REASSESSING CLIMATE VARIABILITY THROUGH GEOLOGICAL TIME: IMPLICATIONS FOR ENVIRONMENTAL MANAGEMENT AND HAZARD MITIGATION

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EXTENDED ABSTRACT

Il presente studio esamina il complicato rapporto dei processi climatici, geologici e atmosferici che modellano le forme, i paesaggi e gli ecosistemi compresi i cambiamenti del reticolo idrografico, l'erosione del suolo e la generale degradazione del territorio, con effetti diretti sui rischi idrogeologici. Il record geopaleontologico rivela che il clima è il risultato cumulativo di decine di migliaia di anni di fenomeni sub-climatici che, a loro volta, derivano da eventi atmosferici che si verificano nel corso di decenni o secoli. Questa comprensione gerarchica degli eventi climatici, che abbraccia la scala meteorologica, sub-climatica e climatica, sfida le definizioni attuali fornite da istituzioni come il World Meteorological Organization le quali non considerano adeguatamente le complessità temporali e geologiche presenti nel record geologico. Gli archivi geologici, infatti, sottolineano che le fluttuazioni climatiche si verificano su scale temporali millenarie, con effetti profondi sulle forme del suolo e sugli ecosistemi. Queste fluttuazioni sono influenzate da fattori terrestri e astronomici, inclusi i cicli di Milanković, che forniscono un quadro matematico validato per comprendere le oscillazioni climatiche a lungo termine. Tuttavia, le definizioni moderne di clima e dei fenomeni sub-climatici non integrano tali prove, portando a strategie non coerenti nell'affrontare le sfide ambientali.

Questo studio sostiene la necessità di una rivisitazione della terminologia climatica, enfatizzando la natura gerarchica di questi fenomeni: 1) i fenomeni meteorologici si sviluppano nell'arco di decine o centinaia di anni; 2) i fenomeni sub-climatici si accumulano nel corso di centinaia o poche migliaia di anni; 3) i fenomeni climatici si manifestano in periodi di decine di migliaia di anni o più. Adottando questo quadro, lo studio offre una lente attraverso cui comprendere il clima come un processo multilivello e cumulativo, alimentato sia da cicli naturali che da eventi episodici. Riconoscere queste distinzioni è fondamentale per prevedere le pericolosità ambientali e creare strategie efficaci e sostenibili per la gestione delle risorse terrestri e idriche e dei rischi geologici. I risultati evidenziano anche i limiti dell'affidarsi a misurazioni strumentali, che coprono solo gli ultimi due secoli, rispetto alle ampie informazioni offerte dai record geologici e paleontologici che si estendono su milioni di anni. Questa discrepanza sottolinea la necessità di una prospettiva temporale più coerente nelle politiche climatiche, concentrandosi su tendenze naturali a lungo termine piuttosto che sugli impatti antropogenici isolati.

Infine, lo studio critica l'assunzione che il riscaldamento globale moderno sia prevalentemente antropogenico, suggerendo che l'interazione tra i livelli di CO_2 e la temperatura nel corso del tempo geologico è più complessa di quanto i modelli climatici suggeriscano. Sebbene la mitigazione dei gas serra sia fondamentale per ridurre le polveri sottili e migliorare le condizioni ambientali, le tendenze climatiche più ampie rimangono governate da forze che sono al di fuori del controllo umano. Questa prospettiva gerarchica sugli eventi climatici pone le basi per strategie adattive in geologia applicata e gestione ambientale. Integrare le intuizioni climatiche, per definizione a lungo termine, nei quadri di valutazione degli eventi regionali può migliorare la conservazione delle risorse naturali, mitigare i rischi idrogeologici e guidare la pianificazione dell'uso del territorio. Una definizione più chiara e delineata dei fenomeni climatici e sub-climatici a livello globale, regionale e territoriale è essenziale per sviluppare misure mirate ed efficaci per affrontare le sfide ambientali contemporanee e promuovere una gestione sostenibile delle risorse. Con una definizione chiara dei cambiamenti climatici che durano migliaia di anni, nessun essere vivente potrà mai sperimentare un cambiamento climatico. Pertanto, affermare che stiamo vivendo un cambiamento climatico, e che questo sia imputabile all'attività umana, risulta difficilmente sostenibile, alla luce delle evidenze scientifiche provenienti dagli archivi naturali.

ABSTRACT

Present-day landscapes and biomes result from interactions among climate, landform dynamics, and atmospheric processes, driving environmental risks such as soil erosion, hydrological changes, and land degradation. Geological records show transitions between cool-cold and temperate-warm climate cycles, shaping both landforms and ecosystems. The geopaleontological record, from deep geological time to present, shows climate as the cumulative result of tens of thousands of years of sub-climate phenomena, which stem from weather events unfolding over decades to centuries. These long-term records provide vital context for assessing geological hazards and guiding sustainable land and water management. Geological evidence shows that climatic fluctuations occur over millennial time scales, far beyond the lifespan of any organism and human influence. This reveals the inadequacy of current meteorological and climatic definitions, which overlook geological complexities. A precise redefinition is needed, distinguishing decadal, centennial, and millennial phenomena to prevent flawed definitions that misguide climate mitigation efforts. Revising meteorological terminology would refocus efforts on adapting to climate realities and implementing effective land and water management policies. This study emphasizes adaptive management integrating geological and climatic data. Clear definitions of climate, sub-climate, and meteorological events at global, regional, and local levels are vital for forecasting risks and promoting sustainable solutions.

INTRODUCTION

Present-day biomes, with all their diverse characteristics and ecosystems, are the culmination of intricate relationships forged over geological time between climate, biota, and landform dynamics. Climate change has been a driving force shaping the distribution, structure, and composition of biomes on Earth (MONCRIEFF *et alii*, 2016; HUNTER *et alii*, 2021). Temperature fluctuations, alterations in precipitation patterns, and other climatic factors have exerted profound influences, sculpting the landscapes we observe today.

The Earth's climate on a global scale can, in turn, be impacted by numerous interdependent components of the atmosphere, hydrosphere, geosphere and biosphere, as well as by their variations and variable interactions through time (LOWE & WALKER, 2015). These include not only the size and composition of terrestrial ecosystems and the biomass present in the oceans, but also biotic responses such as biodiversity shifts, speciation and extinction patterns. Additionally, factors like the distribution and depth of permafrost and ice masses, ocean circulation patterns, and changes in sea level play crucial roles in shaping environmental conditions and influencing biome distribution. Moreover, the climate system can exhibit a degree of inertia across multiple temporal scales, from short-term feedbacks to millennial-scale processes. The present discussion focuses on the delayed responses linked to long-standing drivers, such as orbital forcing and ocean-atmosphere interactions.

Biomes exert significant influence on climate dynamics, hydrological processes, and serve as interfaces for energy flux between the atmosphere and terrestrial systems (MCPHERSON, 2007; LIU & REN, 2012; MUSAU *et alii*, 2016; MALHI *et alii*, 2022). Forests can influence Earth's albedo, as well as local to regional temperatures by providing shade and releasing moisture through transpiration (WOODWARD *et alii*, 2004; LOWE & WALKER, 2015), while large bodies of water, such as oceans, can moderate nearby climates by absorbing and releasing heat. Additionally, the distribution of vegetation across biomes affects atmospheric circulation patterns and precipitation regimes. Thus, biomes not only respond to climate changes but also contribute to the complex feedback loops that regulate Earth's climate system. Throughout Earth's history, the interplay between climate and biome has been a continuous story of adaptation and transformation. Past climatic variations have acted as catalysts for the emergence, expansion, and contraction of various biomes, each adapting to the prevailing environmental conditions. From the lush rainforests of the tropics to the vast expanses of deserts and tundra, the present-day mosaic of biomes reflects the legacy of these historical interactions. By delving into the geological archives of climate change and examining the fossil record, we gain insights into the processes that have shaped the present biome. Understanding how past climates influenced biome evolution provides essential context for interpreting current ecological patterns and anticipating future changes, underscoring the dynamic nature of ecosystems and the resilience of life in the face of environmental upheavals. By contextualizing present-day biomes within the framework of past climatic interactions, we can better appreciate the complexity of Earth's ecological tapestry and chart a course towards sustainable management of our planet's precious biodiversity.

Climate science deals with a complex archive of records of both terrestrial and extraterrestrial events that occurred through geological time. Earth has undergone significant climatic changes, particularly during the period known as the Quaternary, commencing approximately 2.588 Ma. In this geological interval, the planet experienced alternate cycles of colder and milder periods, manifesting as glacial and interglacial phases at higher latitudes, and as rainy or arid phases at mid-low latitudes (HAYS *et alii*, 1976; BRADLEY, 1999; NICHOLSON, 2000; DEMENOCAL, 2001; RUDDIMAN, 2001; LISIECKI & RAYMO, 2005; LOWE & WALKER, 2015). Nevertheless, climatic variations were not exclusive to the Quaternary Period. Other time intervals in geological history have also documented substantial climate changes (CROWLEY &

NORTH, 1991; SCOTESE *et alii*, 2001b; ROYER *et alii* 2001; ZACHOS *et alii*, 2001; KUMP *et alii.* 2011). Geopaleontological evidence traces a complex story of climate fluctuations resulting from an intricate interplay of terrestrial and extraterrestrial factors. Exploring this detailed documentation of geoclimatic events helps researchers towards a more comprehensive understanding of climatic variations in the past and through time. By studying these detailed geoclimatic records, researchers can more accurately interpret modern weather patterns by considering the influence of Earth's ever-changing geological history.

This article provides an outline of the geological evolution of climate, depicted through a condensed synthesis of geopaleontological evidence. The past provides us with an appropriate perspective on the ever-changing, cyclical nature of climate, enabling more reliable forecasts of potential future atmospheric events and facilitating informed and correct land management to mitigate the adverse impacts of extreme weather occurrences. Nevertheless, it seems that misunderstandings regarding the definition of climatic and meteorological phenology have led to divergent interpretations of available data. The aim of the present study is to reframe these discussions by integrating deep-time geopaleontological evidence with contemporary meteorological models, thereby offering a novel perspective on how cyclical climatic processes have shaped biomes over geological time. It will be demonstrated that a more holistic interpretation of climatic records, one that fully accounts for both terrestrial and extraterrestrial influences, can resolve current ambiguities and improve forecasts of future atmospheric events. This integrative approach provides a fresh framework for understanding the interplay between climate dynamics and ecosystem evolution, ultimately guiding more informed land management and sustainability strategies.

CLIMATE: YES, BUT WHAT IS IT?

When discussing climate, it is imperative to precisely define what we mean by this term. The Quaternary Period serves as an ideal backdrop for this discussion, as it is characterized by significant climatic variability.

The Quaternary, which began around the time of the emergence of the genus Homo, is distinguished by its dramatic climate fluctuations (LOWE & WALKER, 2015). These fluctuations entail alternations between glacial periods, characterized by extensive ice coverage and colder temperatures, and interglacial periods, marked by the retreat of ice caps and ice sheets, resulting in more temperate global conditions. While these variations are most prominent at higher latitudes, they also manifest as shifts between wetter and drier phases at medium and low latitudes.

A notable feature of Quaternary climate is the discernible and consistent periodicity of its variations. These patterns, involving warmer intervals (interglacials) and colder phases (glacials),

occur approximately every 41,000 years, beginning roughly 2.5 Ma. Around 1 to 0.8 Ma, a transition to 100,000-year-paced cycles in climate changes commenced (MILANKOVIĆ, 1923, 1941; LISIECKI & RAYMO, 2005). Our civilization has developed within this latter climatic regime. Despite widespread attention to global warming and the commonly held but mistaken belief that we are living in a "post"-glacial phase, it is crucial to recognize that we are currently in an interglacial period (Marine Isotope Stage 1-MIS 1) that began approximately 11.7 ka, following the Last Glacial Maximum (~20 ka) (*e.g.*, RASMUSSEN *et alii,* 2006; VINTHER *et alii,*, 2006; MASSON-DELMOTTE *et alii,*, 2011; TZEDAKIS *et alii,*, 2012). In contrast, some authors (*e.g.*, HUIJZER & VANDENBERGHE, 1998; HELMENS, 2014; PAST INTERGLACIALS WORKING GROUP OF PAGES, 2016) describe the broader climate history of the last 100 ky as the Pleniglacial, a period characterized by alternating glacial (MIS 4, MIS 2) and milder interstadial (the Middle Pleniglacial, MIS 3) conditions rather than a single, continuous glacial cycle. From this viewpoint, the long-term trend beginning with MIS 4 suggests that we are likely to enter a new glacial phase in the geologically near future.

The World Meteorological Organization (WMO) provides an official definition of "climate," which considers climatic phenomena occurring over a 30-year timespan [(https://community.wmo.int/en/activity-areas/climate-services/climate-products-and-initiatives/wmo-climatological-normals (June 2025). See also pdf available at https://www.agroorbi.pt/livroagrometeorologia/DocsProg/Temas&Exerc%C3%ADciosExtraPorCap%C3%ADtulo/Cap1_Introdu%C3%A7%C3%A3o/Docs/WMO%20Guidelines%20on%20the%20Calculation%20of%20Climate%20Normals_en.pdf]. However, this definition fails to capture the full complexity of climate as understood in geological and paleontological contexts. While the WMO's operational definition of climate is applied primarily to instrumentally recorded data spanning only the past 150-200 years (collected through thermometers, rain gauges, tide gauges, barometers, anemometers, probes, satellites, *etc.*), natural archives, such as glaciers, sediments, loess-paleosol sequences, pollen content, tree growth rings, coral development, fossil records of the evolution and spatial distribution of plants, large and small mammal paleoecology and stratigraphy, human evolution and dispersal, *etc.*, indicate that real climate encompasses meteorological events occurring across much longer timescales, spanning thousands of years. This geological perspective situates climate change within a vastly broader framework, encompassing millennia rather than mere decades. From this perspective, climate does not align with the definition provided by meteorologists, but instead corresponds to what is commonly identified today as paleoclimate.

In light of this geological understanding, it becomes evident that Earth's climate has always undergone natural fluctuations

over geological time, predating the influence of human activities. The notion that climate should remain stable or that humanity is solely responsible for climate shifts is highly questionable when viewed through this broader lens of past climate variability (KAGEYAMA *et alii*, 2024; see also https://www.ipcc.ch/report/ar6/wg1/downloads/faqs/IPCC_AR6_WGI_FAQ_Chapter_03.pdf; https://energyeducation.ca/encyclopedia/Natural_vs_anthropogenic_climate_change).

THE CAUSES OF CLIMATE CHANGE: COMPLEX INTERACTIONS OF TERRESTRIAL AND EXTRATERRESTRIAL VARIABLES

Climate variability arises from a multitude of factors, both terrestrial and extraterrestrial, which are only partially understood and often imperfectly so. Milutin Milanković (1923, 1941), inspired by the ideas of other scholars (CROLL, 1875; KÖPPEN & WEGENER, 1924), elucidated some of the terrestrial causes of climate change. He correlated these factors with shifts in how the Earth "exposes" to solar irradiation, identifying regular fluctuations ca. every 100,000-400,000 years in the eccentricity of Earth's orbit, ca. every 41,000 years in the tilt angle of the planet's axis, and ca. every 26,000-23,000 years in the precession of the equinoxes and perihelion. It is worth noting that all these changes unfold in many thousands of years, and not in hundreds or tens of years. Incidentally, we now know that variations in solar radiation alone are insufficient to account for Earth's pronounced 100,000-year climatic cycle, indicating the potential involvement of internal feedback mechanisms (SALTZMAN *et alii*, 1984; TZIPERMAN *et alii*, 2006; LISIECKI, 2010; HUYBERS, 2011; ABE-OUCHI *et alii*, 2013). Previous theoretical frameworks, for instance, proposed that glacial terminations coincide with the accumulation of 'excess ice' in the Northern Hemisphere, yet the specific physical processes driving the 100,000-year cycle remain ambiguous (RAYMO, 1997; PAILLARD, 1998; PARRENIN & PAILLARD, 2003; HUYBERS, 2011; ABE-OUCHI *et alii*, 2013; HERBERT, 2023).

Milanković's research unequivocally demonstrated the pivotal role of orbital geometric variations in shaping the Earth's climate. His studies, which were foundational in developing our understanding of orbital forcing, have been strongly supported by subsequent research. However, some aspects, such as the relatively weak influence of orbital eccentricity on the 100,000-year glacial cycles and the role of the 400,000-year periodicity, remain the subject of ongoing investigation (SZARKA *et alii*, 2020). The substantive merit of Milanković's research and the veracity of his conclusions are also acknowledged by the IPCC (Intergovernmental Panel on Climate Change), the esteemed international authority responsible for assessing climate change. In so doing, the IPCC implicitly affirmed the protracted timescale over which climate changes take place, spanning millennia.

However, there are numerous other terrestrial factors whose cumulative effects over extended time periods equally contribute to shaping Earth's climate. These encompass an intricate web of factors, involving exchanges of gases amidst the hydrosphere, biosphere, and atmosphere; volcanic phenomena; greenhouse gases and aerosols; geothermal energy contributions; the spatial configuration and orientation of a majority of continental land masses in the Northern Hemisphere; the disposition of prominent mountain ranges; intricate thermohaline circulation patterns; the albedo attributes characterizing diverse regions of Earth's surface; as well as the influence of biotic components such as vegetation and animal life, to cite but a sparse selection. All these components interact, contributing to determining the overall energy balance of the planet and thus influencing meteorological changes on a scale of decades. However, we know that these variables redistribute, modulate, amplify, and recycle in various ways a complex energy input primarily of extraterrestrial origin. The Sun is undeniably the main source of energy that reaches Earth and sustains life on it. Our star possesses an extremely complex dynamo-magnetic activity, both cyclical and aperiodic (aperiodic perhaps due to our still very limited and imperfect knowledge). Seventy percent of solar activity can be considered "normal," while 15%-20% exhibits characteristics of the so-called "Grand Solar Minima," and 10%-15% displays characteristics of "Grand Solar Maxima" (the last "Grand Solar Maximum" began in the early 1900s and ended with the 23rd solar cycle in the early years of this century; USOSKIN, 2017; HANSLMEIER, 2020; ZHARKOVA, 2020; BISWAS et alii, 2023; SCAFETTA, 2023; SCAFETTA & BIANCHINI, 2023). We know that the solar wind interferes with the cosmic rays that reach the Solar System, which significantly contribute to cooling the Earth's surface (STEFANI *et alii*, 2020; CONNOLLY *et alii*, 2021). Gravitational interferences from other planets in the Solar System may also influence climate, especially when these planets assume specific alignments (CIONCO & SOON, 2015; SCAFETTA *et alii*, 2016; YNDESTAD & SOLHEIM, 2017; CIONCO & PAVLOV, 2018; CONNOLLY *et alii*, 2021). Furthermore, lunar tidal forces have been shown to modulate atmospheric circulation, affecting Rossby wave dynamics and the Polar Jet Stream, as demonstrated by BEST & MADRIGALI (2015, 2016).

The role of the sun in shaping Earth's atmosphere, hydrosphere, and biosphere, and thereby driving meteorological, sub-climatic, and climatic events (RAISBECK *et alii*, 1990; PEKAREK, 2000; KERN *et alii,* 2012; ABE-OUCHI *et alii*, 2013; CIONCO & SOON, 2017; PANCHANG *et alii*, 2023) is often marginalized in both scientific literature and public reports, while other factors are overemphasized, greenhouse gases above all. There is no doubt whatsoever that neither greenhouse gases nor aerosols, nor any other factors conventionally deemed pivotal in driving "climate change," possess the capacity to generate the requisite energy

for Earth's climatic evolution. Solar activity exhibits evident correlations with numerous terrestrial phenomena, spanning from alterations in Earth's temperatures (Friis-Christensen & Lassen, 1991; Pekarek, 2000; Marsh & Svensmark, 2003) to changes in global sea levels (Mörner, 2019), terrestrial environments (Zharkova *et alii*, 2023), atmospheric and oceanic circulation and rainfall patterns (Bond *et alii*, 2001; Agnihotri *et alii*, 2002; Azharuddin *et alii*, 2019; Berisha, 2023; Maghrabi *et alii*, 2023; Wu *et alii*, 2024), ecological dynamics (Kasatkina *et alii*, 2023), all the way down to, say, human lifespan (Davis Jr & Lowell, 2018) and proliferation of epidemics among human populations (Chen *et alii*, 2023).

Considering the complexity of Earth's climate and its short- and long-term changes, a careful examination of paleoclimatic signals provided by glaciers, sediments, corals, tree rings, fossil records of past faunal and floral communities, and other natural repositories becomes imperative (Scafetta, 2022; Prestininzi, 2022). Such analysis offers a comprehensive understanding of (true) climate changes throughout far longer, more ancient periods than those documented through bicentennial instrumental coverage. But what does geological and paleontological evidence actually tell us?

COMPREHENSIVE ANALYSIS OF EARTH'S THERMAL HISTORY

An examination of the geo-paleontological archive delineates a clear pattern of climatic evolution during the Phanerozoic. In the Paleozoic Era, the four temperature maxima, much warmer average surface temperatures than modern ones, documented by the $\delta 18O$ (18O/16O oxygen isotope ratio) curve date approximately 500, 430-420, 380-370 and 310-300 Ma (Fig. 1a; Scotese *et alii*, 2021b). They are interspersed with as many minima. One of these, corresponding to the Late Ordovician mass extinction, occurred around 445 Ma. This event was driven by significant glaciation, which led to a dramatic drop in sea levels and subsequent anoxia (lack of oxygen) in marine environments (Finnegan *et alii*, 2012; Zhou *et alii*, 2015; Bartlett *et alii*, 2018; Qiu *et alii*, 2022). As a result, there was a substantial loss of marine biodiversity, as many species could not adapt to the changing conditions. Another mass extinction, induced by or associated with intense global cooling and likely also by massive volcanic activity, occurred in the Late Devonian, around 372-359 Ma (Huang *et alii*, 2018; Kravchinsky *et alii*, 2002). This extinction was accompanied by a series of declines in biodiversity and disruptions to marine ecosystems, especially among reef-building organisms. This interval also coincides with the diversification of early terrestrial vertebrates and the spread of vascular plants, which likely influenced atmospheric composition and climate feedbacks. Two additional Palaeozoic thermal minima, dated around 330-320 and 290-280 million

years ago, were as cold as, or even colder than, the Quaternary glacial periods (Fig. 1a; Fielding *et alii*, 2008; Montañez, 2022). These cooling events correspond to the Carboniferous glaciations, linked to the assembly of the supercontinent Pangaea and extensive ice sheet development in the southern hemisphere. The Carboniferous also saw high atmospheric oxygen levels, fostering gigantism in terrestrial arthropods and amphibians.

The Palaeozoic-Mesozoic transition was marked by one of the most severe mass extinctions in Earth's history: the Permian-Triassic Extinction, which occurred about 252 Ma. This catastrophe was likely triggered by massive volcanic eruptions in the Siberian Traps. The volcanic activity led to global warming, ocean acidification, and extensive environmental collapse, causing widespread extinctions and reshaping Earth's biota (Jurikova *et alii*, 2020). The extinction eradicated approximately 90% of marine species and 70% of terrestrial vertebrates, fundamentally reshaping Earth's biota and paving the way for the rise of the dinosaurs and other Mesozoic groups.

Moving along the $\delta 18O$ curve, the ensuing Mesozoic Era starts with a particularly warm interval, succeeded by two relatively cooler phases approximately 200 and 150 Ma, coinciding with the initial breakup of Pangaea and associated changes in ocean circulation and climate patterns (Fig. 1a; Song *et alii*, 2019; Scotese *et alii*, 2021b). Two intense warming episodes occurred around 180 and 100-90 Ma, corresponding to the Jurassic and mid-Cretaceous thermal maxima, respectively. These warm intervals facilitated the diversification of dinosaurs, early mammals, birds, and the emergence of angiosperms, which dramatically altered terrestrial ecosystems).

During the early Mesozoic, Pangaea, the vast supercontinent, encompassed the majority of contemporary landmasses. It consists of two principal subcontinents, Laurasia to the north and Gondwana to the south, positioned approximately along the equatorial belt, while the oceans assume a predominantly latitudinal arrangement. This configuration strongly influenced global climate patterns, with vast continental interiors experiencing extreme seasonality and arid conditions, while the surrounding oceans exhibited predominantly latitudinal circulation patterns (Scotese *et alii*, 2021b). The early Mesozoic witnessed the ascendancy of dinosaurs, the prolific radiation of ammonites, and the widespread development of hexacoral reef barriers. It was also the era when birds and primitive mammals first emerged, alongside the initial appearance of angiosperms, which would later transform terrestrial ecosystems.

About 201.4 Ma, volcanic eruptions from the Central Atlantic Magmatic Province contributed to significant global warming and environmental stress (Capriolo *et alii*, 2022). This event precipitated the Triassic-Jurassic mass extinction, a major biotic crisis that, at the transition from between Triassic and Jurassic Periods, reshaped both marine and terrestrial

Fig. 1 - *Δ18O curves of paleotemperatures at various temporal scales: a) Oxygen isotope curve reconstructing surface temperatures of tropical seas over the last 500 Ma (adapted from SCOTESE et alii, 2021b). b) Oxygen isotopic curve reconstructing deep ocean isotopic temperatures during the Cenozoic over the last 66 Ma (adapted from SCOTESE et alii, 2021b). c) Oxygen isotopic curve of the last 2.6 Ma (adapted from LOWE & WALKER, 2015). d) Reconstructed Holocene temperature record from the Greenland Ice Sheet Project 2 (GISP2) ice core (adapted from SCAFETTA et alii, 2016). e) High-resolution sea-surface temperatures (spanning between 2 and 5 years) over the last 2000 y (adapted from SICRE et alii., 2008).*
A.D. = Anno Domini; C = Carboniferous; C O = Climate Optimum; Cm = Cambrian; Cool P = cool period; D = Devonian; E P = Early Pliocene; I C = Ice Cap; J = Jurassic; K = Cretaceous; L M = Late Miocene; LGM = Last Glacial Maximum; MPR = Middle Pleistocene Revolution; MPT = Middle Pleistocene Transition; N = Neogene; O = Ordovician; P = Permian; Pg = Paleogene; S = Silurian; T = Triassic; W P = warm period; δ18O = 18O/16O isotope ratio

ecosystems by eliminating many species and opening ecological niches for the subsequent dominance of dinosaurs and other groups (Whiteside *et alii*, 2010). The extinction also coincides with shifts in ocean chemistry and climate that had long-lasting impacts on biodiversity and ecosystem structure. During the mid-Mesozoic, Pangaea broke up, and the continental fragments predominantly began migrating towards the planet's northern pole, while the oceans gradually assume the longitudinal arrangement we see today (Scotese *et alii*, 2021b). This tectonic reconfiguration influenced ocean circulation and climate, contributing to regional climatic heterogeneity. Progressing towards the end of the Mesozoic, a decline in global temperatures is evident in the δ18O curve, around 80-70 Ma.

Around 66 Ma, three concurrent events profoundly affected Earth's climate: an asteroid impact near the Yucatán Peninsula, a massive resurgence of volcanic activity in the Indian Deccan Traps, and significant changes in sea levels affecting the epicontinental seas that once covered much of North America (Dingus & Rowe, 1997; Alvarez *et alii*, 1980; Self *et alii*, 2022 and references therein; Stringer & Sloan, 2023). This combination of factors led to the Cretaceous-Paleogene Extinction, a world-famous event that triggered drastic climate changes, including atmospheric dust loading, acid rain, and greenhouse warming, which together reshaped global biodiversity and resulting in the extinction of approximately 75% of Earth's species. This included not only the non-avian dinosaurs but also flying and marine reptiles, as well as a wide range of marine organisms such as ammonites, rudists, foraminifera, coccolithophores, and various zooplankton taxa.

This catastrophic event was followed by a substantial temperature rebound, with global climates becoming significantly warmer, upon transitioning to the Cenozoic era (Figs. 1a, b). The escalation of global temperatures culminated around 57 to 50 Ma with a series of global perturbations of atmospheric CO_2 and CH_4 content and global climate of still debated origin, defined by Paleogene "hyperthermal" events (such as the Paleocene-Eocene Thermal Maximum, PETM, and the Early Eocene Climatic Optimum; Zachos *et alii*, 2001, 2008; Higgins & Schrag, 2006; Dunkley Jones *et alii*, 2013; Gutjahr *et alii*, 2017; Harper *et alii*, 2020) representing much warmer peaks than any intervals since the emergence of hominids (Fig. 1b). The PETM, in particular, is noted for its profound impacts on marine and terrestrial ecosystems, including rapid species migrations, extinctions, and evolutionary radiations.

From that juncture onwards, the δ18O curve, with more or less extensive oscillations, descends towards progressively colder temperatures. The start of the Oligocene, approximately 34-33 million years ago, coincided with the progressive paleogeographic isolation of Antarctica due to its separation from South America and Australia, leading to the opening of the Drake and Tasmanian gateways. This allowed for the establishment of the Antarctic Circumpolar Current, thermally isolating Antarctica from warmer ocean currents and initiating the formation of a continental-scale ice sheet that eventually blanketed the continent with thousands of meters of ice (Zachos *et alii*, 2001) (Fig. 1b). In parallel, a substantial decline in atmospheric CO_2 concentrations across the Eocene-Oligocene transition likely contributed to the global temperature drop, consistent with the so-called CO_2 Hypothesis (Lunt *et alii*, 2014). For the first time in many million years, one of Earth's poles came to be permanently shrouded by an ice cap. Since then, the δ18O curve has displayed an ongoing, relentless, and inexorable planetary cooling (Railsback *et alii*, 2015; Scotese *et alii*, 2021a, 2021b).

The stratigraphic records worldwide serve as eloquent testaments to the substantial influence exerted by astronomical forcing on climate change (Hinnov, 2013). Carbonates were the dominant lithologies in lower Mesozoic to early Cenozoic sedimentary successions, extending up to their earliest Oligocene strata (Berner *et alii*, 1983; Bosellini, 1989; Milliman & Droxler, 1996; Arvidson *et alii*, 2006; Pomar & Kendall, 2008). Conversely, terrigenous siliciclastic sediments predominate in the more recent, upper parts of the stratigraphic successions, which have significantly lower carbonate contents. The carbonates largely derive from oozes that are fed by a continuous rain-out from the water column of mixed organic detritus, termed "marine snow" (Lowe & Walker, 2015). In warm tropical to subtropical seas marine snow is largely constituted by carbonate shells of planktonic and benthic microorganisms. The marked reduction of these carbonate accumulations in the past submarine archives preserved in stratigraphic sequences worldwide thus serves as a marked signal of significant and gradual global cooling of the Earth's oceans over the last 34-33 My (Zachos *et alii*, 2001; Coxall *et alii*, 2005; Bohaty *et alii*, 2009; Liu *et alii*, 2009; Prothero & Berggren, 2014; Westerhold *et alii*, 2020).

The most recent peak of relatively warmer and more humid climatic conditions occurred during the early to mid-Miocene, approximately 18-15 Ma (Railsback *et alii*, 2015; Scotese *et alii*, 2021a, 2021b) (Early-Middle Miocene C O in Fig. 1b). Lush, warm-moist tropical-subtropical forests spread over wide expanses of land, from the equator to temperate regions. Alternating warmer and cooler phases characterized the Late Miocene, around 7 Ma, and the following Pliocene Epoch, from 5.3 to 2.6 Ma, all set against the backdrop of an overarching and discernible trend of gradual cooling (L M - E P C O in Fig. 1b).

Most prominent changes in Pliocene biome distribution compared to today include northwards shift of temperate and boreal vegetation zones in response to a warmer and wetter climate as well as an expansion of tropical savannas and forests at the expense of deserts (Salzmann *et alii*, 2011). Similar large-scale biome shifts had also occurred during earlier Cenozoic hyperthermal events, such as the PETM (Zachos *et alii*, 2001;

MUDELSEE *et alii*, 2014), when Arctic and subarctic latitudes were covered by extensive paratropical forests (SUNDERLIN *et alii*, 2011; CLIFTON, 2012; AKHMETIEV, 2015; GOLOVNEVA *et alii*, 2023).

During the Pliocene, the Arctic region was devoid of ice, and boreal forests, primarily dominated by coniferous trees, extend northward, reaching as far as northern Greenland and the Arctic Archipelago situated to the north of mainland Canada (MACPHEE, 2018). In the marine realm, the Pliocene is characterized by a reconfiguration of ocean gateways, particularly the narrowing of the Indonesian Seaway and closure of the Central American Isthmus, which produced an essentially modern pattern of ocean circulation (MCGIRR *et alii*, 2021). In the Southern Ocean, a warm early Pliocene climate gave way to late Piacenzian cooling. Proxy data indicate a reduced east-to-west sea surface temperature gradient in the tropical Pacific during this period of Pliocene warmth (SALZMANN *et alii*, 2011).

These climatic and oceanographic conditions influenced terrestrial ecosystems as well. Between 5 and 2.6 Ma, Eurasia was dominated by warm and humid sequoia forests (COMBOURIEU-NEBOUT *et alii*, 2015), inhabited by mastodons, tapirs, rhinoceroses, small-sized cervids, black bears, saber-toothed tigers, and other solitary carnivores, typical ambush predators well-adapted to densely forested environments (KAHLKE *et alii*, 2011). These ecological contexts closely resemble the warm and humid forests of present-day Southeast Asia.

As the Pliocene gave way to the Pleistocene, increasing climate variability became a defining feature, particularly in tropical Africa.

Although fragmentary, the African faunal and paleoclimatic records reveal periodic shifts between wetter and drier conditions, during the Plio-Pleistocene, notably around 2.8 Ma, 1.7 Ma, and 1.0 Ma, in alignment with glacial cycles (PETER, 2004). However, these records do not support a unidirectional trend toward sustained aridity. Instead, under conditions of diminished summertime insolation, which typically prompted glacial expansion at high-latitudes and heightened aridity in tropical Africa, there is evidence for an intensification of millennial-scale climate fluctuations (LUPIEN *et alii*, 2020). Faunal transformations occured at key temporal junctures, such as 2.9-2.4 Ma and after 1.8 Ma, corresponding to pivotal stages in early hominid evolution (PETER, 2004). Hominins likely had to contend with increasing climate instability amid already pre-existing exceptionally challenging environmental conditions.

Progressive cooling during the Late Pliocene culminated around 2,588 Ma, when Greenland became covered with ice and the Arctic ice sheet expanded, essentially forming for the first time (Arctic I C in Fig. 1b). This pivotal event marked the beginnig of the Pleistocene, the first Epoch of the Quaternary Period, and the Earth's most recent geological interval. At this juncture, both poles of the planet are occupied by glacial caps, an unprecedented situation at least since the Mesozoic Era (250 Ma).

Following this event, global climate conditions appear to primarily respond to the 41,000-year obliquity orbital periodicity (IMBRIE *et alii*, 1992; LISIECKI & RAYMO, 2005) (Figure 1C). Temperatures inexorably continued to decrease, with each cold phase accompanied by growing aridity. The warm moist forests were gradually replaced by cool-temperate forests during interglacial phases and by wooded-grasslands/steppe-savannas during glacial phases (COMBOURIEU-NEBOUT *et alii*, 2015).

The drastic environmental transformation leads to the replacement of the original tropical-subtropical fauna, associated with warm moist forested habitats, with species adapted to typical steppe-like settings. Gradually, faunal assemblages ecologically akin to present-day African savannahs, albeit adapted to cooler-colder environments, began to take shape (KAHLKE *et alii*, 2011). This transformation is initiated by the arrival of antelope-like forms, ecologically similar to wildebeests. Subsequently, elephants, zebra-like equids, rhinoceroses, large suids, cervids of varying sizes, carnivorous bears more akin to today's brown bear, canids resembling modern wolves, coyotes, and African wild dogs, panthers, lynxes, wildcats, giant cheetahs, giant hyenas, and beavers, to mention but a few characteristic faunal components of this interval, arrived (KAHLKE *et alii*, 2011). Herds of seasonably mobile grazing herbivores gradually supplant the original solitary browsers and grazers, and the mostly ambushing carnivores of the Pliocene, typical of densely vegetated forested settings, were replaced by gregarious predators and fleet-footed runners of open environments. Towards the mid-Early Pleistocene, around 1.8 Ma, *Homo georgicus*, the earliest known hominin in Eastern Europe, arrived from Africa and settled in what is now Georgia (VEKUA *et alii*, 2002). This was followed by subsequent arrivals of a close relative, Homo erectus. Soon after, hippopotamuses and giant deer enrich the faunal communities.

A pivotal transformation in vegetation occurred approximately 1.2 Ma, characterized by a reduction in needle-leaved forest and a considerable spread of Artemisia, Chenopodiaceae, and Poaceae grasslands. Subsequently, a persistent deterioration of the local forest vegetation ensued, ultimately yielding to its displacement by woody grassland around 0.7 Ma (ZHOU *et alii*, 2018). In fact, towards the end of the Early Pleistocene, starting approximately 1,000,000-900,000 years ago, the cool-cold/temperate-warm alternations became irregular. This is possibly caused by an extremely warm interglacial event in the Ross Sea, Antarctica (SCHERER *et alii*, 2004). After about 800,000 years ago, hence from the onset of the Middle Pleistocene, there was a marked prolongation and intensification of the glacial/interglacial climate cycles to 100,000 years: it is the so-called MPR (Mid-Pleistocene Revolution) (MAASCH & SALTZMAN, 1990; BERGER & JANSEN, 1994; MUDELSEE & STATTEGGER, 1997; KAHLKE, 2000; LISIECKI & RAYMO, 2005; MASLIN & RIDGWELL, 2005) or MPT (Mid-Pleistocene Transition) (HERBERT, 2023)

(Fig. 1c). Environmental conditions demonstrated a progressive rise in continentality, with greater disparity between winter and summer temperatures. These alterations in climate, especially the heightened severity and prolonged duration of cold periods, exerted a profound impact on both the biota and the physical landscape, with particular impact in the Northern Hemisphere. In Eurasia, periodic temperate phases, characterized by the proliferation of broad-leaved forests in the plains and needle-leaved forests on the highlands, alternate with cold phases during which the plains transition to grassy steppes as the forests recede (COMBOURIEU-NEBOUT *et alii*, 2015). This leads to a major reorganization of large-mammal communities, with the extinction of many original species from the Early Pleistocene and their replacement by new species originating from both Asia and Africa, better suited to the modified environmental contexts. New elephants and rhinoceroses appeared, alongside wild horses, wild boar, bison, aurochs, red deer, roe deer, spotted hyena, bears (both brown and cave), wolf, lion, and leopard (HEAD & GIBBARD, 2005; KAHLKE *et alii*, 2011). Eurasia served as the destination for subsequent hominin migrations, especially marked by one that ultimately results in the emergence of *Homo neanderthalensis*.

The Middle Pleistocene, from approximately 800,000 to about 130,000 years ago, witnessed fifteen climatic oscillations, seven temperate-warm ones (two notably warm, around 400,000 and 220,000 years ago) and eight cool-cold ones (two particularly cold, at 650,000 and 350,000 years ago) (HEAD & GIBBARD, 2005). The Late Pleistocene started with a very warm event around 123,000-109,000 years ago (also known as the Eemian Interglacial; TURNER, 2002; SHACKLETON *et alii*, 2003), during which temperatures were so high that elephants, rhinoceroses, and hippopotamuses reached the high latitudes of the British Isles. Following this event, temperatures gradually began to decrease, albeit punctuated by a series of significant warm-humid oscillations (as many as twenty, known as Dansgaard–Oeschger events; DANSGAARD *et alii*, 1993; MENVIEL *et alii*, 2014) and cold-dry periods (six of which are particularly cold, referred to as Heinrich events; HEINRICH, 1988; BOND *et alii*, 1992) (PEDRO *et alii*, 2022). According to multiple sources, approximately 50,000 years ago, during the last glacial interval, habitats underwent fragmentation, resulting in the isolation of large mammal populations. The fauna experienced a progressive decline and ultimately becomes extinct from Eurasia (LISTER & BAHN, 1994; WARD, 1997; REUMER, 2007; MONDANARO *et alii*, 2021). Pachyderms vanish swiftly, followed by most carnivores. The climate change trend culminated in an intense glacial phase, dubbed the LGM (Last Glacial Maximum) (Figure 1C). The LGM occurred approximately 20,000 years ago, followed by the so-called 'post-glacial' period, marked by a progressive global climatic amelioration (the end of the LGM actually marks the onset of the current interglacial, the geological

interval of warmer average global temperatures in which we are living today). Nevertheless, this improvement in climatic conditions was abruptly interrupted by a momentaneous, short-lasting (in geological terms) yet intense cooling event, occurring approximately between 12,900 and 11,700 years ago (Younger Dryas) (BROECKER *et alii*, 2010; MAHANEY, 2023). This dramatic climate change resulted in the extinction of 34 genera of large mammals in North America and 46 additional genera in South America. Moreover, it coincided with the disappearance of the Clovis culture, the earliest known human culture in North America. The Pleistocene Epoch concludes 11,700 years ago, starting the current Epoch, known as the Holocene.

In the early part of the Holocene, there are pervasive trends of environmental "banalization", here understood as a significant reduction in overall biodiversity, alongside simplification, marked by declining species richness and habitat homogenization (SMITH *et alii*, 2022; PUZACHENKO & MARKOVA, 2023). Eurasia becomes predominantly covered by near-continuous forestation, stretching from western Spain to the eastern fringes of Russia. Conversely, the Near and Middle East gradually undergo desertification, while extensive grasslands blanket North America. This substantial environmental degradation is perhaps the primary among the numerous contributing factors that compel the majority of human populations across various parts of the planet to transition almost simultaneously from a nomadic, hunting and gathering lifestyle, to a sedentary one. This transition is particularly evident in the Fertile Crescent region, where archaeological evidence correlates with significant environmental shifts driving the domestication of wheat and barley (NYU, 2024). This marks the so-called "Neolithic Revolution" of the ancient Holocene, during which the domestication of both plants and animals experiences its greatest momentum, culminating in agriculture and animal husbandry. These agricultural practices become the sole means to procure the resources necessary for the survival of exponentially growing human populations (BLAKEMORE, 2019).

It is crucial not to misconceive the Holocene as a climatically stable interval; quite the contrary. Understanding Holocene solar and climatic variations on centennial to millennial timescales has been advanced by recent research employing new proxies and analytical methods. Studies utilizing nitrate concentrations from ice cores and advanced wavelet analysis have identified fundamental solar modes and their correlations with climate proxies across various global regions (SOON *et alii*, 2014). This research highlights the significant role of solar activity in shaping long-term climatic variations and underscores the complexity of climatic responses to solar modulation.

The present interglacial phase initially leads to a series of warm peaks, around 10,000 and 4,800 years ago, referred to as the early Holocene Optimum (ARZHANOV & MOKHOV, 2017; MAGNY, 2023) (Fig. 1d). The rest of the Holocene presents intermittent

cooler periods interspersed within generally warmer phases. Specifically, there were three warm intervals, one at the time of the Minoans, another during Ancient Rome (Roman Warm Period), and a third during the High Middle Ages (Medieval Warm Period), with the Dark Ages cool period in between (Figs. 1d, e).

The Holocene further encompasses the Little Ice Age, spanning from 1300 through 1900, with its coldest phase known as the Maunder Minimum (1645–1715), and culminates in the ongoing warm modern period (HOLZHAUSER, 1997; PFISTER *et alii*, 1998; WANNER *et alii*, 2000; MCGANN, 2008; SICRE *et alii*, 2006, 2008; HONG *et alii*, 2009; LÜNING *et alii*, 2017, 2018, 2019) (Figs. 1d, e). Notice the centennial pacing of the sub-climatic oscillations and the decadal ones of the meteorological events (Fig. 1e).

Around 10,550 years ago, near Pisa, the sea level is approximately 35 m below the current average level. Later on, and until around 7,050 years ago, it rises rapidly, slowing down its rate of growth only after this date. Around 6,050 years ago, the sea level is some -5 m relative to the current average level (KANIEWSKI *et alii*, 2018). From then on, the rate of sea level rise further slows down, reaching a minimum over the last 4,000 years, during which the global variation in relative sea level stays within 1.5 m of the modern mean level. Recent high-resolution studies further refine these reconstructions, offering insights into localized coastal dynamics and sedimentary processes in the Western Mediterranean (ONAC *et alii*, 2022).

Two major sub-climatic events punctuate the Holocene Epoch. The first, occurring approximately 8,200 years ago, is a short-lived but abrupt cooling episode that defines the boundary between the Greenlandian and Northgrippian stages (ALLEY & ÁGÚSTSDÓTTIR, 2005; ROHLING & PÄLIKE, 2005). The second, more prolonged event occurs around 4,200 years ago, marking the transition from the Northgrippian to the Meghalayan stage (WEISS *et alii*, 1993; STAUBWASSER & WEISS, 2006). Around this time, a sharp reduction in rainfall diminishes the overall fluvial discharge, leading to a decrease in agricultural and pastoral activities in the Pisa area, reaching a nadir around $4,150 \pm 45$ years ago. The event concludes around $3,950 \pm 45$ years ago, transforming the basin into an extensive alluvial area with a significant influx of freshwater (KANIEWSKI *et alii*, 2018).

These reconstructions reflect the melting trends of the Laurentide ice sheet in North America and are perfectly consistent with what was also recorded in the central and northern parts of the Western Mediterranean. Historical sources inform us that around 2,200 years ago, a natural lagoon formed near Pisa, connected to the sea through a strait; there the Romans built Portus Pisanus, which survives until the 5th century CE. The decline of the protected lagoon began around 1350 and peaked around 1500 when it transformed into a coastal lake (KANIEWSKI *et alii*, 2018). This compelled Cosimo I de' Medici to establish the city and port of Livorno. As seen, the evolution of the Pisan port basin was significantly influenced by sea-level excursions, governed by substantial sub-climatic changes.

History offers further evidence regarding the Roman Warm Period. The principal ancient authorities on the invasion routes followed by the Punic Army in 218 BC across the Alps are Polybius and Livy (POLYBIUS; LIVY; OAKLEY, 2019). Of the two, Polybius holds a position of prominence due to his personal exploration of the invasion route, conducted some 60 years after the event. Conversely, Livy, who resided in Padua, did not undertake a similar journey and based his account on sources that are no longer available. In the third volume of his Ἱστορίαι Polybius informs us that Hannibal crossed the Alps towards the end of September leading a force of 38,000 men, 8,000 cavalry mounts, an "immense string of beasts" (pack animals), thousands of handlers and 37 elephants (POLYBIUS), the modern equivalent of nearly four infantry divisions. The army presumably passed through a valley about 3000 m asl (MAHANEY, 2008; MAHANEY *et alii*, 2008, 2016). "He" (Hannibal) "had spent fifteen days in crossing the Alps" (POLYBIUS) completing the journey at "the setting of the Pleiads" when "snow had already gathered on the summit" (October) (POLYBIUS). The elephants most probably were of the species Loxodonta cyclotis (LAZENBY, 1978; GERKENS, 2013; ESPOSITO, 2023), now prevalent in the warm climates of West Equatorial Africa.

It is worth highlighting that in his accounts of Hannibal's mountain crossings, such as the Pyrenees or the Alps, Polybius refers to "snow," whereas any mention of "ice" or "glacier" remains conspicuously absent. In fact, it is important to recognize that the term "glacier" is not found in ancient Latin, and the concept itself was likely unfamiliar to the ancient Romans. Etymologically, the word glacier is a loanword from French language, with its origins tracing back, through Franco-Provençal language, to the Vulgar Latin term glaciārium. This term, in turn, stems from the Late Latin glacia, which can be ultimately traced back to the Latin word glaciēs, meaning "ice" (SIMPSON, 1979).

Concerning the Medieval Warm Period, during the High Middle Ages, concurrent with the Maya civilization succumbing to a severe drought reaching its apex around 1000 CE (DOUGLAS *et alii*, 2016), Icelandic settlers established themselves in Greenland circa in the year 985. They occupied regions corresponding to present-day districts of Narsaq, Julianehaab, and Godthaab (LAMB, 1982). Their deceased could be buried at a depth in the soil that has remained consistently frozen in permafrost since. During the warm early 12th century, the fjord waters were sometimes warmer by at least 4°C compared to the current average temperature (MCGOVERN, 1981). These climatic conditions may have facilitated trans-Atlantic exploration, such as Norse expeditions to North America, while simultaneously supporting agricultural expansion in Europe (OGILVIE & PALSSON, 2003; COSTELLO, 2021; SKOGLUND, 2023). During that time,

drifting ice only reached the shores of Iceland for a few weeks a year (Koch, 1945). Also, in the early 12th century, in central and western Europe, there is an increasing spread of grape cultivation northwards: medieval vineyards in England are documented up to a latitude of 53° N (McGovern, 1981). Medieval sources report grape harvests even in Bohemia, Thuringia, and Belgium (Alexandre, 1987). During this phase, vineyards were even cultivated at altitudes ranging from 600 to 700 m in the pre-Alpine Toggenburg valley (Scherer, 1874). Indeed, in Norway, agricultural settlements extend up to an altitude of 200 meters on the hills, and wheat is cultivated almost up to the latitude of the Arctic Circle (Lamb, 1984). In Alpine territories, pastures are used up to an altitude of 2800 m (Röthlisberger, 1976). During this climatic "Little Optimum", the transitional seasons are presumably warmer by about 0.7-1.0°C compared to the 20th-century average in England and 1.0-1.4°C in central Europe (Röthlisberger, 1976; Lamb, 1984; Pfister, 2006).

Rich documentation related to cereal cultivation in central Europe are crucial for understanding the cumulative influence of meteorological conditions over time, and thus of sub-climatic changes, on agriculture. In the first half of the 16th century, early cereal harvest events in the hop and vine cultivation region of Bohemia are repeated, as indicated, for example, in the accounting books of Louny (Brázdil & Kotyza, 2000). In the same region, records of grape harvests in the period 1501-1560 show that vine cultivation progressively expand from traditional locations, such as Mělník, Roudnice nad Labem, and Litoměřice, in the Elbe Valley, to Děčín. The main grape varieties cultivated are Traminer and Pinot Noir. The various available datasets are perfectly consistent, demonstrating the solidity and reliability of the information (Možný et alii, 2012).

The existence of an unusually warm period in the 16th century is evidenced by reports of thermophilic cultivation practices that are no longer possible in subsequent years. For instance, in 1558, Martin Rakovský observed, in a description of the city of Louny (Czech Republic) (Okál, 1974), 'The meadows and orchards are enchanting, with extensive orchards of Damask plums, peaches, quinces, chestnuts, almonds, and various other fruits; here grow saffron and melons [. . .]. Wheat on the plain is growing well; on the hills, vines are found everywhere.' It was noted (Pejml, 1966) that during this period, trees are planted in vineyards as protection against direct sun. Melons (probably Cucumis melo) cultivated in the Kolín region (Czech Republic) are used as gifts to curry favor with Prague administrators (Pejml, 1974). The 1530s and 1550s the warmest and driest summer decades of the 16th century in central Europe (Pfister & Brázdil, 1999). Indeed, the year 1540, with its very hot and dry conditions, is probably the most exceptional of its kind in the last 500 years in central Europe (Glaser et alii, 1999; Pfister, 1999). The very warm May-July period in the 16th century, comparable even to the end of the 20th century, has recently been reconstructed from the grape harvest dates series in Lower Austria (Maurer et alii, 2009).

CONCLUSIONS

The climatic evolution of Earth throughout geological time serves as the backdrop for gaining a deeper understanding of the intricate ecological relationships between climate, landforms, and ecosystems at risk. Milutin Milankovitć's foundational work, still widely accepted by the scientific community and referenced by the IPCC, offers a comprehensive mathematical framework for understanding orbital forcing and its role in climatic oscillations. Although certain aspects, such as the relatively weak influence of eccentricity on the ~100,000-year glacial cycles and the significance of the 400,000-year periodicity, remain topics of ongoing investigation, the theory has been broadly validated by recent studies, across both short-term interannual and long-term millennial timescales (Szarka et alii, 2020).

Insights gleaned from geological and paleontological records reveal the intrinsic variability of climate over vast timescales, driven by both terrestrial and astronomical factors. This perspective is essential for understanding how natural climate fluctuations, spanning hundreds of thousands to millions of years, have profoundly shaped Earth's landscapes and ecosystems at risk. Recognizing millennial-scale climatic cycles is essential to mitigate geological hazards, such as soil instability, hydrological shifts, and land-use challenges. Integrating long-term climatic insights into hazard assessment frameworks can enhance predictive models and support sustainable management practices. The shaping of Earth's landforms and ecosystems over geological time reflects the combined effects of significant climatic changes identified by Milanković's cycles and major geological events of extraordinary scale and importance. This integrated perspective should form the fundamental framework for improving the forecasting of geological hazards and guiding sustainable land-use planning.

The five major mass extinctions that punctuate Earth's history, the Late Ordovician, Late Devonian, Permo-Triassic, Triassic-Jurassic, and Cretaceous-Paleogene extinctions, are among the most compelling examples of the profound impact that these climatic and geological interactions have had on life, with implications that may extend into the geological future. It could even be argued that biological evolution itself has been shaped over hundreds of thousands to millions of years by these forces. However, reliable evidence of such long-term climate fluctuations is found only in geological and paleontological records, which vastly exceed the limited scope of instrumental measurements. These measurements mostly cover merely the past two centuries and suffer from well-known issues of comparability and standardization, due to the inevitable evolution of data-gathering techniques and recording practices over time (e.g. Brath et alii,

2004; GLASER & RIEMANN, 2009; CHRISTIANSEN & LJUNGQVIST, 2017; CAPOZZI *et alii*, 2020). Relying solely on these narrow records risks overlooking the comprehensive insights provided by geological and paleontological archives, which offer a far deeper understanding of long-term climate patterns.

The most recent glacial cycle, which began around 100,000 years ago, culminated in the Last Glacial Maximum approximately 20,000 years ago. This was followed by the Last Glacial–Interglacial Transition, leading to the onset of the Holocene, the current interglacial period, around 11,700 years ago. These transitions represent the most recent, significant long-term climatic cycles. Glacial and interglacial cycles have direct implications for understanding soil erosion dynamics, sediment transport, and flood risks in vulnerable regions. The findings of this study underscore the importance of integrating paleoclimatic data to discriminate atmospheric phenomena across appropriate timesclaes, thereby enabling more effective regional hazard assessments and improved landscape management.

The current interglacial period, in which we are living today, has experienced secular oscillations, including warm peaks such as the Holocene Optimum, the Minoan Warm Period, the Roman Warm Period, the Medieval Warm Period, and the ongoing modern warm period, interspersed with cooler periods such as the Dark Age cool period and the Little Ice Age.

The examination of long-term climatic patterns provides essential context for understanding contemporary climate projections. To appreciate how modern models fit into this broader narrative, we must consider how they align with or diverge from historical climate variability, and how their structural assumptions may limit their reliability when extrapolated beyond their calibration window (SCAFETTA, 2019). CLARK *et alii* (2016) emphasize that policy decisions made today could have profound effects on climate and sea levels over the next 5,000 to 10,000 years. Their projections are based on current carbon emissions and their potential long-term impacts, utilizing CO_2 concentrations and paleotemperature values derived from ice samples dating back 20,000 years. However, they do not specifically address the complexities of CO_2 − temperature relationships across deeper geological timescales. For example, DAVIS (2017), drawing on over 400 million years of geological data, highlights that there have been significant temporal decouplings have occurred between atmospheric CO_2 levels and paleotemperatures. These decouplings occurred across a wide range of time scales, depending on the resolution and extent of the data analyzed. The time spans range from annual and decadal fluctuations in modern instrumental records, through the last two millennia of high-resolution proxy data, to intervals approaching about one million years in the more fragmentary Phanerozoic proxy records. These mismatches between CO_2 and temperature were modulated by factors such as continental

configurations and drift, ocean circulation patterns, variations in silicate weathering rates, and changes in solar radiation. Such findings underscore the importance of contextualizing present-day CO_2 dynamics within a broader temporal framework that accounts for non-linear and lagged climate responses. They also caution against uncritical acceptance of projections of catastrophic future warming, which may fail to reflect the complexities and phase lags revealed by deep-time climate proxies, particularly the recurrent absence of a consistent in-phase relationship between CO_2 concentrations and global temperatures over geological timescales.

JUDD *et alii* (2024) have recently contributed to this field by presenting a new reconstruction of global mean surface temperature (GMST) over the past 485 My, emphasizing the strong correlation between GMST and atmospheric CO_2 levels. However, their work relies heavily on data assimilation models, which integrate proxy data with climate simulations, raising concerns about the validity of the correlation, as it may reflect the model's assumptions rather than actual historical data. Additionally, their findings do not align with studies using purely observational proxies (*e.g.*, DAVIS, 2017). Furthermore, they overlook the possibility that rising CO_2 concentrations could be a consequence of temperature change rather than the cause, given that CO_2 solubility in oceans is temperature-dependent. Even accepting high climate sensitivity to CO_2 proposed by some models, up to 8°C, the fundamental question remains unresolved: what mechanisms drove the fluctuations in atmospheric CO_2 concentrations during the pre-industrial era, long before anthropogenic emissions? Some contend that recent exponential increases in CO_2 levels reflect human amplification of natural processes. However, such claims warrant careful scrutiny, particularly in the light of the extremely short time span involved and our still-limited understanding of how carbon cycle dynamics influence Earth's temperatures and atmospheric behavior. The attribution of CO_2 as the primary driver of long-term temperature changes over geological timescales remains problematic, given the complexity of natural carbon cycle feedbacks and the many non-anthropogenic factors influencing both temperatures and atmospheric composition. Nevertheless, some hypotheses suggest that pre-industrial human activities, such as early extensive farming and deforestation, may have contributed to greenhouse gas fluctuations on shorter timescales (*e.g.*, RUDDIMAN & THOMSON, 2001; KAPLAN *et alii*, 2011; RUDDIMAN, 2017; NEVLE & BIRD, 2008; DULL *et alii*, 2010; ZALASIEWICZ *et alii*, 2015). However, the extent of these influences remains debated and does not fully explain the large-scale CO_2 variations observed in deep-time records.

As we have seen, while CLARK *et alii* (2016), MCKAY *et alii* (2022), and JUDD *et alii* (2024) provide critical insights into the potential impacts of current policies and global

warming thresholds, their models must be interpreted with an awareness of the long-term climate patterns identified in geological records. A clearer and more delineated understanding of climatic events and their effects at the global, regional, and territorial levels can aid in developing more targeted and effective strategies for forecasting and mitigating their impacts. By grounding these strategies in accurate definitions, we can better assess the most appropriate measures for environmental containment, ensuring that responses are both judicious and precise. These recommendations highlight the importance of mitigating soil degradation, optimizing water resources, and interpreting landform changes within the appropriate temporal context of geological and environmental variations. CO_2 and temperature relationships, as illustrated by these patterns, are complex and not always synchronous, a factor that could significantly influence the accuracy of future projections. Although such models underscore potential risks, they must be considered within a broader geological framework that presents a different narrative. Despite the widespread focus on global warming as evidence of climate change, the δ18O curve suggests we may be approaching the next ice age (see HECHT, 1994; BERGER & LOUTRE, 2002; STAGER, 2011), albeit on geological timescales. Rather than Earth overheating due to human activity, Milanković's cycles and geological data indicate a long-term trend toward another glacial period.

Given this, it is clear that to understand climate change effectively, it is crucial to adopt a hierarchical perspective, distinguishing meteorological phenomena, occurring over decades, and sub-climatic events, which accumulate over centuries, from climatic events manifesting over millennia (or longer). The geopaleontological record demonstrates that climate is the cumulative result of tens of thousands of years of sub-climate phenomena, which themselves arise from hundreds to a few thousand years of weather events (SHACKLETON, 1987; EPICA COMMUNITY MEMBERS, 2004; LISIECKI & RAYMO, 2005; ALLEY, 2014). These weather events are sets of conditions that unfold over decades to centuries. This layered understanding of timeframes is essential for properly interpreting Earth's climatic evolution. By adopting the appropriate temporal perspective, it becomes evident that sub-climatic changes may only be perceivable by certain long-lived organisms, such as specific sponges and trees, while climatic changes unfold over timescales that far exceed the lifespan of any individual organism. Consequently, no living being will ever directly experience a climate change within its lifetime, as such changes manifest over millennia. Therefore, asserting that we are currently experiencing a phase of accelerated climate change and attributing it to human activity is a misunderstanding of the true nature and magnitude of climatic processes. Current definitions of climate, sub-climate, and meteorological phenomena,

as outlined by the WMO, fail to capture the complexities revealed by geological and paleontological data, which span vast timescales. These definitions remain inadequate and imprecise, necessitating their careful and official redefinition to better reflect an accurate understanding of Earth's climatic history. Misunderstanding the scale and nature of climatic events, and confusing extreme meteorological phenomena with long-term climate change, can lead to misguided efforts and squandered resources. It can also have important implications for understanding future environmental risks, including hydrological changes and sediment stability. Without a precise grasp of these distinctions, we risk directing significant efforts, energy, and funding towards actions that are fundamentally ineffective. Can we genuinely believe that our actions today will impact the climate thousands of years from now? And again, paradoxically, if current global warming were genuinely a result of anthropogenic climate change, a proper geological and scientific perspective would impose that human activities dating back to the end of the Pleistocene or the beginning of the Holocene are responsible for today's warming. Anthropogenic activities over the past few decades would be irrelevant to this warming; such impacts should have started millennia ago if they were to be a significant factor. In other terms, the blame would be on early Homo sapiens. Once this is understood, the WMO's thirty-year timescale for climate changes appears entirely untenable.

Thus, it becomes apparent that while greenhouse-gas mitigation efforts play a role in addressing environmental impacts, they may have limited influence on broader climate trends, which are governed by more significant natural processes beyond human control. Given the terrestrial and extraterrestrial energies at play, as elucidated in this discourse, mankind has minimal capacity to interfere even with meteorological phenomena, truth be told. This study's hierarchical framework for understanding climatic events offers actionable insights for engineering geology and environmental management. By differentiating between short-term meteorological phenomena and long-term climatic patterns, the findings provide a valuable lens for addressing critical environmental issues, including groundwater conservation, landslide risk mitigation, and the reclamation of degraded lands. These insights contribute to the development of adaptive strategies that balance environmental resilience with sustainable resource management. Aware of this reality, our focus should instead be directed towards measures that yield maximum efficacy in environmental impact containment, involving a drastic reduction in pollution, plastic production, and the implementation of proper management of land, water, plant, and animal resources. However, without a comprehensive understanding of what climate really is and of its complexities, our efforts may be misdirected, leading to an inefficient and possibly damaging use of time, energy, and resources.

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