



# Temporal Stratification in Climate Science: Integrating Geological and Instrumental Perspectives Across Temporal Scales

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**Abstract.** This study examines the concept of climate within a multiscale Earth-system perspective, with particular attention to the coexistence of different temporal frameworks across disciplines. In meteorology, climate is commonly defined through statistical properties of atmospheric variables over multi-decadal intervals, whereas geological and paleoclimatic records document long-term climatic states emerging over millennial to multimillion-year timescales. This divergence in temporal scope can lead to interpretive ambiguities when phenomena operating at different scales are considered within a single conceptual framework. Drawing on evidence from geology, paleoclimatology, astronomy, and atmospheric science, this paper proposes a hierarchical temporal structure distinguishing meteorological variability (years to decades), sub-climatic oscillations (centuries), and long-term climatic regimes (millennia and longer). Within this framework, large-scale boundary conditions—such as orbital dynamics, tectonic configurations, and ocean circulation—govern the evolution of long-term climate states, while radiative agents and feedback processes operate primarily within shorter temporal domains. This multiscale perspective does not challenge the physical basis of radiative forcing or contemporary observations, but situates them within a broader temporal architecture of the Earth system. By integrating instrumental records with paleoclimate archives, the proposed framework aims to enhance conceptual clarity and improve the interpretation of climate variability across scales. This approach provides a basis for reconciling disciplinary definitions and for more consistent interpretation of climate dynamics in both short-term and long-term contexts.

## 1 Introduction

The concept of climate is central to Earth system science, yet it is used across disciplines with differing temporal scopes and methodological frameworks. In operational meteorology, climate is commonly defined as the statistical description of atmospheric variables over multi-decadal intervals, typically standardized over 30-year periods. In contrast, geological and paleoclimatic sciences approach climate as a long-term emergent property of the Earth system, structured by processes operating over millennial to multimillion-year timescales (Zachos et al., 2001; Ruddiman, 2006; Mudelsee et al., 2014; Mazza, 2025).



These distinct usages are not mutually exclusive; rather, they reflect different observational windows onto a multiscale system.

30 However, when phenomena operating at different temporal scales are interpreted within a single conceptual framework, ambiguities may arise. Short-term atmospheric variability, centennial-scale oscillations, and long-term climatic regimes are often discussed under the same terminology, despite being governed by processes with different characteristic timescales, persistence, and physical drivers.

Paleoclimate archives—including marine sediment cores, ice cores, isotope records, and fossil assemblages—consistently

35 show that major climatic reorganizations unfold over extended intervals and are paced by large-scale boundary conditions such as orbital dynamics, tectonic configurations, ocean circulation changes, and long-term biogeochemical cycles (Hays et al., 1976; Petit et al., 1999; Mudelsee, 2001; Kawamura et al., 2007). At the same time, instrumental records provide high-resolution insights into atmospheric variability over the past century, capturing processes that operate on much shorter timescales.

40 The coexistence of these perspectives raises a fundamental question: how can climate variability be interpreted consistently across such disparate temporal domains? Addressing this question does not require replacing existing definitions, but rather situating them within a broader, explicitly multiscale framework.

Building upon previous work that emphasized the hierarchical organization of climatic processes across geological time (Mazza, 2025), the present study proposes a structured temporal stratification of climate variability. Three nested domains are

45 distinguished: meteorological variability (years to decades), sub-climatic oscillations (centuries), and long-term climatic regimes (millennia and longer). This stratification is not intended to redefine climate in a normative sense, but to provide a conceptual framework for interpreting how different processes interact across temporal scales.

Within this framework, processes capable of structuring long-term climatic regimes—such as orbital forcing, tectonic boundary conditions, and large-scale ocean–atmosphere interactions—are distinguished from feedback mechanisms and

50 radiative processes that primarily modulate variability within shorter temporal domains. This perspective allows for the integration of molecular greenhouse-gas physics, ecosystem feedbacks, and climate modeling within a consistent multiscale architecture, without diminishing their physical relevance.

The aim of this study is therefore to develop a coherent framework that links paleoclimate evidence with contemporary observations, clarifying how climate variability can be interpreted across nested temporal scales. By explicitly recognizing the

55 stratified nature of climatic processes, this approach seeks to enhance conceptual clarity and provide a more consistent basis for interpreting both long-term climate evolution and short-term atmospheric variability.

This study builds upon previous work (Mazza, 2025) by extending the hierarchical framework to examine its implications for the interpretation of climate variability, attribution, and modeling across temporal scales.



## 60 **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.

65 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?

70 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<sub>2</sub>,” “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.

75 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.

## **3 Temporal stratification of climate variability**

85 The analysis of climate variability across geological and observational records suggests that climatic phenomena can be meaningfully interpreted within a stratified temporal framework. Rather than representing a single class of processes, climate-related variability emerges from the interaction of mechanisms operating across distinct but interconnected temporal domains. For the purposes of conceptual clarity, three nested domains can be distinguished: meteorological variability, sub-climatic oscillations, and long-term climatic regimes. These domains differ in their characteristic timescales, physical persistence, and dominant controlling processes, while remaining dynamically coupled within the Earth system.

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### 3.1 Meteorological variability (years to decades)

Meteorological variability encompasses atmospheric processes unfolding over short timescales, from seasonal to decadal. These include fluctuations in temperature, precipitation, and circulation patterns driven by internal atmospheric dynamics and short-term energy redistribution.

95 Instrumental records, which extend over approximately the last century to century and a half, provide high-resolution observations of this domain. Within this temporal window, variability reflects the combined influence of radiative forcing, ocean–atmosphere interactions, and internal climate variability. While these processes are essential for understanding present-day atmospheric behavior, their temporal scope remains limited relative to longer-term Earth-system evolution.

### 3.2 Sub-climatic oscillations (centuries)

100 At intermediate timescales, sub-climatic oscillations emerge from the cumulative integration of atmospheric and oceanic processes over centuries. These oscillations reflect the persistence of coupled ocean–atmosphere dynamics, including thermal inertia, circulation variability, and feedback mechanisms involving water vapor, clouds, and biospheric interactions. Paleoclimate reconstructions from the late Holocene and high-resolution proxy records indicate that such variability can produce significant fluctuations in regional and global climate indicators over centennial intervals. These processes operate  
105 within existing climatic regimes and contribute to the modulation of atmospheric conditions without necessarily altering the underlying large-scale boundary conditions of the Earth system.

### 3.3 Long-term climatic regimes (millennia and longer)

Long-term climatic regimes are expressed over millennial to multimillion-year timescales and correspond to persistent states of the Earth system structured by large-scale boundary conditions. Geological and paleoclimatic archives demonstrate that  
110 these regimes are governed primarily by processes such as orbital forcing, tectonic reorganization, long-term ocean circulation changes, and large-scale biogeochemical cycles (Milanković, 1941; Hays et al., 1976; Zachos et al., 2001; Lisiecki and Raymo, 2005; Mudelsee et al., 2014).

These processes operate independently of short-term variability and impose externally paced constraints on the Earth’s energy balance. Their effects are recorded in stratigraphic sequences, isotope records, and fossil assemblages, which collectively  
115 document transitions between different climatic states over extended intervals.

Within this framework, long-term climate evolution reflects the interaction between externally driven boundary conditions and internally mediated feedback processes. Radiative agents, including greenhouse gases, play an important role in modulating energy transfer within the atmosphere–ocean system, particularly over shorter timescales. However, their effects are embedded within the broader structure defined by large-scale drivers that operate over much longer temporal domains.

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### 3.4 Coupling between temporal domains



Although analytically distinct, these temporal domains are not independent. Instead, they form a nested system in which processes operating at shorter timescales are embedded within, and constrained by, longer-term climatic regimes. Conversely, the cumulative effects of short- and intermediate-term variability can influence the expression and timing of longer-term transitions through feedback amplification and nonlinear interactions.

This stratified perspective provides a framework for interpreting climate variability as a multiscale phenomenon, in which the significance of individual processes depends on the temporal domain under consideration. Recognizing this structure allows for a more consistent interpretation of climate dynamics across observational and geological records, and reduces the risk of conflating processes that operate at fundamentally different scales.

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#### 4 Astronomical and heliophysical modulation

Within the temporal framework developed in Section 3, it becomes necessary to identify the processes capable of establishing and pacing long-term climatic 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 cyclicality, 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,

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2002). These processes unfold over similarly extended timescales and contribute to transitions between greenhouse and icehouse states.

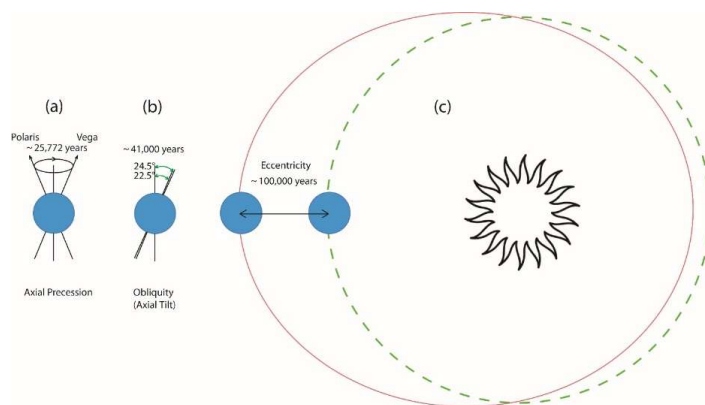
All of these drivers interact within a nonlinear dynamical system in which feedback mechanisms—water vapor amplification, cloud responses, ice–albedo effects, and carbon-cycle dynamics—mediate the magnitude and timing of climatic responses  
160 (Bony et al., 2006; Ghil, 2019). In the hierarchical framework 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

Within the temporal stratification framework outlined above, high-resolution paleoclimate records provide key empirical  
165 constraints on the hierarchy of climate forcings (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<sub>2</sub> 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<sub>2</sub> functions as a feedback amplifier within a broader forcing hierarchy rather than as the primary pacing  
170 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  
175 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  
180 variability. Figure 1 illustrates the three principal orbital parameters and their characteristic periodicities.



**Figure 1: Orbital parameters relevant to long-term climate variability within the temporal stratification framework.**

185 (a) Axial precession (~25.7 kyr) alters the seasonal timing of perihelion and aphelion, thereby redistributing incoming solar radiation between hemispheres. (b) Obliquity (axial tilt) varies between ~22.5° and ~24.5° with a characteristic periodicity of ~41 kyr, modulating latitudinal insolation gradients and influencing ice-sheet dynamics. (c) Orbital eccentricity (~100 kyr) controls the degree of orbital ellipticity and modulates the amplitude of the precessional signal. Together, these parameters define the astronomical boundary conditions that pace long-term climatic regimes.

190 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.

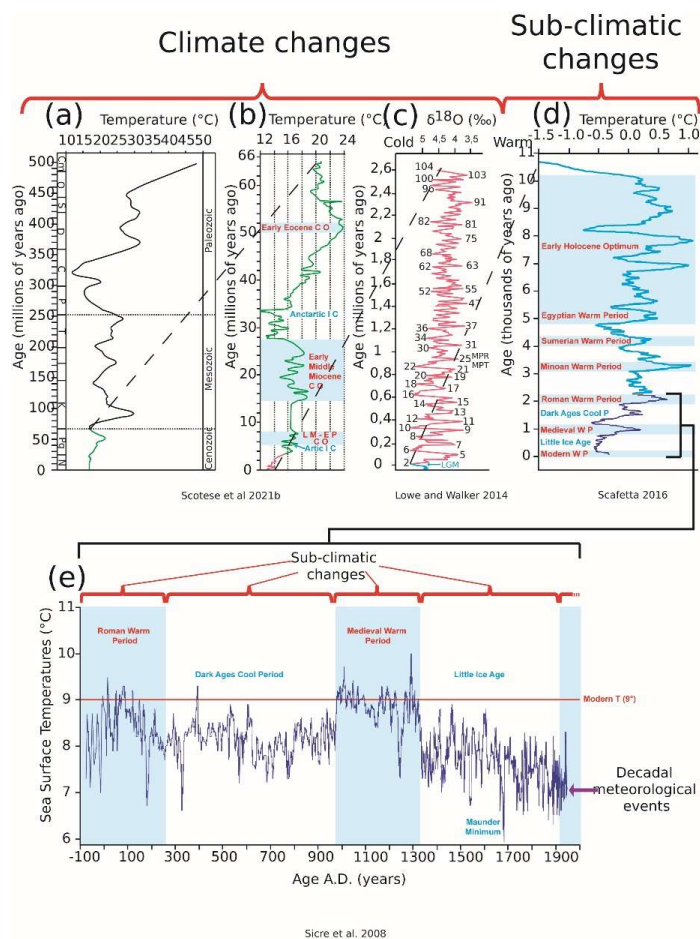
In combination, these astronomical cycles form the backbone of long-term climate pacing during the Quaternary, setting the boundary conditions within which internal feedbacks—albedo, water vapor, clouds, and carbon cycling—operate. In the  
195 multiscale interpretation adopted in this study, Milanković 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).  
200 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  $\delta^{18}\text{O}$ -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;



205 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.



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**Figure 2: Multiscale  $\delta^{18}\text{O}$ -derived paleotemperature records illustrating climate variability across nested temporal domains.**

(a) Phanerozoic-scale surface temperature reconstruction (~500 Ma) based on carbonate  $\delta^{18}\text{O}$  data (after Scotese et al., 2021). (b) Cenozoic deep-ocean temperature evolution (0–66 Ma) derived from benthic foraminiferal  $\delta^{18}\text{O}$  (after Scotese et al., 2021). (c) Quaternary  $\delta^{18}\text{O}$  stack (last 2.6 Ma), highlighting orbital-scale glacial–interglacial variability (after Lisiecki and Raymo, 2005; Lowe and Walker, 2015). (d)



215 Holocene temperature reconstruction from the GISP2 ice core, showing millennial- to centennial-scale variability (after Scafetta et al., 2016).  
(e) High-resolution sea-surface temperature record for the last ~2000 years, capturing decadal-scale variability (after Sicre et al., 2008).  
These records illustrate the hierarchical organization of climate variability, from geological-scale regimes to sub-climatic and meteorological  
fluctuations, emphasizing the temporal nesting of processes within the Earth system.  
Abbreviations:  $\delta^{18}\text{O}$  = oxygen isotope ratio ( $^{18}\text{O}/^{16}\text{O}$ ); kyr = thousand years; Ma = million years; °C = degrees Celsius; ‰ = per mille.

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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

225 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.

## 6 Recent climate trends within a multiscale temporal framework

The hierarchical framework outlined in the previous sections provides a useful basis for interpreting recent climate trends  
230 within the broader temporal structure of the Earth system. Instrumental records document a measurable increase in global  
mean surface temperature over approximately the past century. Within the temporal stratification adopted here, this trend is  
situated primarily within the meteorological to sub-climatic domains, reflecting atmospheric and oceanic variability operating  
over decadal to centennial timescales.

This classification does not call into question the physical reality of observed warming or the role of radiative forcing in  
235 influencing atmospheric energy balance. Rather, it places these processes within a temporal context that distinguishes short-  
term variability from long-term climatic regimes structured by boundary conditions operating over millennial and longer  
intervals. Importantly, this framework does not diminish the established role of greenhouse-gas forcing in shaping atmospheric  
energy balance but rather situates it within a temporally stratified Earth-system context.

The oceans play a central role in mediating short- to intermediate-term climate variability. Due to their high heat capacity and  
240 long overturning timescales, oceanic processes integrate radiative perturbations over decades to centuries, influencing surface  
temperature trajectories and modulating atmospheric responses (Levitus et al., 2012; Cheng et al., 2017). This integrative  
behavior contributes to the persistence of temperature trends within the sub-climatic domain, while remaining embedded within  
longer-term climatic structures.

Feedback mechanisms further contribute to the amplification or damping of atmospheric variability at these timescales. Water  
245 vapor feedback, cloud dynamics, and biospheric interactions influence the magnitude and spatial distribution of temperature  
changes (Held and Soden, 2000; Allen et al., 2009; Sherwood et al., 2020; Zelinka et al., 2020). These processes operate within  
the coupled atmosphere–ocean system and play a key role in shaping observed climate variability on decadal to centennial  
scales.



250 From a multiscale perspective, the interpretation of recent warming depends on the temporal horizon considered. While short-term observations capture significant atmospheric trends, the classification of such trends within the broader context of climate evolution requires consideration of their persistence relative to the longer-term processes that define climatic regimes. Geological records indicate that regime-scale climatic transitions are typically associated with sustained changes in boundary conditions over extended intervals, rather than short-term perturbations alone.

255 Within this framework, recent warming can be interpreted as a significant atmospheric–oceanic signal within the shorter temporal domains of the Earth system, interacting with internal variability and feedback processes. Its long-term significance depends on its persistence and its interaction with larger-scale boundary conditions that govern the evolution of climatic regimes.

260 This stratified interpretation makes it possible to integrate contemporary observations with paleoclimate evidence, without conflating processes operating at different temporal scales. It provides a consistent basis for analyzing climate variability across observational and geological records, while maintaining compatibility with established physical principles and empirical data.

## **7 Implications of temporal stratification for climate interpretation**

265 The temporal stratification framework outlined in the previous sections provides a basis not only for describing climate variability, but also for refining its interpretation across observational and geological contexts. By explicitly distinguishing between meteorological variability, sub-climatic oscillations, and long-term climatic regimes, this approach allows for a more consistent evaluation of climate processes and their relative significance within the Earth system.

### **7.1 Interpretation of climate variability across temporal scales**

270 One of the primary implications of a stratified framework is that the interpretation of climate variability depends fundamentally on the temporal domain considered. Processes that appear dominant within short observational windows may represent only a subset of the mechanisms governing long-term climate evolution. Conversely, processes that structure climate over geological timescales may not be directly observable within instrumental records (Mudelsee et al., 2014; Zachos et al., 2001).

275 Recognizing this temporal dependency helps to avoid conflating phenomena that differ in scale, persistence, and physical drivers. It also provides a basis for interpreting apparent discrepancies between short-term observations and long-term paleoclimate trends, which may reflect differences in temporal resolution rather than contradictions in underlying processes (Hays et al., 1976; Lisiecki and Raymo, 2005).

### **7.2 Implications for attribution of climate variability**

280 The attribution of climate variability is inherently scale-dependent. Within meteorological and sub-climatic domains, variability reflects the combined influence of radiative forcing, internal dynamics, and feedback mechanisms operating over decadal to centennial timescales (IPCC, 2021). At longer timescales, however, paleoclimate records indicate that climatic



regimes are structured by externally paced boundary conditions, including orbital forcing and tectonic processes (Milanković, 1941; Ruddiman, 2006).

285 A multiscale perspective therefore suggests that attribution should be interpreted within the temporal context in which specific processes operate. Rather than assigning a single dominant cause across all scales, climate variability can be understood as the outcome of interacting mechanisms whose relative influence varies with temporal domain.

### 7.3 Implications for climate modeling

290 Climate models are designed to simulate atmospheric and oceanic processes over finite temporal horizons, typically spanning decades to centuries. Within these domains, they provide valuable insights into radiative transfer, feedback mechanisms, and circulation dynamics (Knutti and Sedláček, 2013; Edwards, 2010), as widely discussed in recent climate model intercomparison studies (e.g., IPCC, 2021). Their ability to represent coupled processes within the atmosphere–ocean system makes them essential tools for investigating short- to intermediate-term climate variability.

295 From a multiscale perspective, however, the interpretation of model outputs depends on the temporal domain for which the models are constructed. Processes that govern long-term climatic regimes—such as orbital forcing, tectonic boundary conditions, and large-scale ocean reorganizations—operate over timescales that extend beyond those typically explored in standard modeling frameworks (Stouffer, 2004; WCRP, 2019). This does not represent a limitation of modeling per se but reflects the inherent differences between short-term simulation frameworks and the temporal structure of Earth-system evolution.

300 The stratified framework proposed here highlights the importance of aligning model interpretation with the temporal scales of both the processes being simulated and the questions being addressed. In this context, model outputs can be understood as detailed representations of variability within meteorological and sub-climatic domains, while paleoclimate records provide the longer-term constraints necessary to characterize regime-scale climate dynamics.

305 This perspective suggests that future advances may benefit from closer integration between modeling approaches and paleoclimate evidence, including the incorporation of long-term boundary conditions and proxy-based constraints. Such integration may help bridge the gap between short-term simulations and long-term climate evolution, contributing to a more consistent multiscale understanding of the Earth system.

### 7.4 Integration of instrumental and paleoclimate records

310 A key challenge in climate science lies in the integration of high-resolution instrumental observations with lower-resolution but longer-term paleoclimate archives. These datasets differ not only in temporal extent, but also in the processes they capture and the scales at which variability is expressed (Lowe and Walker, 2015; Mudelsee et al., 2014).

The temporal stratification framework provides a conceptual bridge between these domains by situating each type of record within its appropriate temporal context. Instrumental records can be interpreted as detailed observations of meteorological and



315 sub-climatic variability, while paleoclimate archives provide the temporal depth necessary to identify long-term climatic regimes and their controlling mechanisms.

### 7.5 Conceptual implications for climate definitions

320 Finally, the stratified perspective has implications for how the term “climate” is used across disciplines. Rather than viewing different definitions as mutually incompatible, they can be understood as reflecting distinct observational scales within a unified multiscale system.

In this sense, operational meteorological definitions and geological interpretations of climate are not contradictory, but complementary (IPCC, 2021; WMO, 2017). Each captures processes that are valid within its respective temporal domain. A multiscale framework therefore does not replace existing definitions, but situates them within a broader conceptual structure that clarifies their scope and applicability.

325 This perspective contributes to a more flexible and scale-aware understanding of climate, in which the meaning of climate variability is interpreted in relation to the temporal domain under consideration.

### 8 Biomes, ecosystem feedbacks, and climate-system dynamics

330 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

340 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<sub>2</sub> 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<sub>2</sub> 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.



350 **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**

360 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**

375 Interpreting climate-model outputs within a multiscale Earth-system perspective requires explicit consideration of temporal scope. Climate models are primarily designed to simulate atmospheric and oceanic processes over decadal to centennial timescales, representing radiative transfer, feedback mechanisms, and large-scale circulation dynamics within computationally tractable frameworks. Their strengths and limitations are therefore best understood in relation to the temporal domains they are intended to address.

380 **9.1 Climate modeling: temporal scope and structural constraints**

General circulation models and Earth System Models incorporate 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 investigating short- to centennial-scale climate variability and for  
385 exploring the response of the climate system to radiative forcing scenarios.

From a multiscale perspective, however, the processes that structure long-term climatic regimes—such as orbital configuration, tectonic reorganization, ocean-gateway changes, and long-term carbon-cycle adjustments—operate over timescales that extend beyond those typically addressed in standard modeling applications (Crowley, 1989; Stouffer, 2004; WCRP, 2019). This reflects differences in temporal scope rather than a limitation of modeling itself, and highlights the importance of interpreting  
390 model results within the temporal framework for which they are designed.

Accordingly, model outputs describing centennial-scale climate variability can be understood as detailed representations of processes operating within meteorological and sub-climatic domains, while geological-scale climate evolution requires integration with paleoclimate evidence that captures longer-term boundary conditions and system responses.

Cloud feedbacks remain a significant source of uncertainty in climate sensitivity estimates (Bony and Dufresne, 2005; Zelinka et al., 2020; Hill et al., 2025). Paleoclimate records provide complementary constraints by documenting climate responses to  
395 large-scale forcings over extended intervals (Hays et al., 1976; Lisiecki and Raymo, 2005). Together, modeling and paleoclimate evidence offer a more complete basis for understanding climate variability across temporal scales.

## 9.2 Policy considerations in a multiscale temporal context

400 Policy-relevant climate assessments are often based on model projections extending over the coming decades to century. These projections are well suited for evaluating risks associated with atmospheric and oceanic variability within human-relevant timescales, including extreme events, hydrological changes, and ecosystem responses (IPCC, 2021, 2022).

Within a multiscale framework, such projections can be interpreted as describing processes operating within meteorological and sub-climatic domains, while longer-term climate evolution reflects interactions with boundary conditions that operate over  
405 extended temporal horizons. Recognizing this distinction does not diminish the relevance of short-term projections, but provides a clearer context for interpreting their scope and applicability.

From this perspective, anthropogenic influences are most directly expressed through changes in atmospheric composition, land use, and biospheric processes within shorter temporal domains. Over longer timescales, climate evolution involves the interaction of these processes with larger-scale drivers documented in the geological record (Ruddiman, 2006; Mudelsee et al.,  
410 2014).

Future research may benefit from continued integration of modeling approaches with paleoclimate archives, strengthening the connection between short-term projections and long-term Earth-system dynamics. Such integration can contribute to a more coherent understanding of climate variability across temporal scales, supporting interpretation across both scientific and applied contexts.

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## 10. Conclusions



This study has explored climate variability within a multiscale Earth-system framework, emphasizing the importance of explicitly distinguishing between processes operating across different temporal domains. Geological and paleoclimatic evidence demonstrates that long-term climatic regimes are structured by boundary conditions operating over millennial to multimillion-year timescales, including orbital dynamics, tectonic configurations, large-scale ocean circulation, and long-term biogeochemical cycles (Milanković, 1941; Hays et al., 1976; Zachos et al., 2001; Mudelsee et al., 2014).

Within this context, atmospheric processes and radiative forcing mechanisms, including greenhouse gases, play a fundamental role in modulating energy transfer within the atmosphere–ocean system, particularly over decadal to centennial timescales. Climate sensitivity estimates and feedback processes therefore provide important insights into short- to intermediate-term variability, while long-term climate evolution reflects the interaction between externally paced boundary conditions and internally mediated feedbacks across extended temporal intervals.

The hierarchical temporal stratification proposed here—distinguishing meteorological variability, sub-climatic oscillations, and long-term climatic regimes—offers a framework for interpreting climate as a multiscale phenomenon. This perspective allows for the integration of high-resolution instrumental observations with long-term paleoclimate archives, reducing the risk of conflating processes that operate at fundamentally different temporal scales.

Recognizing this stratified structure has important implications for the interpretation of climate variability, the use of climate models, and the integration of paleoclimate data into contemporary analyses. Climate models are highly effective in simulating atmospheric and oceanic dynamics over decadal to centennial intervals, while geological records provide the temporal depth necessary to identify the large-scale drivers of long-term climate evolution. A multiscale framework can therefore contribute to a more consistent interpretation of climate processes across observational and geological domains.

This approach does not replace existing definitions of climate used in meteorology or climate science, but situates them within a broader temporal context in which different definitions correspond to different observational scales. By explicitly acknowledging the coexistence of these temporal domains, the framework proposed here aims to enhance conceptual clarity and support more coherent interpretation of climate variability across disciplines.

Future research may further develop this perspective by integrating paleoclimate archives with modeling approaches, improving continuity between short-term simulations and long-term Earth-system dynamics. Advances in proxy reconstruction, data assimilation, and multiscale modeling will be essential for further refining our understanding of climate as a layered and temporally structured system.

#### 445 **Competing interests**



The author declares that there are no competing interests.

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