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Article

Unveiling Climate Complexity: A Multiscale Geological–Molecular Perspective

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Abstract: This narrative review examines the conceptual foundations of the term "climate" and argues for its rigorous redefinition within a geopaleontological framework. Geological and paleoclimatic archives demonstrate that climate, in the Earth-system sense, represents a long-term emergent state governed primarily by orbital dynamics, tectonic boundary conditions, heliophysical variability, ocean circulation reorganizations, and large-scale biogeochemical feedbacks operating across multi-millennial to multimillion-year timescales. In contrast, contemporary usage often applies the term "climate change" to centennial-scale atmospheric trends derived from instrumental records spanning little more than a century. This scale compression generates conceptual ambiguity by conflating meteorological variability, sub-climatic oscillations, and geological climate states. Drawing upon paleoclimate phase relationships, stratigraphic evidence, Milanković orbital theory, molecular greenhouse-gas physics, and modeling constraints, this review proposes a hierarchical temporal framework distinguishing meteorological (decadal), sub-climatic (centennial), and climatic (millennial and longer) domains. Within this framework, greenhouse gases are interpreted as radiative agents operating within the shorter temporal strata of the Earth system, while long-term climatic regimes remain structured primarily by astronomical and geophysical boundary conditions. This distinction does not deny measurable radiative perturbations but clarifies their position within a multiscale system. By restoring climate to its geological context, the study aims to resolve definitional inconsistencies and promote greater epistemological coherence in climate science and its applications.

Keywords: deep-time climate dynamics; narrative review; hierarchical climate forcing; paleoclimate archives; Milankovitch cycles; solar variability; climate sensitivity; Earth system feedbacks.

1. Introduction

The term "climate" is widely used in contemporary scientific, institutional, and public discourse, yet its conceptual boundaries remain insufficiently examined. In operational meteorology, climate is often defined as the statistical behavior of atmospheric variables over a 30-year interval. In geological and paleontological sciences, by contrast, climate denotes long-term Earth-system states structured by orbital geometry, tectonic boundary conditions, heliophysical variability, ocean circulation reorganizations, and large-scale biogeochemical feedbacks operating across multi-millennial to multimillion-year timescales (Zachos et al., 2001; Ruddiman, 2006; Mudelsee et al., 2014; Mazza, 2025). These two usages coexist, but they are not equivalent.

This scale divergence raises a foundational methodological question: what temporal threshold must be satisfied for a phenomenon to qualify as "climate change" in the geological sense? Meteorological variability unfolds over years to decades. Sub-climatic oscillations may span centuries. Geological climate evolution, however, is documented in paleoclimate archives as cumulative state transitions occurring over thousands to millions of years. Marine sediment cores, ice cores, stratigraphic records, isotope series, and fossil assemblages consistently reveal that major climatic reorganizations are paced by orbital dynamics and large-scale boundary-condition shifts rather than by short-term perturbations (Hays et al., 1976; Petit et al., 1999; Mudelsee, 2001; Kawamura et al., 2007).

The Quaternary record provides a clear example of this temporal hierarchy. Variations in orbital eccentricity, obliquity, and precession, first formalized by Milanković, have been empirically validated as pacing mechanisms of glacial–interglacial cycles (Hays et al., 1976; Zachos et al., 2001). These cycles operate over tens to hundreds of thousands of years. Superimposed upon them are shorter sub-climatic oscillations and feedback amplifications. Beyond orbital dynamics, tectonic reorganizations, solar variability, heliophysical modulation, volcanic activity, and ocean-circulation changes contribute to the long-term structure of climatic regimes (Shaviv, 2003; Lisiecki and Raymo, 2005; Berger et al., 2006; Soon et al., 2015; Zharkova et al., 2015; Cheng, et al., 2022; Ganopolski, 2024; Wang et al., 2024;).

Within this broader framework, greenhouse gases—including CO_2—constitute radiatively active components of the atmosphere whose molecular absorption properties are well established. However, their climatic interpretation depends on temporal scale. Radiative perturbations operating over decades or centuries must be distinguished from the geological boundary conditions that define climate regimes. Contemporary climate models, though powerful for simulating short-to-centennial variability, are structurally constrained by temporal scope and parameterization limits, particularly in representing cloud processes, carbon-cycle feedbacks, and deep-time dynamics (Palmer et al., 2000; Stainforth et al., 2005; Stainforth et al., 2007a,b; Edwards et al., 2011; Edwards, 2013; Knutti and Sedláček, 2013).

This narrative review addresses the definitional tension between operational meteorological climate and geopaleontological climate. Drawing upon paleoclimate archives, orbital theory, heliophysical research, molecular greenhouse-gas physics, ecosystem feedback studies, and climate modeling literature, it proposes a hierarchical temporal framework distinguishing meteorological, sub-climatic, and geological climate domains. The aim is not to dismiss radiative physics or contemporary observations, but to restore conceptual coherence by grounding the term “climate” within its appropriate temporal and Earth-system context. Section 2 formalizes astronomical and heliophysical modulation. Section 3 examines paleoclimate evidence and hierarchical forcing structure. Section 4 situates recent warming within a multiscale temporal framework. Section 5 analyzes molecular CO_2 physics in this context. Section 6 evaluates biospheric feedbacks. Section 7 discusses modeling constraints. The concluding section synthesizes these elements into a geopaleontologically grounded definition of climate.

2. Study Design and Methodological Framework

This study is a structured narrative review combined with the development of a conceptual and epistemological framework. Its objective is not to perform a quantitative meta-analysis or to re-evaluate attribution estimates, but to synthesize multidisciplinary evidence in order to clarify the temporal and ontological foundations of the term “climate.” The review integrates geological, paleoclimatic, astronomical, atmospheric, and ecological literature to examine how climate has been defined and operationalized across disciplines and timescales.

The analysis is guided by four central questions:

(i) What temporal criteria define climate in the geological and paleontological sciences?

(ii) How do paleoclimate records inform distinctions between short-term variability and long-term climatic state transitions?

(iii) How should molecular greenhouse-gas physics be interpreted within a multiscale Earth-system hierarchy?

(iv) What conceptual limitations arise when centennial atmospheric trends are equated with geological climate change?

Relevant literature was identified through targeted searches in Web of Science, Scopus, and Google Scholar using combinations of terms including “Milankovitch cycles,” “paleoclimate phase lag,” “climate definition,” “solar variability,” “radiative forcing CO_2,” “climate sensitivity,” and “Earth system feedbacks.” Priority was given to peer-reviewed primary research, foundational paleoclimate datasets, high-impact review articles, and major assessment reports. No strict date restriction was imposed; emphasis was placed on seminal contributions and recent syntheses to ensure both historical continuity and contemporary relevance.

The synthesis proceeds through qualitative comparative analysis structured around temporal stratification. Climate phenomena are classified according to scale domain (meteorological: years to decades; sub-climatic: centuries; climatic sensu geologico: millennia and longer), physical persistence, spectral validation in paleoclimate records, and their role in shaping long-term Earth-system states. In this framework, processes capable of pacing climatic regimes—such as orbital dynamics, tectonic boundary conditions, heliophysical variability, and large-scale ocean reorganizations—are distinguished from feedback mechanisms operating within those regimes, including greenhouse gases, water vapor, albedo variations, and biospheric interactions.

Conflicting interpretations in the literature were evaluated by examining temporal scale, phase relationships, spectral coherence, physical plausibility, and independence from model-dependent assumptions. This approach allows for a consistent distinction between atmospheric variability and geological climate change, thereby clarifying the epistemological basis of the term “climate” across scientific contexts.

3. What Is Climate? A Geopaleontological Definition

The term “climate” is widely used across scientific, institutional, and public domains, yet its temporal boundaries are rarely examined explicitly. In operational meteorology, climate is commonly defined as the statistical description of atmospheric variables over a 30-year reference period. While this convention facilitates instrumental standardization, it represents a methodological construct rather than a physically derived threshold grounded in Earth-system dynamics (Mazza, 2025).

From a geopaleontological perspective, climate denotes a long-term emergent state of the Earth system structured by boundary conditions operating across millennial to multimillion-year timescales. This definition builds directly upon the methodological framework outlined in Section 2. Geological and paleoclimatic archives—marine sediment cores, benthic $\delta^{18}O$ stacks, ice cores, loess–paleosol sequences, and fossil assemblages—demonstrate that major climatic reorganizations unfold over extended intervals governed primarily by orbital geometry, tectonic boundary conditions, heliophysical variability, ocean circulation reorganizations, and large-scale biogeochemical cycles (Hays et al., 1976; Ruddiman, 2006; Lisiecki and Raymo, 2005; Mudelsee et al., 2014; Scotese et al., 2021).

These long-term regimes are characterized by persistent reorganizations of cryosphere extent, ocean circulation, biome distribution, and global energy balance. In this geological context, climate is not synonymous with short-term temperature trends or decadal anomalies but corresponds to sustained Earth-system states maintained by large-scale forcing structures (Milanković, 1941; Saltzman, 2002; Mazza, 2025).

To clarify this temporal architecture, three nested domains may be distinguished. These domains are introduced as analytical stratifications for conceptual clarity and are not intended to replace established operational definitions used in meteorology and climate monitoring: 1) meteorological variability, operating over years to decades and reflecting atmospheric dynamics and short-term energy redistribution; 2) sub-climatic oscillations, spanning decades to centuries, representing cumulative atmospheric–oceanic variability; 3) climatic regimes in the geological sense, unfolding over millennia and longer intervals, structured by orbital, tectonic, heliophysical, and large-scale boundary conditions (Milanković, 1941; Lisiecki and Raymo, 2005).

This stratified definition does not deny measurable radiative perturbations on shorter timescales. Rather, it distinguishes between transient atmospheric adjustments and regime-scale climatic transitions. Under this framework, “climate change” acquires a precise meaning: it refers to shifts in geological-scale boundary conditions that restructure the long-term state of the Earth system.

Clarifying this definition is not merely semantic. This temporal distinction is grounded in the timescales over which boundary-condition processes documented in paleoclimate archives demonstrably operate, rather than in an arbitrary redefinition of terminology. Conceptual conflation between meteorological variability and geological climate regimes can introduce interpretive ambiguity in both scientific analysis and policy discourse. A geopaleontological definition restores temporal coherence by grounding climate within the physical processes that have demonstrably governed Earth’s climatic evolution over deep time (Ruddiman, 2006; Mudelsee et al., 2014; Mazza, 2025).

4. Astronomical and Heliophysical Modulation

Having defined climate in the geological sense as a long-term Earth-system regime structured by boundary conditions, it becomes necessary to identify the processes capable of establishing and pacing such regimes. Paleoclimate evidence consistently indicates that long-term climate evolution is strongly influenced by astronomical and heliophysical drivers operating across multi-millennial to multimillion-year timescales.

Orbital variations in eccentricity, obliquity, and precession alter the spatial and seasonal distribution of incoming solar radiation, thereby modulating high-latitude insolation and ice-sheet stability. These parameters, first formalized by Milanković and subsequently validated through spectral analyses of marine and ice-core archives, provide a pacing mechanism for glacial–interglacial transitions and other long-term climatic reorganizations (Milanković, 1941; Hays et al., 1976; Zachos et al., 2001; Lisiecki and Raymo, 2005). Their periodicities, on the order of tens to hundreds of thousands of years, are consistent with the temporal scale required for regime-level climatic shifts.

Beyond orbital geometry, heliophysical variability—including fluctuations in solar irradiance, solar magnetic activity, and cosmic-ray modulation—introduces additional variability across centennial to millennial intervals (Raisbeck et al., 1990; Bond et al., 2001; Usoskin et al., 2007, 2009; Solanki et al., 2004; Zharkova, 2020). Although the magnitude and climatic amplification of some of these influences remain subject to ongoing research, their persistence across extended temporal domains situates them within the boundary-condition layer of the hierarchical framework defined above. Current attribution assessments emphasize anthropogenic greenhouse forcing at centennial scales (IPCC, 2021), while heliophysical variability is more commonly discussed in the context of longer-term modulation.

Within this stratified architecture, astronomical and heliophysical processes are treated as primary large-scale drivers because they operate independently of internal Earth-system feedbacks and impose externally paced energy constraints on the system. Their imprint is detectable in paleoclimate archives through spectral coherence, stratigraphic cyclicity, and the timing of major climatic reorganizations (Hays et al., 1976; Lisiecki and Raymo, 2005; Scotese et al., 2021).

Terrestrial processes—including tectonic reorganizations, continental drift, volcanic outgassing, ocean-gateway reconfiguration, and long-term carbon-cycle adjustments—further modify climatic boundary conditions by altering albedo, greenhouse-gas reservoirs, ocean heat transport, and biogeochemical fluxes (Mudelsee et al., 2014; Ruddiman, 2006; Saltzman, 2002). These processes unfold over similarly extended timescales and contribute to transitions between greenhouse and icehouse states.

All of these drivers interact within a nonlinear dynamical system in which feedback mechanisms—water vapor amplification, cloud responses, ice–albedo effects, and carbon-cycle dynamics—mediate the magnitude and timing of climatic responses (Bony et al., 2006; Ghil, 2019). In the hierarchical framework adopted here, such feedbacks do not independently establish long-term climatic regimes but amplify or modulate variability initiated by large-scale boundary-condition drivers.

5. Paleoclimate Evidence and the Hierarchy of Forcings

High-resolution paleoclimate records from ice cores and marine sediments document systematic phase relationships between temperature and atmospheric CO_2 during major Quaternary glacial–interglacial transitions (Hays et al., 1976; Fischer et al., 1999; Petit et al., 1999; Mudelsee, 2001; Caillon et al., 2003; Kawamura et al., 2007). In several well-resolved terminations, increases in temperature precede measurable rises in atmospheric CO_2 by several centuries to millennia. This pattern is consistent with orbital pacing initiating climatic shifts, followed by carbon-cycle responses that amplify and redistribute the initial perturbation. In this glacial–interglacial context, CO_2 functions as a feedback amplifier within a broader forcing hierarchy rather than as the primary pacing mechanism.

The Quaternary record offers a particularly clear empirical example of scale-structured climatic dynamics. Variations in orbital eccentricity, obliquity, and axial precession—first quantified by Milanković—have been validated through spectral analyses of deep-sea and ice-core records as pacing mechanisms of glacial cycles (Milanković, 1941; Hays et al., 1976; Zachos et al., 2001; Lisiecki and Raymo, 2005). These orbital parameters regulate seasonal and latitudinal insolation distribution and thereby influence ice-sheet growth, albedo feedbacks, and ocean circulation. Their characteristic periodicities—on the order of tens to hundreds of thousands of years—align with the temporal domain defined in Section 3 as geological-scale climate.

Within the hierarchical interpretation adopted here, orbital forcing functions as a large-scale pacing mechanism capable of structuring regime-level climatic states. This interpretation follows the temporal stratification criteria defined in Section 2. Greenhouse gases, water vapor, albedo changes, and ocean circulation act as amplifiers or modulators of externally initiated variability. Figure 1 illustrates the three principal orbital parameters and their characteristic periodicities.

Operating in concert, these astronomical cycles form the backbone of Quaternary climatic pacing, establishing boundary conditions within which internal feedbacks operate. The persistence and spectral coherence of these periodicities in paleoclimate archives distinguish them from shorter-term atmospheric variability.

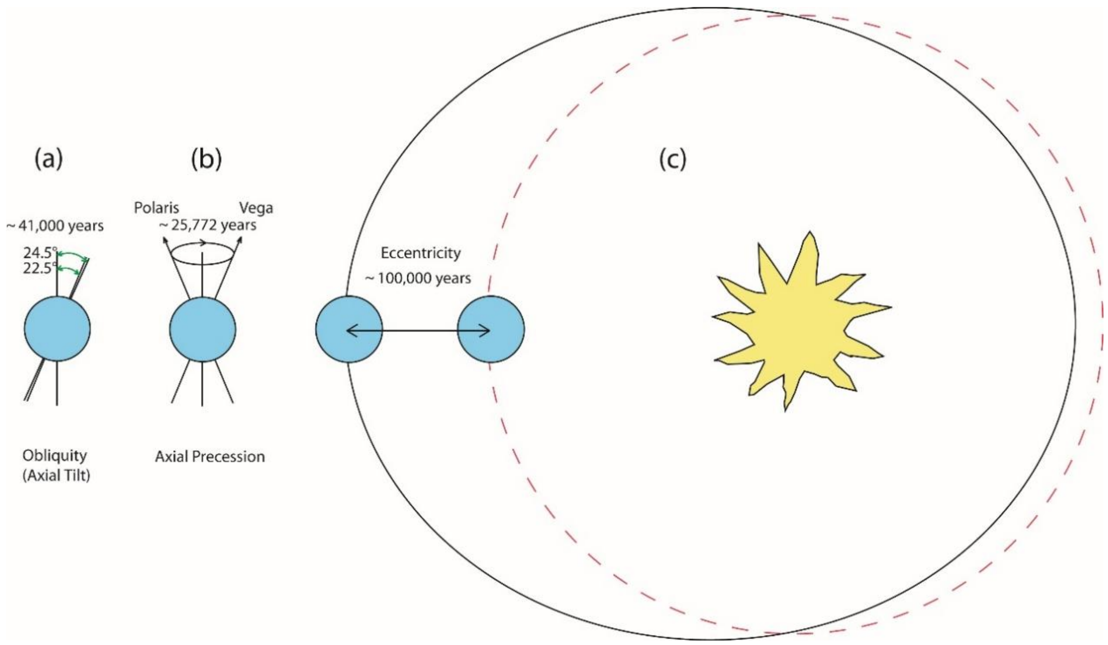

Figure 1. Schematic representation of the three Milanković orbital cycles that modulate long-term climate variability. (a) Obliquity (axial tilt) oscillates between ~22.5° and ~24.5° with a characteristic period of ~41 kyr. This cycle regulates the contrast between seasons, particularly at high latitudes, and plays a central role in the growth and decay of polar ice sheets by modulating summer insolation. (b) Axial precession, with a periodicity of ~25.7 kyr, describes the slow gyration of Earth's rotational axis, shifting the timing of perihelion and aphelion relative to the seasons and altering the hemispheric distribution of solar energy. (c) Orbital eccentricity, varying over ~100 kyr cycles, modifies the shape of Earth's orbit from more circular to more elliptical, thereby regulating the amplitude of the precession signal.

In combination, these astronomical cycles form the backbone of long-term climate pacing during the Quaternary, setting the boundary conditions within which internal feedbacks—albedo, water vapor, clouds, and carbon cycling—operate. In the multiscale interpretation adopted in this study, Milanković forcing represents a primary deep-time driver that governs climate evolution over tens to hundreds of millennia, far beyond the timescales addressed by modern observational records or short-term climate assessments.

In addition to orbital modulation, reconstructions indicate variability in solar irradiance, solar magnetic flux, cosmic-ray modulation, and heliospheric shielding across centennial to millennial timescales (Raisbeck et al., 1990; Bond et al., 2001; Shaviv, 2003; Solanki et al., 2004; Usoskin et al., 2007, 2009; Soon et al., 2015; Zharkova et al., 2015; Zharkova, 2020). Although the magnitude and climatic amplification of some of these influences remain debated, they represent additional components of the multiscale forcing architecture documented in paleoclimate records.

Figure 2 synthesizes $\delta^{18}O$-derived temperature reconstructions across multiple temporal domains: (a) Phanerozoic-scale variability spanning hundreds of millions of years (Scotese et al., 2021); (b) Cenozoic-scale cooling trends (Ruddiman, 2006; Mudelsee et al., 2014; Scotese et al., 2021); (c) orbital-scale Quaternary oscillations (Lisiecki and Raymo, 2005); (d) millennial-scale Holocene fluctuations (Lowe and Walker, 2015; Scafetta et al., 2016); and (e) decadal variability over the last two millennia (Sicre et al., 2008). The purpose of this figure is not to minimize shorter-term variability but to illustrate temporal nesting. Decadal meteorological oscillations are embedded within centennial-to-millennial sub-climatic patterns, which themselves are embedded within geological-scale climatic regimes.

Importantly, rapid transitions documented in the paleoclimate record—such as Dansgaard–Oeschger events or the Younger Dryas—do not contradict this hierarchy. Although abrupt in onset, these events occur within established glacial boundary conditions and do not constitute independent restructuring of long-term climatic regimes. Their rapidity reflects nonlinear internal dynamics within a pre-existing regime rather than the establishment of a new geological-scale climate state.

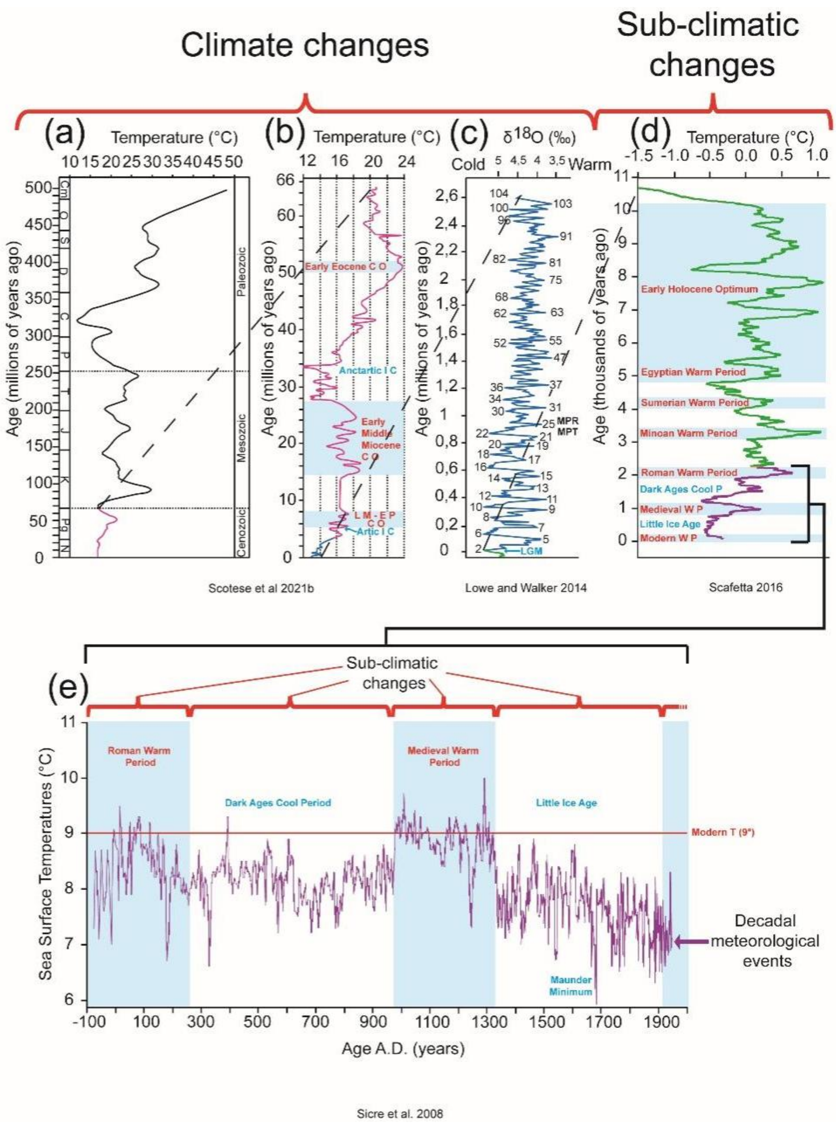

Figure 2. Multiscale δ¹⁸O-derived paleotemperature records illustrating climate variability across geological, subclimatic, and meteorological timescales. (**a**) Surface-water tropical temperature reconstruction for the past 500 Ma, based on carbonate δ¹⁸O records (Author's elaboration based on Scotese et al., 2021). (**b**) Deep-ocean temperature curve for the Cenozoic (0–66 Ma), derived from benthic foraminiferal δ¹⁸O (Author's elaboration based on Scotese et al., 2021). (**c**) High-resolution δ¹⁸O stack for the Quaternary (last 2.6 Ma), reflecting orbital-scale glacial–interglacial variability (Author's elaboration based on Lowe and Walker, 2015). (d) Holocene temperature reconstruction from the GISP2 ice core, illustrating millennial- to centennial-scale subclimatic phases (Author's elaboration based on Scafetta et al., 2016). (e) High-resolution (2–5 yr) sea-surface temperature record for the last ~2000 years, capturing decadal-scale meteorological variability and known historical climatic episodes (Author's elaboration based on Sicre et al., 2008).

Abbreviations: °C = degrees Celsius; ‰ = per mille; A.D. = Anno Domini;
C = Carboniferous; CO = Climate Optimum; Cm = Cambrian; Cool P = cool period;
D = Devonian; EP = Early Pliocene; IC = Ice Cap; J = Jurassic; K = Cretaceous;
LM = Late Miocene; LGM = Last Glacial Maximum; MPR = Middle Pleistocene Revolution;
MPT = Middle Pleistocene Transition; N = Neogene; O = Ordovician; Pg = Paleogene;
S = Silurian; T = Triassic; WP = warm period; δ¹⁸O = oxygen-isotope ratio (¹⁸O/¹⁶O).

Taken together, paleoclimate archives demonstrate that climate evolution reflects the interaction of externally paced boundary-condition drivers and internally mediated feedback amplifiers operating across nested temporal domains. This empirical structure provides the basis for distinguishing meteorological variability, sub-climatic oscillations, and geological climate regimes as formally defined in Section 3.

6. Recent Warming Within a Multiscale Temporal Framework

The hierarchical definition of climate developed in Sections 3–5, grounded in the methodological framework introduced in Section 2, provides a framework for interpreting recent warming trends without conflating temporal domains. Instrumental records document a rise in global mean surface temperature over approximately the past century. From a meteorological perspective, this constitutes a significant atmospheric trend. From a geopaleontological perspective, however, its temporal duration remains confined to the meteorological–sub-climatic domain.

Climate, as defined in this study, refers to regime-scale states structured by long-term boundary conditions operating over millennia and longer intervals. By contrast, contemporary warming unfolds, at most, within a centennial observational window that is short relative to orbital and tectonic timescales; its long-term classification depends on whether such trends persist sufficiently to interact with regime-scale boundary conditions (Milanković, 1941; Hays et al., 1976; Zachos et al., 2001; Lisiecki and Raymo, 2005). This temporal distinction does not deny the physical reality of observed warming or the existence of radiative forcing; rather, it classifies the phenomenon within the appropriate hierarchical stratum of the Earth system.

Periods of elevated solar activity, including the 20th-century interval commonly termed the Modern Grand Solar Maximum, provide an example of centennial-scale heliophysical variability operating within this sub-climatic domain (Usoskin et al., 2007, 2009; Solanki et al., 2004; Zharkova, 2020). Reconstructions indicate that solar magnetic and irradiance variability can fluctuate on multidecadal to centennial intervals. Regardless of the precise magnitude of their radiative contribution relative to other forcings, such variations remain temporally confined to the atmospheric–oceanic integration layer and do not, in themselves, constitute geological-scale climatic restructuring.

6.1. Ocean Thermal Inertia and Energy Integration

The oceans store the majority of excess heat in the climate system (IPCC, 2021; Levitus et al., 2012; Cheng et al., 2017). Because of their high heat capacity and slow overturning timescales, radiative perturbations—whether solar- or greenhouse-gas–induced—are integrated over decades to centuries. Observed increases in ocean heat content during the 20th century are consistent with such integrative behavior.

This integrative mechanism highlights an important structural feature of the climate system: short-term radiative perturbations are mediated by oceanic heat uptake and redistribution. Such processes operate within the sub-climatic domain defined above. They influence atmospheric temperature trajectories on centennial timescales but do not, in themselves, constitute regime-scale climatic restructuring unless sustained across millennial horizons sufficient to alter boundary conditions.

6.2. Feedback Processes and Temporal Stratification

Enhanced evaporation from warming oceans increases atmospheric water vapor, reinforcing warming through well-established greenhouse feedbacks (Goody and Yung, 1995; Held and Soden, 2000; Bony and Dufresne, 2005; Sherwood et al., 2020; Zelinka et al., 2020; Hill et al., 2025). Cloud responses remain a major source of uncertainty in climate sensitivity estimates, and differences in cloud representation contribute substantially to model spread (Bony and Dufresne, 2005; Zelinka et al., 2020; Hill et al., 2025). These feedbacks amplify or dampen radiative perturbations within the meteorological and sub-climatic domains but remain embedded within existing climatic regimes unless accompanied by sustained boundary-condition shifts.

6.3. Carbon-Cycle Adjustments

Surface-ocean warming reduces CO_2 solubility, promoting outgassing—a mechanism observed during past deglaciations (Petit et al., 1999; Mudelsee, 2001; Kawamura et al., 2007). In the contemporary system, anthropogenic emissions dominate the net atmospheric increase (IPCC, 2021); however, ocean–atmosphere exchange processes modulate variability and participate in short-term carbon-cycle adjustments. These processes operate within the sub-climatic temporal layer and are superimposed upon long-standing geological carbon-cycle structures.

6.4. Temporal Classification Rather Than Attribution Competition

Mainstream assessments attribute the majority of recent warming to anthropogenic forcing (IPCC, 2021). The present framework does not seek to replace or refute attribution studies. Instead, it situates observed warming within a multiscale temporal architecture. Regardless of the relative contributions of anthropogenic and natural forcings, the duration of recent warming remains confined to the meteorological–sub-climatic domain.

In the geological record, regime-scale climatic transitions are typically associated with sustained boundary-condition restructuring over millennial or longer intervals. Contemporary warming, measured over approximately one century, does not yet meet this criterion. It represents a significant atmospheric perturbation within an existing climatic regime rather than the establishment of a new geological-scale climate state.

7. Molecular Physics of Carbon Dioxide and Its Role in Climate

The preceding sections have defined climate in a geological sense as a long-term regime structured by boundary conditions operating across millennial to multimillion-year timescales. The role of greenhouse gases must therefore be examined within this temporal architecture. The molecular absorption properties of carbon dioxide (CO_2) are well established in atmospheric physics and constitute an essential component of Earth's radiative balance. The question addressed here is not whether CO_2 absorbs infrared radiation—it does—but how such radiative processes are situated within the hierarchical temporal structure of the Earth system.

7.1. Radiative Absorption and Logarithmic Forcing

Carbon dioxide interacts with terrestrial infrared radiation primarily through vibrational–rotational absorption bands, particularly the 15 μm bending-mode band, with additional bands near 4.3 μm and 2.7 μm (Goody and Yung, 1995; Petty, 2006). At atmospheric pressures, line broadening due to pressure and temperature effects produces overlapping absorption features. Radiative-transfer calculations demonstrate that increases in CO_2 concentration continue to alter outgoing longwave radiation, with the incremental forcing increasing approximately logarithmically with concentration (Myhre et al., 1998; Etminan et al., 2016).

While the central portion of the 15 μm band is highly opaque at present concentrations, additional forcing arises in the band wings and in higher, colder atmospheric layers where absorption remains sensitive to concentration changes (Zhong and Haigh, 2013; Mlynczak et al., 2016; Shine and Perry, 2023). Thus, CO_2 forcing does not cease at current concentrations; rather, it increases in a progressively diminishing manner as concentration rises.

This logarithmic relationship establishes that CO_2 operates as a radiative amplifier within the atmosphere. However, the magnitude and climatic significance of this amplification must be interpreted in relation to the temporal scale under consideration.

7.2. Coupling with Water Vapor and Cloud Processes

Water vapor, with its extensive rotational–vibrational spectrum, absorbs across large portions of the thermal infrared (Goody and Yung, 1995; Petty, 2006). In humid lower-tropospheric regions, significant spectral overlap occurs between H_2O and CO_2 absorption bands (IPCC, 2021). Water vapor therefore functions as a dominant feedback mechanism, amplifying temperature perturbations initiated by various forcings (Held and Soden, 2000; Sherwood et al., 2020).

Cloud processes introduce additional complexity. Differences in cloud microphysics and convective organization remain major contributors to uncertainty in climate sensitivity estimates (Bony and Dufresne, 2005; Zelinka et al., 2020; Hill et al., 2025). These feedbacks operate within the meteorological and sub-climatic domains, influencing atmospheric temperature trajectories on decadal to centennial timescales.

Within the hierarchical framework adopted here, CO_2 is best understood as one component of a coupled H_2O–CO_2–cloud system that modulates radiative balance within existing climatic regimes rather than independently establishing geological-scale boundary conditions.

7.3. Climate Sensitivity in Temporal Context

Climate sensitivity is conventionally defined as the equilibrium global-mean temperature response to a doubling of atmospheric CO_2, including fast feedbacks (Stainforth et al., 2007). Mainstream assessments estimate this sensitivity within a range of approximately 2–4.5 °C per doubling, with ongoing debate primarily concerning feedback strength rather than the basic radiative properties of CO_2 (IPCC, 2021; Sherwood et al., 2020).

From a multiscale perspective, such sensitivity estimates describe the response of the atmosphere–ocean system over centennial adjustment intervals. They quantify sub-climatic amplification processes operating within established boundary conditions. They do not, by themselves, determine transitions between icehouse and greenhouse states, nor do they override orbital or tectonic pacing documented in paleoclimate archives (Milanković, 1941; Hays et al., 1976; Zachos et al., 2001; Lisiecki and Raymo, 2005).

Accordingly, CO_2 may exert significant influence within the meteorological and sub-climatic temporal domains. However, regime-scale climatic restructuring, as defined geopaleontologically, requires sustained shifts in boundary conditions operating over millennial or longer intervals. Molecular greenhouse-gas physics constrains atmospheric energy transfer, but the long-term evolution of climate states remains structured by the broader astronomical and geophysical architecture outlined in Sections 4 and 5.

8. Biomes, Ecosystem Feedbacks, and Climate-System Dynamics

Evaluating ecosystem responses and feedbacks requires situating them within the hierarchical temporal framework established in previous sections. Biomes both respond to and interact with atmospheric and oceanic processes through complex biogeochemical, hydrological, and ecological feedbacks. These interactions influence vegetation distribution, species dynamics, carbon exchange, surface albedo, and evapotranspiration. The key question within a geopaleontological definition of climate is not whether ecosystems influence atmospheric composition—they clearly do—but at what temporal scale such interactions operate and whether they constitute regime-level climatic restructuring.

8.1. Positive and Negative Biotic Feedbacks

Projections for the late 21st century suggest potential reorganization of biomes, including poleward and elevational shifts in vegetation zones under warming scenarios. Such adjustments unfold over decades to centuries and therefore belong to the meteorological–sub-climatic domain defined in Section 3. CO_2 fertilization may enhance plant growth under certain conditions but can be constrained by nutrient availability, water stress, and temperature extremes (Cramer et al., 2001). Under changing environmental conditions, ecosystems may transition between carbon-sink and carbon-source behavior.

Biotic contributions to the carbon cycle—including deforestation, afforestation, and land-use change—modify regional albedo, evapotranspiration, and atmospheric composition. For example, degradation of Amazonian forests may influence regional hydrology and carbon storage (Gitz and Ciais, 2003; Cox et al., 2004). These feedbacks can alter atmospheric CO_2 concentrations and surface energy balance on centennial scales. However, within the hierarchical framework adopted here, such processes represent internal adjustments within existing climatic regimes rather than externally imposed boundary-condition shifts.

8.2. Ecosystem Responses and Temporal Mismatch

Ecological disruption induced by warming episodes, hydrological variability, and extreme events can propagate through food webs and ecosystem networks. Phenological shifts, altered migration patterns, and localized biodiversity changes affect carbon storage, methane fluxes, and land–atmosphere coupling. These responses may amplify or moderate atmospheric perturbations.

Yet a temporal distinction remains critical. Ecological processes typically operate over decadal to centennial intervals, whereas regime-scale climatic transitions documented in the geological record unfold across millennia or longer. Rapid ecological responses do not automatically equate to regime-level climate change unless sustained over durations sufficient to alter large-scale boundary conditions. This distinction concerns temporal scale rather than ecological importance.

8.3. Ecosystem Carbon Balance Within a Multiscale Framework

Dynamic Global Vegetation Models project biome redistribution and shifts in carbon sink strength under various environmental scenarios (Bondeau et al., 2007; Piao et al., 2012; Schaphoff et al., 2013). These simulations highlight the sensitivity of biospheric carbon balance to land-use change, disturbance regimes, and temperature variability.

Within a geopaleontological perspective, biospheric feedbacks are understood as modulatory components of the Earth system. They influence atmospheric composition and surface energy exchange, particularly within the meteorological and sub-climatic temporal domains. Long-term climatic regimes, however, are structured by sustained boundary-condition drivers such as orbital configuration, tectonic reorganization, and large-scale ocean circulation changes documented across geological time (Mudelsee et al., 2014; Zachos et al., 2001).

Ecosystem restoration, reforestation, and biodiversity conservation therefore remain environmentally significant interventions, particularly for land stability, hydrological regulation, and carbon management.

Their climatic relevance, however, must be interpreted within a stratified temporal architecture in which ecological processes operate primarily as internal feedbacks rather than as regime-defining boundary conditions.

9. Climate Modeling and Policy Implications in a Multiscale Feedback Framework

Interpreting climate-model outputs within a geopaleontological definition of climate requires explicit recognition of temporal scope. Climate models are designed primarily to simulate atmospheric and oceanic processes across decadal to centennial intervals. They represent radiative transfer, feedback mechanisms, and large-scale circulation dynamics within computationally tractable time horizons. Their strengths and limitations must therefore be evaluated relative to the temporal domain they are intended to address.

9.1. Climate Modeling: Temporal Scope and Structural Constraints

General circulation models and Earth System Models employ mathematical representations of water vapor feedbacks, cloud–radiation interactions, ice–albedo coupling, carbon-cycle dynamics, and internal variability. These models operate at finite spatial resolution and rely on parameterization schemes to approximate sub-grid-scale processes (Lorenz, 1963; Edwards, 2010; Deser et al., 2012). They are highly effective tools for exploring short-to-centennial atmospheric variability and testing radiative-forcing scenarios.

However, geological-scale climate evolution—spanning millennia to millions of years—is structured by boundary conditions such as orbital configuration, continental rearrangement, ocean-gateway opening and closure, and long-term carbon-cycle adjustments (Crowley, 1989; Stouffer, 2004; WCRP, 2019). While models can incorporate such boundary conditions in paleoclimate simulations, their routine application focuses on comparatively short observational windows. Consequently, outputs describing centennial-scale warming trends should be interpreted within the meteorological–sub-climatic domain rather than as direct representations of regime-scale climatic restructuring.

Cloud feedbacks remain a major source of uncertainty in climate sensitivity estimates (Bony and Dufresne, 2005; Zelinka et al., 2020; Hill et al., 2025). Paleoclimate archives further demonstrate that major climatic transitions involve pacing mechanisms operating over tens to hundreds of thousands of years (Hays et al., 1976; Lisiecki and Raymo, 2005). This does not invalidate modeling approaches; rather, it underscores that climate, as defined geopaleontologically, encompasses temporal scales beyond those typically emphasized in short-term projections.

9.2. Policy Considerations in a Stratified Temporal Context

Policy decisions are often informed by model-based projections extending several decades into the future. Such projections are appropriate for assessing meteorological and sub-climatic risks, including extreme weather frequency, regional hydrological shifts, and ecosystem vulnerability. Within these temporal domains, anthropogenic forcing and land-use change exert measurable influence (IPCC, 2021, 2022).

The hierarchical framework developed in this study does not deny the relevance of such projections. Instead, it emphasizes the importance of distinguishing between atmospheric perturbations observable within human timescales and geological-scale climate regimes governed by long-term boundary conditions. Conflating these domains may generate conceptual ambiguity regarding what constitutes "climate change."

From a stratified perspective, anthropogenic activity most directly affects land cover, biospheric stability, hydrological systems, and atmospheric composition within the meteorological–sub-climatic layer. Long-term climatic regime transitions, as documented in the geological record, require sustained restructuring of boundary conditions across millennial horizons (Ruddiman, 2006; Mudelsee et al., 2014).

Future research would benefit from deeper integration of paleoclimate archives with modeling frameworks, thereby strengthening continuity between short-term simulations and long-term Earth-system history. An epistemically coherent approach acknowledges both the power and the limits of modeling, situating projections within a multiscale temporal architecture consistent with the geological definition of climate advanced here.

10. Conclusions

This study has argued that the concept of climate requires explicit temporal clarification. Geological and paleoclimatic archives demonstrate that long-term climatic regimes are structured by boundary conditions operating over millennial to multimillion-year timescales. These include orbital geometry, tectonic reorganizations, long-term ocean–atmosphere circulation patterns, heliophysical variability, and large-scale biogeochemical adjustments (Milanković, 1941; Hays et al., 1976; Crowley and Kim, 1996 ; Zachos et al., 2001; Shaviv, 2003; Ruddiman, 2006; Mudelsee et al., 2014; Soon et al., 2015; Zharkova et al., 2015). Within this architecture, feedback mechanisms—ice–albedo responses, water vapor amplification, cloud processes, and carbon-cycle dynamics—modulate the magnitude and expression of externally paced variability but do so within boundary conditions established by large-scale drivers (Saltzman, 2002; Bony et al., 2006; Ghil, 2019).

By integrating molecular greenhouse-gas physics with paleoclimate evidence, this study has emphasized that radiative forcing operates within a multiscale hierarchy. Carbon dioxide exerts a logarithmically increasing radiative effect (Myhre et al., 1998; Etminan et al., 2016), and climate sensitivity quantifies the atmospheric response over centennial adjustment intervals (Stainforth et al., 2007; Sherwood et al., 2020; IPCC, 2021). Paleoclimate archives, however, show that major regime-scale climatic reorganizations are paced by orbital and geophysical boundary conditions, with greenhouse gases functioning as amplifiers within those transitions (Petit et al., 1999; Mudelsee, 2001; Valentine, 2004; Kawamura et al., 2007). Recognizing this stratification does not deny the physical relevance of greenhouse forcing; rather, it situates it within the temporal layer in which it operates.

A central clarification follows from this hierarchy. Climatic regime transitions in the geological sense unfold across intervals that substantially exceed ecological and generational timescales. Organisms experience environmental variability and sub-climatic oscillations, but regime-scale climatic restructuring requires sustained boundary-condition shifts over millennial or longer horizons. Maintaining this distinction preserves terminological precision and prevents conflation between short-term atmospheric variability and geological-scale climate evolution.

This temporal framework also refines interpretation of climate-model output. General circulation models and Earth System Models provide valuable insights into atmospheric and oceanic dynamics over decadal to centennial intervals (Lorenz, 1963; Stouffer, 2004; Edwards, 2010; Deser et al., 2012; WCRP, 2019). Their structural constraints—finite resolution, parameterization limits, internal variability, and restricted temporal windows—reflect the domains for which they are designed. Interpreting model projections within a geopaleontological perspective clarifies that they represent simulations of sub-climatic variability rather than direct representations of geological-scale regime transitions.

A reconsideration of the distinction between "climate" and "paleoclimate" therefore emerges naturally. Climate, when considered within its full Earth-system context, encompasses geological timescales and boundary-condition dynamics that extend beyond the shorter intervals typically addressed in operational meteorology; paleoclimate is not a separate domain but the temporal extension necessary for understanding climate as a regime-scale phenomenon (Mazza, 2025). Instrumental records provide high-resolution insight into recent atmospheric variability, yet geological archives supply the temporal depth required to identify the structural drivers of long-term climate evolution.

Recognizing this stratified temporal architecture does not diminish the importance of environmental stewardship. Anthropogenic activities demonstrably influence land cover, hydrological systems, ecosystem stability, and atmospheric composition within meteorological and sub-climatic domains (Cramer et al., 2001; Gitz and Ciais, 2003; Cox et al., 2004; IPCC, 2022). These impacts carry significant ecological and societal consequences. However, regime-scale climate evolution, as documented in the geological record, is governed by boundary-condition processes operating over far longer intervals.

Future research would benefit from deeper integration of paleoclimate archives with modeling frameworks, thereby strengthening continuity between short-term atmospheric dynamics and long-term Earth-system evolution. Advances in stable-isotope geochemistry, sedimentary analysis, paleoecological reconstruction, and multiscale modeling will remain essential for refining our understanding of climate as a layered, hierarchical, and deeply temporal phenomenon.

In summary, the framework advanced here situates climate within its appropriate temporal and disciplinary context. By grounding climate in geological timescales while recognizing the role of atmospheric physics within shorter domains, this approach restores conceptual coherence between modern climate science and the deep-time record in which climate is fundamentally rooted.

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Conflict of Interest Statement
Author declares no conflict of interest.

Data Availability Statement
This study does not present new empirical data. All analyses are based on previously published datasets and peer-reviewed literature cited in the manuscript. No new data were generated or analyzed, and therefore no data are available for archiving. All sources used are publicly accessible through the references listed.

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