gradient is steep due to a strong subtropical high and a deep Icelandic low, northern Asia and northern Europe continue to have wet, warm winters with frequent intense winter storms (positive phase). South Europe is dry at the same period. Positive NAO phases also result in warmer, less snowy winters in the eastern United States, albeit the effect is less pronounced than it is in Europe. When both a weak subtropical high and an Icelandic low coexist, the NAO is in a negative mode, which attenuates the pressure gradient. When this happens, northern Europe gets a dry and cold winter while the Mediterranean region receives substantial winter rainfall. During a negative NAO phase, the eastern United States usually experiences cooler temperatures and snowfall [32].

The feedback and interactions between the seas and atmosphere cause the ENSO and NAO cycles. Interactions between these and other cycles, Earth system disturbances (e.g., massive volcanic eruption aerosol injections), and several other variables lead to interannual climate change. The 1991 eruption of Mount Pinatubo in the Philippines is one instance of a disturbance caused by volcanism; that summer's worldwide average temperature dropped by about 0.5˚C.

7.3. Decadal Change

The weather changes on a decadal time frame, with many years of wet, dry, chilly, or warm weather clusters. The behavior and welfare of people may be significantly impacted by these multiyear clusters. For example, the "Lost Colony" at Roanoke Island in what is now North Carolina was destroyed by a severe three-year drought in the late 16th century, and the Jamestown Colony in Virginia had high mortality rates during a subsequent seven-year drought. However, recent research suggests that trade disruptions brought on by war may have also been a factor, possibly interacting with famines and other stresses related to the drought. Some academics have also suggested that prolonged, severe droughts were to blame for the collapse of the Maya civilization in Mesoamerica between 750 and 950 CE [59].

It is commonly known that there is decadal-scale climatic fluctuation, although it is not totally known what causes it. Interannual changes contribute significantly to decadal climate variance. The frequency and strength of ENSO, for instance, evolve throughout time. Repeated El Nio episodes dominated the early 1990s, and numerous similar clusters have been shown to have occurred through the last century. Over decadal periods, the NAO gradient's steepness varies as well; the 1970s experienced an especially steep gradient.

Recent research has demonstrated that contacts between atmosphere and the ocean are what produce decadal-scale climate changes. One such fluctuation, known as the Pacific Decadal Oscillation (PDO) or Pacific Decadal Variability (PDV), affects the sea surface temperatures (SSTs) of the North Pacific Ocean. PDO fluctuation is composed of "warm-phase" and "cool-phase" alternating periods [60]. The former, which includes the years 1925-1946 and 1977-1998—is characterized by low precipitation in the Pacific Northwest and comparatively heavy precipitation in coastal Alaska. The latter is marked by coastal Alaska being relatively dry and the former by the opposite (e.g., 1947-76). PDO fluctuation is shown by coral records and tree rings, which date back at least four centuries.

A comparable oscillation that occurs in the North Atlantic, the Atlantic Multidecadal Oscillation (AMO), has a substantial influence on the precipitation patterns in Central and Eastern North America. Florida has comparatively high rainfall levels while most of the Ohio Valley experiences low rainfall levels when an AMO in the warm phase (quite warm North Atlantic SSTs) is present. However, the AMO and PDO have complicated interactions with one another as well as with interannual fluctuations like the ENSO and Nao. Such interactions may amplify droughts, floods, or other abnormalities of the climate. For instance, the early 21st century catastrophic droughts that affected a large portion of the contiguous United States were linked to warm-phase AMO and cool-phase PDO. It is thought that interactions between the ocean and atmosphere, which have longer time constants than interannual fluctuations, are what cause decadal variations, including AMO and PDO. The exact processes causing these variations are not well known. Climate scientists and paleoclimatologists have focused heavily on decadal climate variability [61].

7.4. Thermal Maxima

Sometime in the early to mid-Holocene, temperatures were greater than they are now in many places of the world. In certain situations, the rising temperatures were followed by a drop in the amount of precipitation that was available. Although the phrase "thermal maximum" (also known as the "Thermal Optimum" or the "Xerothermic Interval") was formerly used to refer to a single, global occurrence that occurred in North America and across the world, it is now understood that various places experience multiple peak temperature times. In contrast to central or eastern North America, northwest Canada, for instance, reached its peak temperature several thousand years earlier [62]. Moisture records exhibit a similar level of variation. One of the driest areas on Earth now is the Atacama Desert, and Bolivia and Chile on the western coast of South America. But it was substantially wetter in the early Holocene when many other places were at their driest. Orbital oscillation was the main cause of temperature and moisture variations during the Holocene, gradually altering the latitudinal and seasonal distribution of solar energy on atmosphere and Earth's surface [63].

7.5. Changes in the Climate since the Advent of Civilization

Climate change has affected human populations since agriculture first emerged some 10,000 years ago. The societies and cultures of humans have frequently been significantly impacted by these climate changes. They include the previously mentioned decadal and yearly climatic variations as well as significant changes that take place throughout centuries to millennia [64]. The early cultivation of agricultural plants and domestication as well as the pastoralization and domestication of animals are thought to have been influenced by and even inspired by these achievements. Even while there is enough evidence to demonstrate that several civilizations and cultures have broken down in the face of severe and quick climatic fluctuations, human societies have nonetheless evolved in an adaptable manner.

7.6. Centennial-Scale Variation

The previous 1000 years have seen climatic change on centenary timelines, according to ancient recordings as well as alternative data (especially ice cores, corals, and tree rings). This means that no two centuries have been precisely the same. The Earth system has recovered in the 150 years after the Little Ice Age, which was marked by comparatively cold temperatures in the North Atlantic area and elsewhere. There was a noticeable warming trend in several regions during the last century. This warming may have been caused by other natural processes or by the end of the Little Ice Age. In several areas, the 20th century suffered a significant trend of warming.

On centenary timelines, historical records and proxy data demonstrate that the climate has altered over the past 1000 years. Because of this, no two centuries have ever been precisely the same. The Little Ice Age ended 150 years ago, and the Earth system has since stabilized. Throughout the Little Ice Age, temperatures were extremely low both in the North Atlantic region and globally. The 20th century saw a noticeable warming trend in several places. However, many climate scientists think that the atmospheric buildup of greenhouse gases, particularly CO_2, in the latter decades of the 20th century was a significant contributor to the warming.

The Little Ice Age is most associated with the North Atlantic region and Europe, which experienced some extremely cold temperatures between the early 14th and mid-19th centuries. Since there were many mild years throughout this time due to interannual and decadal fluctuation, it was not a period of consistently chilly weather [65]. Furthermore, the coldest times did not necessarily occur at the same time in every place; some had reasonably moderate circumstances while others saw extremely low temperatures. Churches, farms, and communities were destroyed by Alpine glaciers when they expanded well beyond their predetermined boundaries, affecting France, Switzerland, and other countries. Frequent cold winters and rainy, chilly summers caused damage to wine harvests, failed crops, and starvation in a large portion of central and northern Europe. The eastern colony of Greenland was abandoned, while the western one perished from starvation.

Northern and central Europe experienced a period of comparatively warm weather prior to the Little Ice Age. From around the year 1000 to the beginning of the15th century was the Mediaeval Warm Period. In most of Europe, abundant crops were a result of mild summers and winters. Wheat cultivation and vineyards were extremely effective in latitudes and elevations significantly higher than they are now. The North Atlantic area has extensive documentation of the Mediaeval Warm Period, including ice cores from Greenland [66]. On the Saudi Arabia Northern region many new studies on flora are from [67]-[79].

7.7. Millennial and Multimillennial Variation

Variations and trends at both millennial periods and longer are overlaid atop the climate changes of the previous millennium. The past 3000 years have been marked by patterns of greater cooling and increased effective moisture, according to several indications from eastern North Europe and America. For instance, in the Great Lakes-St. Lawrence region along the US-Canada border, peatlands developed and spread, plants that like wetness, such as hemlock and beech, extended their ranges westward, while populations of boreal trees, such as tamarack and spruce, prospered and expanded southward. All these trends point to an increase in effective moisture that may be caused by an increase in precipitation, a decrease in evapotranspiration owing to cooling [80]. Throughout the previous 3000 years in both eastern North America and Western Europe, spruce in the south and beech thrived in the north. The beech expansions may indicate warmer winters or longer growth seasons, whereas the spruce expansions are associated with milder, more humid summers.

During the same time span, other areas grew warmer and drier. For instance, over the last 3000 years, moisture levels have decreased in northern Mexico and the Yucatan. This kind of heterogeneity is typical of climate change, which entails shifting atmospheric circulation patterns. Heat and moisture are transported through the atmosphere in different ways because of changing circulation patterns. This finding clarifies the seeming paradox of divergent trends in temperature and moisture in various places.

The Holocene Epoch, an interglacial period of around 11,700 years, has seen several changes to the climate, the most recent of which occurred in the last 3000 years. At the beginning of the Holocene, continental glaciers from the previous glacial age still blanketed much of eastern and central Canada and portions of Scandinavia. Many of these ice sheets vanished 6000 years ago. Lack of them had an impact on atmospheric circulation, as did warming sea surfaces, increasing sea levels (from glacial meltwater entering the oceans), and variations in the Earth's surface radiation budget brought on by Milankovitch variations (seasonal shifts brought on by cyclical adjustments of Earth's orbit around the Sun). The presence of early to mid-Holocene heat maxima in several areas, modifications to the ENOS pattern, and an early to mid-Holocene amplification of the Indian Ocean monsoon are a few examples [56].

7.8. The Indian Ocean Monsoon Intensifying

A yearly climate cycle known as the Indian Ocean monsoon has a major influence on most of the Middle East, Africa, and the Indian subcontinent. This area's climate is quite seasonal, with clear skies and dry air in the winter and gloomy skies and copious rains in the summer. Like other facets of the climate, monsoon strength is prone to interannual, decadal, and centenary fluctuations, some of which are correlated with ENSO and other cycles. There is a tone of proof that the severity of the monsoons varied greatly over the Holocene Epoch. According to palaeontological and palaeoecological research, the area saw significantly higher precipitation in the early Holocene (11,700 - 6000 years ago) than it does now. Under the sand in certain areas of the Sahara Desert, materials from lakes and wetlands from this period have been discovered. Elephant, crocodile, hippopotamus, and giraffe fossils are among those found in these strata, which also show woodland flora and pollen evidence of forest [81]. In the arid and semi-arid parts of India, Africa, and Arabia, shallow, saline lakes have replaced deep, massive freshwater lakes in basins that are now dry. These formerly prosperous civilizations, such as the Harappan civilization of northwest India and the neighboring Pakistan, involved the grazing of animals and the cultivation of plants.

These and other lines of evidence imply that the Indian Ocean monsoon was substantially intensified during the early Holocene, providing plenty of moisture deep inside the Asian and African continents, coupled with geochemical and paleontological data from climate modelling and marine strata studies. High solar energy in the summer was the source of this amplification, which was roughly 7% stronger 11,700 years ago than it is now due to orbital forces (variations in the Earth's axial tilt, precession, and eccentricity). Summer air temperatures increased due to high insulation, which decreased surface pressure across continents. As a result, the Indian Ocean sent more humid air into the interior of the continents. According to demonstrating learning, feedback including the atmosphere, plants, and soils increased the monsoonal flow. More moisture led to drier soils and more luxuriant vegetation, which in turn led to an increase in precipitation and made it possible for moist air to travel farther into the interiors of continents. The Indian Ocean monsoon has weakened over the last 4000 - 6000 years because of declining summer insolation [82].

8. Climate Change and Sustainable Development Relationship

Climate change and sustainability are strongly intertwined. They both have an impact on the environment and society, first. Reduced climate change's negative consequences on the environment and society are the goal of sustainable development. Both are negatively impacted by climate change, which is presently a major global problem.

8.1. Sustainability of the Environment and Climate Change

Because of the effects that climate change has on the environment, the latter has a significant influence on how the two interact. Because of the effects that climate change has on the environment, the environment has a significant influence on how the two interact. This indicates that reducing the consequences of climate change requires maintaining environmental sustainability.

Maintaining sustainability in the natural environment is the primary goal of environmental sustainability. It also means safeguarding the natural environment, including wildlife and natural resources like clean water and air, for the benefit of future generations. This indicates the need to maintain environmental sustainability to reduce the consequences of climate change [83].

8.2. Agreement on Trade, Sustainability, and Climate Change

The Agreement on Climate Change Trade and Sustainability (ACCTS), which was introduced in 2019, was developed by five countries: Costa Rica, Switzerland, New Zealand, Iceland, Fiji, and Norway. This initiative's major objective is to reduce environmental problems all around the planet by pressuring nations to act on issues like climate change and the environment. The primary issues resolved by this agreement are:

8.2.1. Restrain Fossil Fuel Subsidies

Greenhouse gases are released when fossil fuels are utilized. The primary cause of greenhouse gases, which include CO_2, nitrous oxide, and hydrocarbons, is global warming, which has the potential to cause long-term climate change. The ACCTS aims to lessen the use of fossil fuels while promoting the improvement of air quality by cutting back on fossil fuel subsidies. Thus, this strategy would lessen the effects of climate change [84].

8.2.2. Remove Tariff on Environmental Goods

Environmental products are now subject to tariffs, which are government-imposed duties on imported commodities that lower the price of the commodity and make domestic goods less competitive. These goods include measures to protect the environment and the climate, as well as alternative energy, lowering air pollution, waste management, and other topics. To make it simpler for nations to protect the environment and the climate, the ACCTS seeks to do away with these tariffs on environmental commodities [85].

8.3. Climate Change and Sustainable Energy

Energy is essential in the fight against climate change. This is since, even though certain energy sources serve to alleviate the consequences of climate change, others can increase harmful environmental effects like global warming. For instance, non-renewable energy sources like gas, oil, nuclear power, and coal are limited in supply. They are not sustainable and fuel the global warming trend, which causes climate change. In contrast, renewable energy sources such as solar, wind, wave, biomass, geothermal, and hydropower are referred to as sustainable energy. Because it doesn't emit greenhouse gases, this form of energy is clean. Pollutants and greenhouse gas emissions will be decreased by adopting these sustainable energy sources, helping to mitigate the long-term effects of climate change [86].

8.4. Sustainability in Cities and Climate Change

Urbanization is growing as the world is expanding. The negative environmental effects that metropolitan cities may have include suburban development, inadequate sanitation, poor water and air characteristic, significant ecological impressions, excessive energy consumption, and climate change, to name just a few [87] [88]. One of the detrimental effects of urbanization that contributes to climate change and further harms metropolitan regions is extreme weather. As a result, climate change may influence metropolitan areas' infrastructure, electricity, and water sources. While reducing the impact that urban areas have on climate change, urban sustainability aims to develop sustainable solutions for urban zones to preserve livable circumstances that are beneficial to society and its economy [89].

9. Conclusions

Long-term changes in temperature and weather are referred to as "climate change." Such fluctuations may be caused by massive volcanic eruptions or variations in the energy of the sun. Global warming is included in climate change, but it also refers to a wider variety of changes that our world is through.

Climate change including: increased sea levels, alpine glaciers that are thinning, Greenland, Antarctica, and the Arctic that are shedding their ice quicker than usual, and time changes for plant and flower blossoming.

To learn more about climate solutions: conserving energy at home, changing the energy source in your house, pedaling a bike, using a bus, or taking a walk, using an electric car instead, thinking about the journey, attempting to learn Reduce, reuse, repair, and recycling all environmental resources; more veggies must be consumed; reducing food waste.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Longair, M. (2021) James Croll, Celestial Mechanics, and Climatic Change. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **112**, 231-238.

[2] Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T. and Minx, J.C., Eds. (2014) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Cambridge University Press, Cambridge and New York.

[3] Lyons, T.W., Diamond, C.W., Planavsky, N.J., Reinhard, C.T. and Li, C. (2021) Oxygenation, Life, and the Planetary System during Earth's Middle History: An Overview. *Astrobiology*, **21**, 906-923. https://doi.org/10.1089/ast.2020.2418

[4] IPCC (2007) Climate Change: The Physical Science Basis, Contribution from Working Group I to the Fourth Assessment Report, Policy Maker Summary. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

[5] Takahashi, K., Birkmann, J., Luber, G., O'Neill, B., Berkhout, F., Dube, P., Foden, W., Greiving, S., Hsiang, S., Johnston, M., Keller, K., Kleypas, J., Kopp, R., Licker, R., Peres, C., Price, J., Robock, A., Schlenker, W., Stepp, J.R., Tol, R. and van Vuuren, D. (2014) Chapter Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the 5th Assessment Report of the Intergovernmental Panel on Climate Change.

[6] Steffen, W., Leinfelder, R., Zalasiewicz, J., Waters, C.N., Williams, M., Summerhayes, C., Barnosky, A.D., Cearreta, A., Crutzen, P., Edgeworth, M., Ellis, E.C., Fairchild, I.J., Galuszka, A., Grinevald, J., Haywood, A., do Sul, J.I., Jeande, C., McNeill, J.R., Odada, E., Oreskes, N., Revkin, A., Richter, D.B., Syvitski, J., Vidas, D., Wagreich, M., Wing, S.L., Wolfe, A.P. and Schellnhuber, H.J. (2016) Stratigraphic and Earth System approaches to defining the Anthropocene. *Earth's Future*, **4**, 324-345. https://doi.org/10.1002/2016EF000379

[7] Chu, E.W. and Karr, J.R. (2017) Environmental Impact: Concept, Consequences, Measurement. In: *Reference Module in Life Sciences*, Elsevier Inc., Amsterdam. https://doi.org/10.1016/B978-0-12-809633-8.02380-3

[8] Hoem, F.S., López-Quirós, A., van de Lagemaat, S.H.A., Etourneau, J., Sicre, M.-A., Escutia, C., Brinkhuis, H., Peterse, F., Sangiorgi, F. and Bijl, P.K. (2023) Late Cenozoic Sea-Surface-Temperature Evolution of the South Atlantic Ocean. *Climate of the Past*, **19**, 1931-1949. https://doi.org/10.5194/cp-19-1931-2023

[9] Hutchinson, D.K., Coxall, H.K., Lunt, D.L., Steinthorsdottir, M., de Boer, A.M., Baatsen, M., von der Heydt, A., Huber, M., Kennedy-Asser, A.T., Kunzmann, L., Ladant, J.-B., Lear, C.H., Moraweck, K., Pearson, P.N., Piga, E., Pound, M.J., Salzmann, U., Scher, H.D., Sijp, W.P., Śliwínska, K.K., Wilson, P.A. and Zhang, Z. (2021) The Eocene-Oligocene Transition: A Review of Marine and Terrestrial Proxy Data, Models and Models-Data Comparisons. *Climate of the Past*, **17**, 269-315. https://doi.org/10.5194/cp-17-269-2021

[10] Hoem, F.S., Valero, L., Evangelinos, D., Escutia, C. and Bijl, P.K. (2021) Temperate Oligocene Surface Ocean Conditions Offshore of Cape Adare, Ross Sea, Antarctica. *Climate of the Past*, **17**, 1423-1442. https://doi.org/10.5194/cp-17-1423-2021

[11] Passchier, S., Ciarletta, D.J., Miriagos, T.E., Bijl, R.K. and Bohaty, M.S. (2017) An Antarctic Stratigraphic Record of Stepwise Ice Growth through the Eocene Oligocene Transition. *GSA Bulletin*, **129**, 318-330. https://doi.org/10.1130/B31482.1

[12] McKay, R.M., Escutia, C., De Santis, L., Donda, F., Duncan, B., Gohl, K., Gulick, S.P.S., Hernández-Molina, F.J., Hillenbrand, C.-D., Hochmuth, K., Kim, S., Kuhn, G., Larter, R., Leitchenkov, G., Levy, R.H., Naish, T.R., O'Brien, P., Pérez, L.F., Shevenell, A. and Williams, T. (2022) Cenozoic History of Antarctic Glaciation and Climate from Onshore and Offshore Studies. In: Florindo, F., *et al.*, Eds., *Antarctic Climate Evolution*, Elsevier, Amsterdam, 41-164.

[13] Joeckel, R.M. and Fielding, C.R. (2018) New Insights into Carboniferous Cyclothems. The Fourth Biennial Field Conference of the American Association of Petroleum Geologists, (AAPG) Midcontinent Section Fourth Biennial Field Conference Abstracts and Guidebook. University of Nebraska-Lincoln, Lincoln.

[14] Dahl, T.W. and Arens, S.K.M. (2020) The Impacts of Land Plant Evolution on Earth's cliMate and Oxygenation State—An Interdisciplinary Review. *Chemical Geology*, **547**, Article 119665. https://doi.org/10.1016/j.chemgeo.2020.119665

[15] Frei, R., Gaucher, C., Poulton, S.W., *et al.* (2009) Fluctuations in Precambrian Atmospheric Oxygenation Recorded by Chromium Isotopes. *Nature*, **461**, 250-253. https://doi.org/10.1038/nature08266

[16] Feulner, G. (2012) The Faint Young Sun Problem. *Reviews of Geophysics*, **50**, RG2006. https://doi.org/10.1029/2011RG000375

[17] Olson, J.M. (2006) Photosynthesis in the Archean Era. *Photosynthesis Research*, **88**, 109-117. https://doi.org/10.1007/s11120-006-9040-5

[18] Hoffman, P.F. and Schrag, D.P. (2002) The Snowball Earth hypothesis: Testing the Limits of Global Change. *Terra Nova*, **14**, 129-155. https://doi.org/10.1046/j.1365-3121.2002.00408.x

[19] Schrag, D.P. and Hoffman, P.F. (2001) Geophysics: Life, Geology and Snowball Earth. *Nature*, **409**, 306. https://doi.org/10.1038/35053170

[20] Sluijs, A. (2008) Carbon Burp and Transient Global Warming during the Paleocene-Eocene Thermal Maximum. *PAGES News*, **16**, 9-11. https://doi.org/10.22498/pages.16.1.9

[21] Stuijs, A. and Brinkhuis, H. (2008) Rapid Carbon Injection and Transient Global Warming during the Paleocene-Eocene Thermal Maximum. *Netherlands Journal of Geosciences—Geologie en Mijnbouw*, **87**, 201-206. https://doi.org/10.1017/S0016774600023271

[22] McInerney, F.A. and Wing, S.L. (2011) The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future. *Annual Review of Earth and Planetary Sciences*, **39**, 489-516. https://doi.org/10.1146/annurev-earth-040610-133431

[23] Berger, W.H. (1990) The Younger Dryas Cold Spell—A Quest for Causes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **89**, 219-237. https://doi.org/10.1016/0031-0182(90)90063-D

[24] Pearce, C., Seidenkrantz, M.-S., Kuijpers, A., Massé, G., Reynisson, N.F. and Kristiansen, S.M. (2013) Ocean Lead at the Termination of the Younger Dryas Cold Spell Ocean Lead at the Termination of the Younger Dryas Cold Spell. *Nature Communications*, **4**, Article No. 1664. https://doi.org/10.1038/ncomms2686

[25] Lohmann, G., Butzin, M., Eissner, N., Shi, X. and Stepanek, C. (2020) Abrupt Climate and Weather Changes across Time Scales. *Paleoceanography and Paleoclimatology*, **35**, e2019PA003782. https://doi.org/10.1029/2019PA003782

[26] Dokken, T., Nisancioglu, K.H., Li, C., Battisti, D.S. and Kissel, C. (2013) Dansgaard-Oeschger Cycles: Interactions between Ocean and Sea Ice Intrinsic to the Nordic Seas. *Paleoceanography and Paleoclimatology*, **28**, 491-502. https://doi.org/10.1002/palo.20042

[27] Borzenkova, I., Zorita, E., Borisova, O., Kalniņa, L., Kisielienė, D., Koff, T., Kuznetsov, D., Lemdahl, G., Sapelko, T., Stančikaitė, M. and Subetto, D. (2015) Climate Change during the Holocene (Past 12,000 Years). In: The BACC II Author Team, Eds., *Second Assessment of Climate Change for the Baltic Sea Basin*, Springer, Cham, 25-49. https://doi.org/10.1007/978-3-319-16006-1_2

[28] Maslin, M.A., Brierley, C.M., Milner, A.M., Shultz, S., Trauth, M.H. and Wilson, K.E. (2014) East African Climate Pulses and Early Human Evolution. *Quaternary Science Reviews*, **101**, 1-17. https://doi.org/10.1016/j.quascirev.2014.06.012

[29] Westling, L. (2022) Deep History, Climate Change, and the Evolution of Human Culture. In: *Elements in Environmental Humanities*, Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009257343

[30] Van den Berg, J., Van de Wal, R.S.W. and Oerlemans, H. (2008) A Mass Balance Model for the Eurasian Ice Sheet for the Last 120,000 Years. *Global and Planetary Change*, **61**, 194-208. https://doi.org/10.1016/j.gloplacha.2007.08.015

[31] Malmierca-Vallet, I., Sime, L.C. and The D-O Community Members (2022) Dansgaard-Oeschger Events in Climate Models: Review and Baseline MIS3 Protocol. *Climate of the Past*, **19**, 915-942. https://doi.org/10.5194/egusphere-2022-707

[32] Monier, E. and Gao, X. (2015) Climate Change Impacts on Extreme Events in the United States: An Uncertainty Analysis. *Climatic Change*, **131**, 67-81. https://doi.org/10.1007/s10584-013-1048-1

[33] Zhou, Y.X., McManus, J.F., Jacobel, A.W., Costa, K.M., Wang, S.Y. and Caraveo, B.A. (2021) Enhanced Iceberg Discharge in the Western North Atlantic during All Heinrich Events of the Last Glaciation. *Earth and Planetary Science Letters*, **564**, Article No. 116910. https://doi.org/10.1016/j.epsl.2021.116910 https://www.sciencedirect.com/science/article/pii/S0012821X21001692

[34] Munk, W. (2002) Twentieth Century Sea Level: An Enigma. *Proceedings of the National Academy of Sciences of the United States of America*, **99**, 6550-6555. https://doi.org/10.1073/pnas.092704599

[35] Suggate, R.P. and Almond, P.C. (2005) The Last Glacial Maximum (LGM) in Western South Island, New Zealand: Implications for the Global LGM and MIS 2. *Quaternary Science Reviews*, **24**, 1923-1940. https://doi.org/10.1016/j.quascirev.2004.11.007

[36] Houben, A.J.P., Bijl, P.K., Sluijs, A., Schouten, S. and Brinkhuis, H. (2019) Late Eocene Southern Ocean Cooling and Invigoration of Circulation Preconditioned Antarctica for Full-Scale Glaciation. *Geochemistry, Geophysics, Geosystems*, **20**,

2214-2234. https://doi.org/10.1029/2019GC008182

[37] Zeder, M.A. (2008) Domestication and Early Agriculture in the Mediterranean Basin: Origins, Diffusion, and Impact. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 11597-11604. https://doi.org/10.1073/pnas.0801317105

[38] Zeder, M.A. (2011) The Origins of Agriculture in the Near East. *Current Anthropology*, **52**, S221-S235. https://doi.org/10.1086/659307

[39] Werner, M., Haese, B., Xu, X., Zhang, X., Butzin, M. and Lohmann, G. (2016) Glacial-Interglacial Changes in $H_2^{18}O$, HDO and Deuterium Excess—Results from the Fully Coupled ECHAM5/MPI-OM Earth System Model. *Geoscientific Model Development*, **9**, 647-670. https://www.geosci-model-dev.net/9/647/2016/ https://doi.org/10.5194/gmd-9-647-2016

[40] Chappellaz, J., Barnola, J.M., Raynaud, D., Korotkevich, Y.S. and Lorius, C. (1990) Ice-Core Record of Atmospheric Methane over the Past 160,000 Years. *Nature*, **345**, 127-131. https://doi.org/10.1038/345127a0

[41] Dean, J.F., Middelburg, J.J., Röckmann, T., Aerts, R., Blauw, L.G., Egger, M., Jetten, M.S.M., de Jong, A.E.E., Meise, O.H., Rasigraf, O., Slomp, C.P., in't, Zandt, M.H. and Dolman, A.J. (2017) Methane Feedback to the Global Climate System in a Warmer World. *Reviews of Geophysics*, **56**, 207-250. https://doi.org/10.1002/2017RG000559

[42] Hobson, T. (2020) The Effect of Stellar Flybys on the Perturbation of Earth's Orbit. MSc Thesis Applied Mathematics, University of Lincoln, Lincoln.

[43] Meier, H.E.M., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., Myrberg, K., Ahola, M.P., Bartosova, A., Bonsdorff, E., Börgel, F., Capel, R., Carlén, I., Carlund, T., Carstensen, J., Christensen, O.B., Dierschke, V., Frauen, C., Frederiksen, M., Gaget, E., Galatius, A., Haapala, J.J., Halkka, A., Hugelius, G., Hünicke, B., Jaagus, J., Jüssi, M., Käyhkö, J., Kirchner, N., Kjellström, E., Kulinski, K., Lehmann, A., Lindström, G., May, W., Miller, P.A., Mohrholz, V., Müller-Karulis, B., Pavón-Jordán, D., Quante, M., Reckermann, M., Rutgersson, A., Savchuk, O.P., Stendel, M., Tuomi, L., Viitasalo, M., Weisse, R. and Zhang, W. (2022) Climate Change in the Baltic Sea Region: A Summary Climate Change in the Baltic Sea Region: A Summary. *Earth System Dynamics*, **13**, 457-593. https://doi.org/10.5194/esd-13-457-2022

[44] Hathaway, D.H. (2010) The Solar Cycle. *Living Reviews in Solar Physics*, **7**, Article No. 1. https://doi.org/10.12942/lrsp-2010-1 http://www.livingreviews.org/lrsp-2010-1

[45] McCormick, M.P., Thomason, L.W. and Trepte, C.R. (1995) Atmospheric Effects of the Mt Pinatubo Eruption. *Nature*, **373**, 339-404. https://doi.org/10.1038/373399a0

[46] Sobolev, S. and Brown, M. (2019) Surface Erosion Events Controlled the Evolution of Plate Tectonics on Earth. *Nature*, **570**, 52-57. https://doi.org/10.1038/s41586-019-1258-4

[47] Bertrand, C., Loutre, M.F. and Berger, A. (2002) High Frequency Variations of the Earth's Orbital Parameters and Climate Change. *Geophysical Research Letters*, **29**, 40-1-40-4. https://doi.org/10.1029/2002GL015622

[48] Joseph, A. (2023) Chapter 2. Geological Timeline of Significant Events on Earth. In: *Water Worlds in the Solar System*, Elsevier, Amsterdam, 55-114. https://doi.org/10.1016/B978-0-323-95717-5.00020-7

[49] Perera, F. (2018) Pollution from Fossil-Fuel Combustion Is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *International*

Journal of Environmental Research and Public Health, **15**, Article 16. https://doi.org/10.3390/ijerph15010016

[50] Brack, D. (2019) Background Analytical Study Forests and Climate Change. Background study prepared for the 14th session of the United Nations Forum on Forests. (UNFF, 2014). Forests and SDG13, March 2019.

[51] Rafferty, J.P. (2010) Climate and Climate Change. Britannica Educational Publishing, New York, 368 p.

[52] McMonigal, K., Larson, S., Hu, S. and Kramer, R. (2023) Historical Changes in Wind-Driven Ocean Circulation Can Accelerate Global Warming. *Geophysical Research Letters*, **50**, e2023GL102846. https://doi.org/10.1029/2023GL102846

[53] Glynn, P.W. (1984) WIDESPREAD coral Mortality and the 1982-83 El Niño Warming Event. *Environmental Conservation*, **11**, 133-146. https://doi.org/10.1017/S0376892900013825

[54] Webb, E.J. and Magi, B.I. (2022) The Ensemble Oceanic Niño Index. *International Journal of Climatology*, **42**, 4989-5392. https://doi.org/10.1002/joc.7535

[55] Oki, D.S. (2004) Trends in Streamflow Characteristics at Long-Term Gaging Stations, Hawaii. U.S. Geological Survey Scientific Investigations Report 2004-5080, 116 p. https://doi.org/10.3133/sir20045080

[56] Leupold, M., Pfeiffer, M., Takaaki, K., Watanabe., Nakamura, N., Reuning, L., Blume, A., McClanahan, T., Mohammed, M., Kiriama, H., Garbe- Schönberg, D., Ritzrau, A.S. and Zinke, J. (2023) Mid-Holocene Expansion of the Indian Ocean Warm Pool Documented in coral Sr/Ca Records from Kenya. *Scientific Reports*, **13**, Article No. 777. https://doi.org/10.1038/s41598-023-28017-0

[57] McPhaden, M., Lee, T. and McClurg, D. (2011) El Niño and Its Relationship to Changing Background Conditions in the Tropical Pacific Ocean. *Geophysical Research Letters*, **38**, L15709. https://doi.org/10.1029/2011GL048275

[58] Deser, C., Hurrell, J.W. and Phillips, A.S. (2017) The Role of the North Atlantic Oscillation in European climate Projections. *Climate Dynamics*, **49**, 3141-3157. https://doi.org/10.1007/s00382-016-3502-z

[59] Middleton, G.D. (2012) Nothing Lasts Forever: Environmental Discourses on the Collapse of Past Societies. *Journal of Archaeological Research*, **20**, 257-307. https://doi.org/10.1007/s10814-011-9054-1

[60] Mantua, N.J. and Hare, S. (2002) The Pacific Decadal Oscillation. *Journal of Oceanography*, **58**, 35-44. https://doi.org/10.1023/A:1015820616384

[61] Singh, S., Abebe, A., Srivastava, P. and Chaubey, I. (2021) Effect of ENSO Modulation by Decadal and Multi-Decadal Climatic Oscillations on Contiguous United States Stream Flows. *Journal of Hydrology: Regional Studies*, **36**, Article 100876. https://doi.org/10.1016/j.ejrh.2021.100876

[62] Clague, J.J., Menounos, B., Osborn, G., Luckman, B.H. and Koch, J. (2009) Nomenclature and Resolution in Holocene Glacial Chronologies. *Quaternary Science Reviews*, **28**, 2231-2238. https://doi.org/10.1016/j.quascirev.2008.11.016

[63] Diederich, J.L., Wennrich, V., Bao, R., Büttner, C., Bolten, A., Brill, D., Buske, S., Campos, E., Fernández-Galego, E., Gödickmeier, P., Ninnemann, L., Reyers, M., Ritter, B., Ritterbach, L., Rolf, C., Scheidt, S., Dunai, T.J. and Melles, M. (2020) A 68 ka Precipitation Record from the Hyperarid Core of the Atacama Desert in Northern Chile. *Global and Planetary Change*, **184**, Article 103054. https://doi.org/10.1016/j.gloplacha.2019.103054

[64] Shivanna, K.R. (2022) Climate Change and Its Impact on Biodiversity and Human Welfare. *Proceedings of the Indian National Science Academy*, **88**, 160-171.

https://doi.org/10.1007/s43538-022-00073-6

[65] Gaglioti, B.V., Mann, D.H., Wiles, G.C., Jones, B.M., Charlton, J., Wiesenberg, N. and Andreu-Hayles, L. (2019) Timing and Potential Causes of 19th-Century Glacier Advances in Coastal Alaska Based on Tree-Ring Dating and Historical Accounts. *Frontiers in Earth Science*, **7**, Article 82. https://doi.org/10.3389/feart.2019.00082

[66] White, S. (2014) The Real Little Ice Age. *The Journal of Interdisciplinary History*, **44**, 327-352. https://doi.org/10.1162/JINH_a_00574

[67] Alhaithloul, H.A.S., Abdein, M.A. and, Awad, N.S. (2022) Anticancer Effect of *Citrullus colocynthis* and *Capparis spinosa* against Human Cervix and Hepatocellular Cancer Cell Lines. *Ecology, Environment and Conservation*, **28**, S586-S596. https://doi.org/10.53550/EEC.2022.v28i01s.081

[68] Ghazzawy, H.S., Gouda, M.M., Awad, N.S., Al-Harbi, N.A., Alqahtani, M.M., Abdel-Salam, M.M., Abdein, M.A., Al-Sobeai, S.M., Hamad, A.A., Alsberi, H.M., Gabr, G.A. and Hikal, D.M. (2022) Potential Bioactivity of *Phoenix dactylifera* Fruits, Leaves, and Seeds against Prostate and Pancreatic Cancer Cells. *Frontiers in Nutrition*, **9**, Article 998929. https://doi.org/10.3389/fnut.2022.998929

[69] Abdel-Mageed, A.M., Osman, A.K.E., Awad, N.S. and Abdein, M.A. (2019) Evaluation of Antidiabetic Potentiality of *Truffles* and *Balanites Aegyptiaca* among Streptozotocin Induced Diabetic Rats. *International Journal of Pharmaceutical Research & Allied Sciences*, **8**, 53-58.

[70] Habeballa, R.S., Ahmedani, E.I., Awad, N.S. and Abdein, M.A. (2020) *In Vitro* Antiviral Activity of *Illicium verum* and *Zingiber officinale* Ethanolic Extracts. *Medical Science*, **24**, 3469-3480.

[71] Al-Harbi, N.A., Awad, N.S., Alsberi, H.M. and Abdein, M.A. (2019) Apoptosis Induction, Cell Cycle Arrest and *in Vitro* Anticancer Potentiality of *Convolvulus spicatus* and *Astragalus vogelii*. *World Journal of Environmental Biosciences*, **8**, 69-75.

[72] Osman, A.K. and Abdein, M.A. (2019) Karyological and Molecular Studies between Six Species of Plantago in the Northern Border Region at Saudi Arabia. *Journal of Taibah University for Science*, **13**, 297-308. https://doi.org/10.1080/16583655.2019.1571400

[73] Abdein, M.A., Wrda, H.N. and Osman, A.K. (2020) Genetic Characterization of Genus Tephrosia Pers. Based on Molecular markers in KSA. *International Journal of Botany Studies*, **5**, 203-209.

[74] Alqahtani, M.M., Abdein, M.A. and Abou El-Leel, O.F. (2020) Morphological and Molecular Genetic Assessment of Some Thymus Species. *Biosciences Biotechnology Research Asia*, **17**, 103-113. https://doi.org/10.13005/bbra/2815

[75] Alhaithloul, H. (2023) Phytochemical Screening of Some Medicinal Plants in Al Jouf, KSA. *Open Journal of Ecology*, **13**, 61-79. https://doi.org/10.4236/oje.2023.132006

[76] Abdein, M.A. (2018) Genetic Diversity between Pumpkin Accessions Growing in the Northern Border Region in Saudi Arabia Based on Biochemical and Molecular Parameters. *Egyptian Journal Botany*, **58**, 463-476.

[77] Osman, A.K. and Abdein, M.A. (2019) Floristic Diversity of Wadi Ar'ar, Saudi Arabia. *Journal of Taibah University for Science*, **13**, 772-789. https://doi.org/10.1080/16583655.2019.1634177

[78] Abdein, M.A. and Osman, A.K. (2020) Plant Diversity Assessment of Wadi Al-Hilali, Northern Border region, Saudi Arabia. *International Journal of Botany Studies*, **5**, 87-95.

[79] Rayan, A.M., Abdein, M.A. and Ibrahim, A.A. (2020) Associated Weeds of Some

Agroecosystems in the Northern Border Region, KSA. *International Journal of Botany Studies*, **5**, 345-351.

[80] Delcourt, P.A., Nester, P.L., Delcourt, H.R., Mora, C. and Orvis, K.H. (2002) Holocene Lake-Effect Precipitation in Northern Michigan. *Quaternary Research*, **57**, 225-233. https://doi.org/10.1006/qres.2001.2308

[81] Spinage, C.A. (2012) African Ecology—Benchmarks and Historical Perspectives. Springer Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-22872-8

[82] Berkelhammer, M. (2012) An Abrupt Shift in the Indian Monsoon 4000 Years Ago. In: Giosan, L., Eds., *et al.*, *Geophysical Monograph Series*: *Climate Landscapes and Civilization*, American Geophysical Union, Washington DC. https://doi.org/10.1029/2012GM001207

[83] Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A.A., Hultman, N., Mcfarland, J.R., Binsted, M., Cui, R., Fyson, C., Geiges, A., Gonzales-Zuñiga, S., Gidden, M.J., Höhne, N., Jeffery, L., Kuramochi, T., Lewis, J., Meinshausen, M., Nicholls, Z., Patel, P., Uth, S.R., Rogelj, J., Waldhoff, S., Yu, S. and Mcjeon, H. (2021) Can Updated Climate Pledges Limit Warming Well below 2˚C? *Science*, **374**, 693-695. https://doi.org/10.1126/science.abl8976

[84] IEA (2021) Technical Note on the Emissions and Temperature Implications of COP26 Pledges. https://iea.blob.core.windows.net/assets/aa17bd09-2ad0-4d0a-b5aa-ee418900c4af/Theimpactsofnewemissionspledgesonlongtermtemperatures.pdf

[85] Tai, K. (2021) National Trade Estimate Report on Foreign Trade Barriers. Office of the United States Trade Representative.

[86] Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J.F., Tokgoz, S., Hayes, D.J. and Yu, T.-H.E. (2008) Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, **319**, 1238-1240. https://doi.org/10.1126/science.1151861

[87] OECD (2009) The Economics of Climate Change Mitigation: Policies and Options for Global Act Ion beyond 2012. OECD, Paris.

[88] OECD (2009) Cities, Climate Change and Multilevel Governance. Environment Working Papers, OECD, Paris.

[89] Liu, H.-Y., Skandalos, N., Braslina, L., Kapsalis, V. and Karamanis, D. (2023) Integrating Solar Energy and Nature-Based Solutions for Climate-Neutral Urban Environments. *Solar*, **3**, 382-415. https://doi.org/10.3390/solar3030022