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Past climates inform our future: Review Summary

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Background: Anthropogenic emissions are rapidly altering Earth's climate, pushing it toward a warmer state for which there is no historical precedent. Although no perfect analogue exists for such a disruption, Earth's history includes past climate states – "paleoclimates" – that hold lessons for the future of our warming world. These periods in Earth's past span a tremendous range of temperatures, precipitation patterns, cryospheric extent, and biospheric adaptations, and are increasingly relevant for improving our understanding of how key elements of the climate system are affected by greenhouse gas levels. The rise of novel geochemical and statistical methods, as well as improvements in paleoclimate modeling, allow for formal evaluation of climate models based on paleoclimate data. In particular, given that some of the newest generation of climate models have a high sensitivity to a doubling of atmospheric CO_2, there is a renewed role for paleoclimates in constraining equilibrium climate sensitivity (ECS) and its dependence on climate background state.

Advances: In the past decade, an increasing number of studies have used paleoclimate temperature and CO_2 estimates to infer ECS in the deep past, in both warm and cold climate states. Recent studies support the paradigm that ECS is strongly state-dependent, rising with increased CO_2 concentrations. Simulations of past warm climates such as the Eocene further highlight the role that cloud feedbacks play in contributing to high ECS under elevated CO_2 levels. Paleoclimates have provided critical constraints on the assessment of future ice sheet stability and concomitant sea level rise, including the viability of threshold processes like marine ice cliff instability. Beyond global-scale changes, analysis of past changes in the water cycle have advanced our understanding of dynamical drivers of hydroclimate, which is highly relevant for regional climate projections and societal impacts. New and expanding techniques, such as analyses of single shells of foraminifera, are yielding sub-seasonal climate information that can be used to study how intra- and interannual modes of variability are affected by external climate forcing. Studies of extraordinary, transient departures in paleoclimate from the background state such as the Paleocene-Eocene Thermal Maximum provide critical context for the current, anthropogenic aberration, its impact on the Earth system, and the timescale of recovery.

A number of advances have eroded the "language barrier" between climate model and proxy data, facilitating more direct use of paleoclimate information to constrain model performance. It is increasingly common to incorporate geochemical tracers – such as water isotopes – directly into model simulations and this practice has vastly improved model – proxy comparisons. The development of new statistical approaches rooted in Bayesian inference has led to a more thorough quantification of paleoclimate data uncertainties. Finally, techniques like data assimilation allow for a formal combination of proxy and model data into hybrid products. Such syntheses provide a full-field view of past climates and can put constraints on climate variables that we have no direct proxies for, such as cloud cover or wind speed.

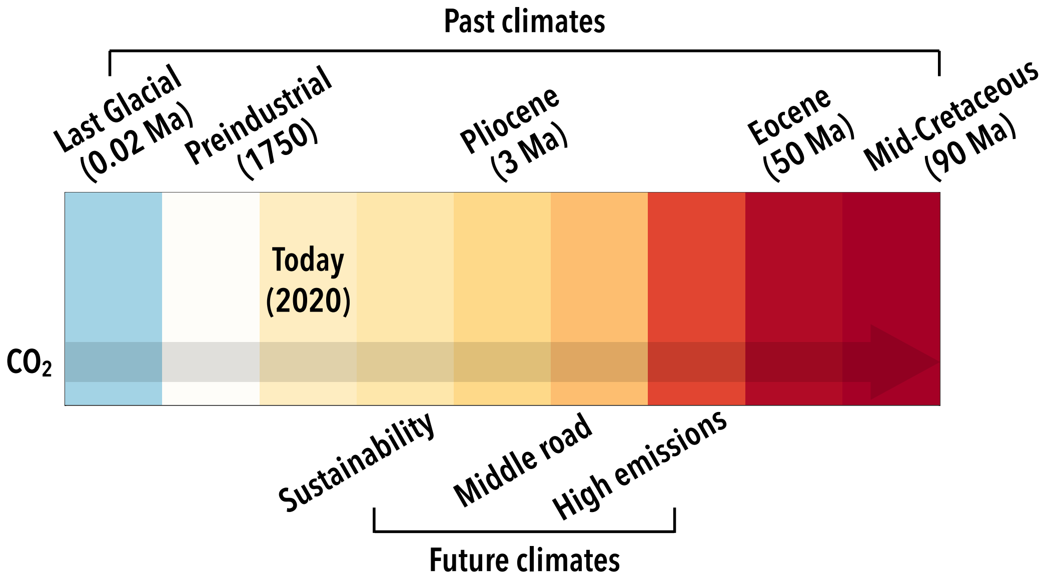

Figure 1: Past climates (denoted on top) provide context for future climate scenarios (at bottom). Ma = millions of years ago. Both past and future climates are colored by their estimated change in global mean annual surface temperature relative to preindustrial conditions. "Sustainability", "Middle road", and "High emissions" represent the estimated global temperature anomalies at 2300 from the Shared Socioeconomic Pathways (SSPs) SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. In both the past and future cases, warmer climates are associated with increases in CO_2.

Outlook: A common concern with using paleoclimate information as model targets is that non-CO_2 forcings, such as aerosols and trace greenhouse gases, are not well known, especially in the distant past. While evidence thus far suggests that such forcings are secondary to CO_2, future improvements in both geochemical proxies and modeling are on track to tackle this issue. New and rapidly evolving geochemical techniques have potential to provide improved constraints on the terrestrial biosphere, aerosols, and trace gases; likewise, biogeochemical cycles can now be incorporated into paleoclimate model simulations. Beyond constraining forcings, it is critical that proxy information is transformed into quantitative estimates that account for uncertainties in the proxy system. Statistical tools have already been developed to achieve this, which should make it easier to create robust targets for model evaluation. With this increase in quantification of paleoclimate information, we suggest that modeling centers include simulation of past climates in their evaluation and statement of their model performance. This practice is likely to narrow uncertainties surrounding climate sensitivity, ice sheets, and the water cycle and thus improve future climate projections.

Past climates inform our future

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As the world warms, there is a profound need to improve projections of climate change. While the latest Earth system models offer an unprecedented number of features, fundamental uncertainties continue to cloud our view of the future. Past climates provide the only opportunity to observe how the Earth system responds to high CO_2, underlining a fundamental role for paleoclimatology in constraining future climate change. Here, we review the relevancy of paleoclimate information for climate prediction and discuss the prospects for emerging methodologies to further insights gained from past climates. Advances in proxy methods

and interpretations pave the way for the use of past climates for model evaluation – a practice we argue should be widely adopted.

1 Introduction

The discipline of paleoclimatology is rooted in the peculiarities of the geological record, which has long hinted that Earth's climate can change in profound ways. In possibly the first paleoclimate study, the 17^{th} century English physicist Robert Hooke concluded, based on observations of large turtles and ammonites in Jurassic rocks, that conditions in England had once been much warmer than now (*1*). Since then, paleoclimate studies have revolutionized our view of the climate system (*2*), documenting both warm and cold worlds much different than the one we inhabit, and establishing the link between atmospheric CO_2 and global temperature (Fig. 1).

While paleoclimatology continues to narrate the history of Earth's climate, it also plays an increasingly central role in understanding future climate change. The study of past climate has never been more relevant than now, as anthropogenic activities increase atmospheric greenhouse gas concentrations and modify the land surface and ocean chemistry at a rate and scale that exceed natural geologic processes. CO_2 levels are higher now than at any point in at least the last three million years and, at the current rate of emissions, will exceed concentrations typical of the last 30 million years by 2300 (Fig. 1). In this context, past climates are windows into our future (*3*) – the geological record is the only observational source of information for how the climate system operates in a state much warmer than the present.

The challenge for paleoclimatology is that there are few direct quantitative records of past climate (e.g. temperature, precipitation). Instead, we make use of "proxies," surrogates for climate variables that cannot be measured directly. In some cases, the physical occurrence (or absence) of a proxy (like glacial deposits) reveals information about past environmental conditions. More often, geochemical data (such as elemental and stable isotope ratios) stored in fossils, minerals, or organic compounds, are used to infer past conditions. The discovery of new proxies, improvements in modeling and analytical techniques, and the increasing number of proxy records are actively expanding the utility of paleoclimate information. These innovations are refining our understanding of how the climate system responds to large changes in atmospheric CO_2, and provide insights into aspects of past climates (such as seasonality and interannual variability) that were heretofore unknowable.

Among the most important contributions that paleoclimatology can make is the evaluation of Earth system models that we rely on for projecting future climate change. The physical parameterizations in these sophisticated models are often tuned to fit the preindustrial or historical record (*4*). However, the latter is short in duration and samples a single climate state with a narrow CO_2 range. The performance of climate models under extreme forcing very different than present is not commonly assessed, despite the fact that the models are used to project changes under high-emissions scenarios. When these models are used to simulate past warm climates, they often predict surface temperatures that are too cold and pole-to-equator temperature gradients that are too large (*5*). However, a new generation of models, alongside developments in proxy techniques and analysis, now provide opportunities to more fully exploit past climates for model evaluation and assessment of key metrics of the climate system.

2 Past climates inform key processes

Earth's paleoclimate record contains tremendous variability. Over the last 100 million years, the climate gradually transitioned from an ice-free world of exceptional warmth (the mid-Cretaceous, 92 Ma, Fig. 1) to the cold ice ages of the past few million years, glacial worlds with kilometers-thick ice caps covering one-fourth of the land surface (such as the Last Glacial Maximum (LGM), 21 ka, Fig. 1). Between Cretaceous and LGM extremes lie intermediate warm climates such as the early Eocene (53–49 Ma) and Pliocene (5.3–2.6 Ma) (Fig. 1). This long-term climate transition was far from steady – short-lived hyperthermal events (*6*) and cold stadials (*7*) punctuated the slower trends.

Atmospheric CO_2 concentrations generally follow these swings in global temperature (Fig. 1). Geochemical modeling demonstrates that the balance of geological sources (degassing through volcanism) and sinks (weathering and sedimentation) explains the general features of CO_2's trajectory (*8*) and establishes causality – high CO_2 leads to high temperatures. The apparent exceptions to this rule, including the end-Cretaceous and early Paleocene (70–60 Ma) and the Miocene (23–5.3 Ma), are areas of active research. One explanation for the decoupling of CO_2 and temperature is that uncertainties associated with the proxies blur the relationship. Estimation of past CO_2 is challenging. Beyond the ice core record (*9*), CO_2 information comes from geochemical data, such as isotope ratios of boron and carbon, or paleobotanical indicators such as the density of leaf stomata. All of these proxies require assumptions about the physical, chemical, and biological state of the past that are not completely understood, sometimes leading to misinterpretations of the signal (*10*). Proxy methodologies and assumptions continue to be refined, and there is some indication that CO_2 at the end of the Cretaceous may have been higher than shown in Fig. 1 (*11*). It is also possible that these discrepancies have another explanation, such as a greater-than-expected role for non-CO_2 forcings and feedbacks. If the paleoclimate record has taught us anything, it is that the more we probe, the more we learn.

Past climate states were profoundly different from today. Their global mean temperatures, latitudinal temperature gradients, polar ice extents, regions of deep-water formation, vegetation types, patterns of precipitation and evaporation, and variability were all different. These differences are invaluable as they provide rich evidence of how climate processes operated across states that span the range of CO_2 concentrations (400–2000 ppm) associated with future emissions scenarios (the Shared Socioeconomic Pathways (SSPs), Fig. 1). Under the sustainable SSP1-2.6 scenario, in which emissions are curtailed and become net-negative by the end of the 21st century, CO_2 concentrations would be stabilized near Pliocene levels (Fig. 1). In contrast, under the fossil-fuel intensive SSP5-8.5 scenario, CO_2 concentrations would approach or even exceed Eocene or mid-Cretaceous levels (Fig. 1). These past warm climates therefore serve as targets against which to measure the increasingly complex generation of climate models that are used for future climate prediction.

Past climates are not perfect analogues for future states – continental configurations are increasingly different with age, and they often represent equilibrium climates as opposed to transient changes associated with rapid greenhouse gas emissions (*12*). But as benchmarks for climate models, ancient climates need not be perfect analogues. In fact, the differences are advantageous; they provide true out-of-sample validation for the strength and stability of key feedbacks; large-scale responses of the hydrological cycle; and the most ubiquitous metric of all, climate sensitivity.

3 Paleoclimate constraints on climate sensitivity

Equilibrium climate sensitivity (ECS) has been widely adopted as a simple metric of how responsive the Earth's climate system is to radiative forcing. It is defined as the change in global near-surface air temperature resulting from a sustained doubling in atmospheric CO_2 after the fast-acting (timescales of years to decades) feedback processes (water vapor, clouds, snow) in the Earth system reach equilibrium. The 5th assessment report of the IPCC determined that ECS was likely between 1.5 and 4.5°C, a large range that has remained essentially unchanged for 40 years (*13*). Because the environmental impacts, socio-economic implications, and mitigation timescales are very different for a low versus a high ECS (*14*), narrowing its range has always been a high priority.

The fact that models with either a low or high present-day ECS can match historical observations (*15*) suggests that preindustrial and industrial climatic changes provide insufficient constraints on this important metric. Furthermore, the emerging view is that ECS is dependent on, and changes with, the background climate state – specifically, it increases in warmer climates (*16–19*). Past warm climates therefore provide key constraints on the range of plausible ECS values as well as the strength of feedbacks involved. Simulations of the early Eocene provide a salient example. Figure 2 shows a comparison between the ECS of Coupled Model Intercomparison Project (CMIP) Phase 5 and Phase 6 models (used in the last and the upcoming IPCC assessments) and the ECS of preindustrial and Eocene simulations conducted with the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM) version 1.2 (*19*). Doubling CO_2 in an Eocene experiment with preindustrial CO_2 (285 ppm; 1X) yields an ECS similar to the preindustrial experiment and overlaps with the CMIP range (Fig. 2). This indicates that non-CO_2 Eocene boundary conditions, including the position of the continents and the absence of continental ice sheets, do not have a large effect on ECS in CESM1.2. In contrast, raising CO_2 levels elevates ECS in the Eocene simulations to values above 6°C (Fig. 2). This increase in ECS with increasing temperature results in accurate simulation of Eocene temperatures at CO_2 concentrations that agree with proxy estimates (Fig. 2, inset). The elevated ECS under high CO_2 in CESM1.2 is due to improved representation of clouds in the CAM5 atmospheric model, which drives a strong low-cloud positive feedback under high CO_2 (*19*) – a finding in agreement with the emerging recognition that cloud feedbacks are a key component of warm climates (*20, 21*). The fact that CESM1.2 simulates Eocene proxy temperatures within the bounds of proxy CO_2 estimates provides support for its cloud physics and increases our confidence in the model's state-dependent ECS. The Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model can also simulate the large-scale features of Eocene proxy temperatures (*22*), likewise suggesting that its ECS is reasonable. On the other hand, CESM2 (the newest version of the NCAR model) estimates Eocene temperatures that exceed the upper bound of proxy constraints at low CO_2 levels (*23*), suggesting that its modern ECS of 5.3°C is too high. A little more than a third of the newest-generation CMIP6 models have an ECS higher than 4.5°C (*15*). From historical observations alone, it is very challenging to assess the plausibility of these higher ECS values. As the Eocene example highlights, warm paleoclimates are key in this respect.

The early Eocene provides an important constraint on model ECS but samples a single high-CO_2 climate state. Given the dependence of ECS on the background climate state, other past climates are critical to constraining ECS and relevant physics under both lower (e.g. LGM, Pliocene) and higher (e.g. Eocene, Cretaceous) background CO_2 levels. One concern about using past climates as model targets is that the forcings, especially aerosol and non-CO_2 greenhouse gas concentrations, are uncertain and increasingly so in the distant past. While important, it is worth noting that these forcings are secondary to CO_2 (e.g. (*24*)) and, for extreme climates like the Eocene and Cretaceous, may largely fall within the climate proxy uncertainties. Moreover, this concern can be mitigated by examining model responses to the potential range of under-constrained forcings and, as is increasingly done, by incorporating biogeochemical cycles and the simulation of aerosol production and transport into the models.

4 Paleoclimate perspectives on the stability of the cryosphere

Future projections of sea level rise have large uncertainties, mainly due to unknowns surrounding the stability and threshold behavior of ice sheets (*25*). The paleoclimate record furnishes true "out-of-sample" tests for understanding the sensitivity of the cryosphere to warming that can lower these uncertainties. The past few years have seen a number of advances on both data and climate modeling fronts to understand past changes in ice sheets and connect these to the future. Advances in the generation and interpretation of proxy indicators of ice sheet size, shape, and extent (*26–28*) are helping to refine our understanding of cryosphere dynamics in warmer climates. Improvements in modeling the effects of dynamic topography and glacial isostatic adjustment are continually reducing uncertainties associated with estimates of past global sea level (*29, 30*), providing more accurate benchmarks for model simulations (*31*).

Paleoclimates also provide critical insights into processes that drive destabilization of ice sheets. Of particular relevance for future projections is assessing the likelihood of marine ice-cliff instability (MICI), a rapid collapse of coastal ice cliffs following the disintegration of an ice shelf, which has the potential to contribute to substantial sea level rise by the end of the 21st century (*32, 33*). The record of sea level change from past warm climates offers a way to test this hypothesis. Recent work has focused on the Pliocene, given that CO_2 concentrations during this time were similar to current anthropogenic levels (Fig. 1). A new reconstruction of global mean sea-level during the mid-Pliocene warm period indicates a rise of ~ 17 m, implying near-to-complete loss of Greenland and the West Antarctic Ice Sheet with some additional contribution from East Antarctica (*34*). While this represents an outstanding loss of ice, MICI is not necessarily needed to explain it (*33, 34*). However, simulated changes in sea level are highly dependent on each model's treatment of ice sheet stability (*35*), and paleoclimate investigations of warmer climates, such as the early Pliocene and the Miocene, indicate larger magnitudes of ice loss, thermal expansion, and consequent sea level rise (*34, 36*). Moving forward, refining our understanding of threshold behavior in ice sheets, and thus improving projections of future sea level rise, will require a synergistic approach that leverages paleoclimate estimates from multiple warm climates alongside solid Earth, ice sheet, and climate modeling (*31*).

5 Regional and seasonal information from past climates

Future warming will shift regional and seasonal patterns of rainfall and temperature, with dramatic consequences for human society (*37, 38*). Regional changes in the land surface (reduced snow cover, melting permafrost, greening, desertification) can further trigger biogeochemical feedbacks that could dampen or amplify initial radiative forcing, with implications for climate sensitivity (*39*). Unfortunately, climate models disagree about the direction and magnitude of future regional rainfall change (*40*). Improving future predictions of regional climate requires separating internal variability in the climate system (i.e., interannual–centennial oscillations) from externally-forced changes (i.e., from greenhouse gases or aerosols). Regional and seasonal paleoclimate data are critical in this respect, as they provide long, continuous estimates of the natural range of variation, augmenting the relatively short observational record (*41, 42*).

Subannually-resolved paleobiological and sedimentary archives, made more accessible by recent advances in geochemical techniques, allow for the study of seasonal-scale variations in both temperature and hydroclimate. For example, $\delta^{18}O$ measurements of fossil bivalves can be used to gain insights into the drivers of seasonal variability during the Eocene greenhouse climate (*43,44*) (Fig. 3a). Since individual planktic foraminifera live for about a month, analyses of single shells yields subannual sea-surface temperature (SST) data from ancient climates (*45*). This can be leveraged to reveal past changes in key seasonal phenomena such as the El Niño–Southern Oscillation (ENSO) (*46*) (Fig. 3). Proxy data can even provide records of changes in the frequency or intensity of extreme events like hurricanes (*47*).

Reconstructions of hydroclimate are considerably more challenging than temperature, as proxy signals tend to be more complex; however, even basic directional information (wetter vs. drier) can be used to test spatial patterns in models (e.g., (*48*)). Past warm climates allow us to test the extent to which the thermodynamic "wet-gets-wetter, dry-gets-drier" response broadly holds with warming (*49*) or if dynamical changes, such as shifts in the Hadley or Walker cells, play more of a key role in the regional water cycle response to changes in surface temperature gradients (*48, 50*).

Comparisons of proxies and models can also be used to identify the processes that are critical for accurate simulation of regional shifts in the water cycle, where local moisture and energy budgets exert an important control (*51*). The processes that drive these budgets – i.e., land surface properties and clouds – must be parameterized in global climate models and are often poorly understood, yet have huge consequences for predicted patterns in humidity and rainfall (*52–55*). Past changes in Earth's boundary conditions offer a much broader set of scenarios where observations can be used to evaluate the performance of parameterization schemes. In particular, paleoclimates spanning the last glacial cycle have helped us better understand the role of land-atmosphere feedbacks in determining hydroclimatic response. Analyses of LGM proxies for SST and water balance in Southeast Asia suggest a direct relationship between convective parameterization and model skill at capturing regional hydroclimate (*48, 56*). Studies of the mid-Holocene 'Green Sahara' highlight the importance of vegetation and dust feedbacks in accurately simulating the response of the west African monsoon to radiative forcing (*57, 58*). These examples demonstrate the value of hydroclimate proxy-model comparison even if the past climate state is not a direct analogue for future warming.

Studies of past warm climates have the potential to provide even more insights into the behavior of regional climate in a warming world. Future model projections broadly simulate a pattern of subtropical drying, while the deep tropics and high latitudes get wetter (*40*). Recently, however, researchers have argued that subtropical drying is transient and might not persist in equilibrium with higher radiative forcing (*59, 60*). Indeed, several paleoclimatic intervals (*61, 62*) suggest that a warmer world could feature a different pattern, with wetter conditions in both the subtropics and high latitudes (*50*). This pattern is especially evident in western North America, where widespread Pliocene lake deposits suggest much wetter conditions (*63*). This evidence stands in stark contrast to future projections for this region, which overwhelmingly predict drier conditions and more intense droughts (*64*), and suggests that paleoclimates can provide vital constraints on the response of arid lands to higher CO_2 concentrations.

6 Climatic aberrations

Among the most important discoveries in paleoclimatology is the occurrence of climatic "aberrations" – extraordinary transient departures from a background climate state. Such events are distinguished by radical changes in temperature, precipitation patterns, and ocean circulation that often leave distinctive marks in the geological record, like the pervasive black shales of the mid-Cretaceous Ocean Anoxic Events (*65*). An aberration typically occurs in response to a short-lived perturbation to the climate system, such as a sudden release of greenhouse gases (e.g., from volcanoes, methane clathrates, or terrestrial organic deposits). Aberrations need not be "abrupt" in the sense that the rate of climate change must exceed the rate of forcing, and they can potentially last for a long time (for example, the Sturtian Snowball Earth lasted 55 million years (*66*)). They are instructive because they provide information on extreme climate states, and the ability of the Earth system to recover from such states.

One of the most striking aberrations in the paleoclimate record, the Paleocene-Eocene Thermal Maximum (PETM), may foreshadow future changes that Earth will experience due to anthropogenic emissions. The PETM, which occurred 56 million years ago, was triggered by rapid emission of greenhouse gases; proxy and model estimates suggest that CO_2 doubled or even tripled from a background state of ~900 ppm (*67–69*) in less than 5,000 years (*70, 71*). In response, global temperatures spiked by 4–6°C (*72*). The surface ocean rapidly acidified (*68, 73*), and seafloor carbonates dissolved (*74*), resulting in dramatic biogeographic range shifts in plankton and the largest extinction in deep-sea calcifying benthic foraminifera ever observed (*75*). Precipitation patterns changed dramatically, with much more rain falling at the high latitudes (*76*). It took the Earth $\sim$ 100,000 years to recover from this perturbation (*68, 77*).

Although the PETM stands out starkly in the geologic record, the rate of CO_2 release was still 4–10 times slower than current anthropogenic emissions (*71, 78*). Indeed, the geological record leaves no doubt that our current rate of global warming, driven by anomalous (anthropogenic) forcing, is an exceptional aberration – the rate and magnitude of change far exceeds the typical multi-thousand year variability that preceded it (Fig. 4). In the last 100 million years, CO_2 has ranged from maximum values in the mid-Cretaceous to minimum levels at the Last Glacial Maximum (Fig. 1). Going forward, we are on pace to experience an equivalent magnitude of change in atmospheric CO_2 concentrations, in reverse, over a period of time that is over 10,000 times shorter (Fig. 4). In just over 150 years, we have already raised CO_2 concentrations (currently at 410 ppm) to Pliocene levels (Fig. 4). Under a middle-of-the-road emissions scenario such as SSP2-4.5 (or the CMIP5 equivalent, RCP4.5), CO_2 will approach 600 ppm by Year 2100, and if we follow the high-emissions SSP5-8.5 (or RCP8.5), CO_2 will rise beyond mid-Cretaceous concentrations (ca. 1000 ppm) by Year 2100 (Fig. 4). In comparison, over the past 800,000 years of geologic history CO_2 only varied between 180 and 280 ppm (*9*) (see also Fig. 4).

How long will it take for the Earth to neutralize anthropogenic CO_2 and return to pre-industrial levels? The Earth has the ability to recover from a rapid increase in atmospheric CO_2 concentration – the PETM is a textbook example of this process. In fact, in every case of past CO_2 perturbations, the Earth system has compensated in order to avoid a runaway greenhouse or a permanent icehouse. Yet the natural recovery from aberrations takes place on geological, not anthropogenic, timescales (Fig. 4). Some of the processes that remove CO_2 from the atmosphere occur on relatively short (100–1000 yr) timescales (e.g. ocean uptake), but others take tens to hundreds of thousands of years (e.g. weathering of silicate rocks) (*79*). Using the intermediate complexity Earth system model cGENIE, we can estimate how long the recovery process takes under different future forcing scenarios. Under an aggressive mitigation scenario (RCP 2.6), CO_2 concentrations remain at Pliocene-like concentrations (>350 ppm) through Year 2350, but it still takes hundreds of thousands of years for concentrations to return to preindustrial levels (Fig. 4). Under a middle-of-the-road scenario (RCP 4.5), CO_2 peaks around 550 ppm and remains above Pliocene levels for 30,000 years. Under a worst-case scenario (RCP 8.5) atmospheric CO_2 will remain at mid-Cretaceous (>1000 ppm) concentrations for 5,000 years, at Eocene concentrations (∼850 ppm) for 10,000 years, and at Pliocene concentrations (>350 ppm) for 300,000 years (Fig. 4). It will be at least 500,000 years, a duration equivalent to 20,000 human generations, before atmospheric CO_2 fully returns to preindustrial levels. Our planet will recover, but for humans, and the organisms with which we share this planet, the changes in climate will appear to be a permanent state shift.

7 Bridging the gap between paleoclimate data and models

Climate models provide direct estimates of quantities like temperatures, wind speed, and precipitation. In contrast, paleoclimate information is indirect, filtered through a proxy – a physical, chemical, and/or biological entity that responds to climate – such as foraminifera, algae, or the chemical composition of sediments. Proxies are imperfect recorders of climate; they have inherent uncertainties associated with, for example, biological processes and preservation. Thus, while proxy data can be transformed into climate variables for direct comparison with models using regression, transfer functions, and assumptions, if these structural uncertainties are not accounted for they can lead to unclear or erroneous interpretations. This creates a "language barrier" between model output and proxy data that has limited the use of paleoclimate information to infer past climate states and evaluate climate models. Three key innovations are now breaking down this barrier, allowing paleoclimate information to directly constrain model performance: 1) the inclusion of chemical tracers relevant to proxies directly in Earth system models; 2) the creation of robust proxy system models that explicitly encode processes, uncertainties, and multivariate sensitivities; and 3) the development of statistical methods to formally combine proxy and model data.

As far as chemical tracers are concerned, the single most important advance has been the increasingly routine incorporation of water isotopes in model simulations. The stable isotopes of water – δ^{18}O and δD – and their incorporation into natural archives are the foundation of modern paleoclimatology (*80*). A large number of paleoclimate proxies record water isotopes, including foraminifera, stalagmites, leaf waxes, soil carbonates, and ice cores. Water isotope composition, however, reflects multiple processes including changes in temperature, moisture source, evaporation, precipitation, and convection. Including water isotopes in models generates simulated isotope fields that are consistent with the model's treatment of these processes, eliminating the need to independently conjecture how these various factors may have influenced the proxy data. This creates an "apples to apples" comparison between proxy information and model output that can be used to evaluate model performance and diagnose climatic processes (e.g. (*81*). For example, using the water-isotope-enabled CESM1.2 (iCESM) (*82*), it is possible to directly compare carbonate δ^{18}O data from Eocene fossil bivalves to model-simulated δ^{18}O (*43, 44, 83*) (Fig. 3a). The model predicts a roughly 3‰ annual range in carbonate δ^{18}O, in good agreement with observed proxy data (Fig. 3a). The match with the δ^{18}O data builds confidence that the model can correctly simulate climatology in this location, and allows us to deconvolve the contribution of SST and δ^{18}O of seawater. The site-specific seasonality in SST is 8–10°C, while δ^{18}O-seawater has a seasonal range of 0.6–0.8‰. This indicates that temperature is primarily responsible for the large seasonal range in carbonate δ^{18}O during this greenhouse climate state.

One aspect of paleoclimate information that has traditionally limited its use in model evaluation is an inability to precisely quantify uncertainties surrounding the proxies. However, in the last decade, increasingly detailed proxy system models (*84*) have been developed to address this issue (e.g.,) (*85–87*). Many of these use Bayesian inference to quantify uncertainties in the sensitivity of proxies to environmental parameters, which can then be used for probabilistic assessments of past climate states, model-proxy agreement, and model evaluation (*88*). These have helped to transform proxy-model comparisons from qualitative statements ("they look similar") to quantitative statements ("there is a 90% probability that the data and the model agree").

A final component of the "language barrier" is the fact that proxy data are sparse in both space and time, because they are fundamentally dependent on the presence and preservation of their archives. Yet proxy data are real-world estimates of the "true" climate state. In contrast, climate model information is spatially and temporally continuous and physically self-consistent – but is only a best "guess" at what did or what will happen. One solution to bridge these fundamentally different pieces of information is to formally combine them in a statistical framework and thus leverage their respective strengths. Reduced space methods – commonly used to produce historical reconstructions of climate – can be used to infill missing data and produce maps of paleoclimate states (*88, 89*). Recently, weather-based data assimilation techniques have been adapted for paleoclimate applications (*90*). The resulting products are spatially-complete reconstructions of multiple climate variables that represent a balance between the proxy information and the physics and covariance structure of the climate model. This allows local paleoclimate proxy information to be used to infer global metrics of climate – such as global mean air temperature (*91*). It also allows for the recovery of climatic variables that are consistent with the proxy information but for which we have no direct proxies, such as cloud cover, wind patterns, or precipitation (Fig. 5).

In sum, the disintegration of the model-proxy language barrier has narrowed uncertainties in proxy interpretation. Recent studies have been able to use proxy data to infer key climatic processes and evaluate models across multiple time periods, including the LGM (*91*), the Pliocene (*88*), and the Eocene (*19, 22*). This opens the door for explicit use of paleoclimates to assess and improve model physics.

8 Moving Forward

Past climates will continue to provide insights into the range, rate, and dynamics of climate change. Over the last decade, we have witnessed breakthroughs in proxy development and refinement as well as the generation of many new high-resolution marine and terrestrial paleoclimate records. In addition to continued advances, the collection of additional temperature and CO_2 proxy records at higher resolution will be paramount for developing better estimates of climate sensitivity. Future proxy collection efforts should also focus on hydroclimate proxies, given the large spread in model projections (*40*). These reconstructions will help us refine our understanding of the response of atmospheric circulation and rainfall to climate change.

On the modeling side, the inclusion of chemical tracers, such as water and carbon isotopes, within many of the newly developed CMIP6 (*92*) models offers more robust means of data-model comparison. With these new model tools, we anticipate the rapid development and improvement of data-model synthesis products (*90, 91*) and more focused proxy collection efforts to help reduce model uncertainties. In addition, evaluating CMIP6 models using both the historical and paleoclimate record will result in a more comprehensive and robust approach to understanding the climate system (*93*). We recommend widespread adoption of this practice, so that model ECS and other emergent properties are constrained by paleoclimate data as well as observations. We suggest that weighting or ranking models that perform well over multiple past climate states is a crucial way to constrain the response of the model to changing background conditions and the validity of simulated climate changes under various emissions scenarios. In general, climate models should be able to accurately simulate multiple extreme paleoclimate states – warm and cold – before being trusted for future climate projection.

Despite promising CMIP6 model advances, maintaining a variety of models with different levels of complexity is important. Not all climate questions require high levels of model complexity, and sometimes complexity is so great that interpretation becomes limited (*94*). In paleoclimatology, complexity can also lead to prohibitive computational expense. Maintained support for lower resolution and variable resolution configurations is vital for better interpreting model results and performing long, transient simulations that can address fundamental questions in paleoclimatology such as glacial cycles and carbon cycle changes.

Looking ahead, there are many outstanding process-based uncertainties associated with future climate change that paleoclimatology can help constrain. For example, paleobotanical records can inform plant physiological responses to changes in CO_2 (*95*), which remain highly uncertain (*96*) but important for quantifying evapotranspirative and surface runoff fluxes. Similarly, past vegetation reconstructions can assess dynamic vegetation models and simulated changes in the hydrologic cycle through time (*97*). Moreover, additional quantitative reconstructions of hydroclimate, in combination with better constraints on plant physiological functioning in the past, will help refine our understanding of the regional water cycle and its dependence on local energy fluxes and large-scale circulation.

New geochemical techniques will also refine our understanding of the Earth system. Development of radiation (*98*), biogenic aerosol (*99*), and dust (*100*) records have the potential to help constrain past aerosol and cloud radiative effects, which are arguably the most uncertain component of Earth system models (*101*). In addition, new geochemical tracers for methane cycling (*102*) and upwelling, which is important for N_2O production (*103*), will provide unique insights into trace greenhouse gases during past climate states. The combination of these new techniques will allow the paleoclimate community to better quantify biogeochemical feedbacks and climate sensitivity to greenhouse gas forcings across a range of climate states, and ultimately improve climate forecasts for the coming decades to millennia.

In summary, the paleoclimate record is the basis for how we understand the potential range and rate of climate change. Past climates represent the only target for climate model predictions at CO_2 concentrations outside of the narrow historical range and, for this reason, are vital tools for evaluating the newest generation of Earth system models. The study of past climates continues to reveal key insights to the Earth's response to elevated concentrations of greenhouse gases. Innovations in Earth system models, geochemical techniques, and statistical methods further allow for a more direct connection from the past to the future – worlds for which the preindustrial and industrial climate states provide limited guidance. The future of paleoclimatology is to incorporate past climate information formally in model evaluation, so that we can better predict and plan for the impacts of anthropogenic climate change.

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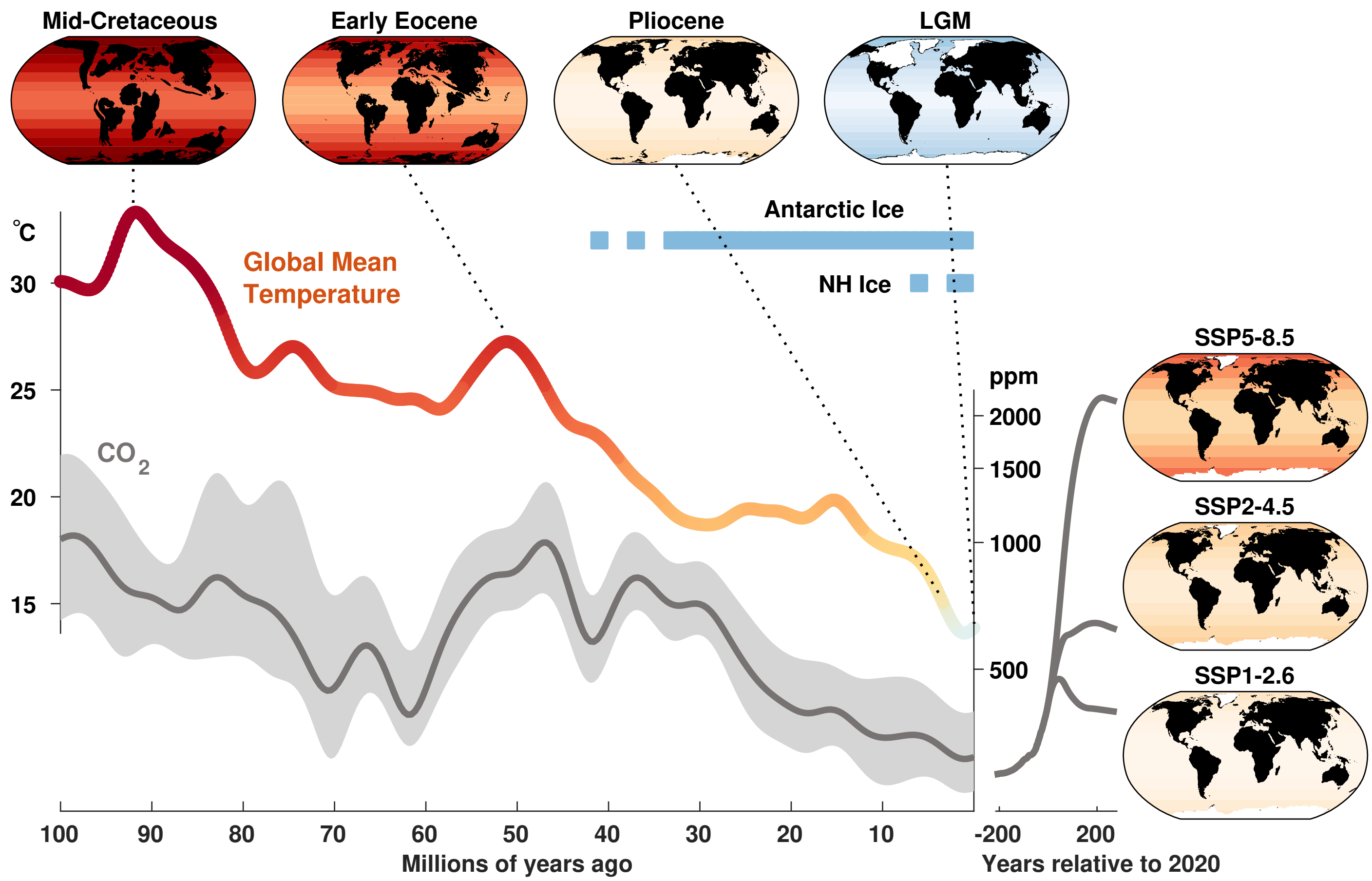

Figure 1: **Paleoclimate context for future climate scenarios.** Global mean surface temperature for the past 100 million years is estimated from benthic δ^{18}O (*2, 106*) using the method of (*104*). CO_2 is estimated from the multi-proxy data set compiled by (*105*) with additional phytane data from (*107*) and boron data from (*108*) and (*11*). Data with unrealistic values (<150 ppm) are excluded. The CO_2 error envelopes represent 1σ uncertainties. Note logarithmic scale for CO_2. Gaussian smoothing was applied to both the temperature and CO_2 curves in order to emphasize long-term trends. Temperature colors are scaled relative to preindustrial conditions. The maps show simplified representations of surface temperature. Projected CO_2 concentrations are from the extended SSP scenarios (*109*). Blue bars indicate when there are well-developed ice sheets (solid lines) and intermittent ice sheets (dashed lines), according to previous syntheses (*2*).

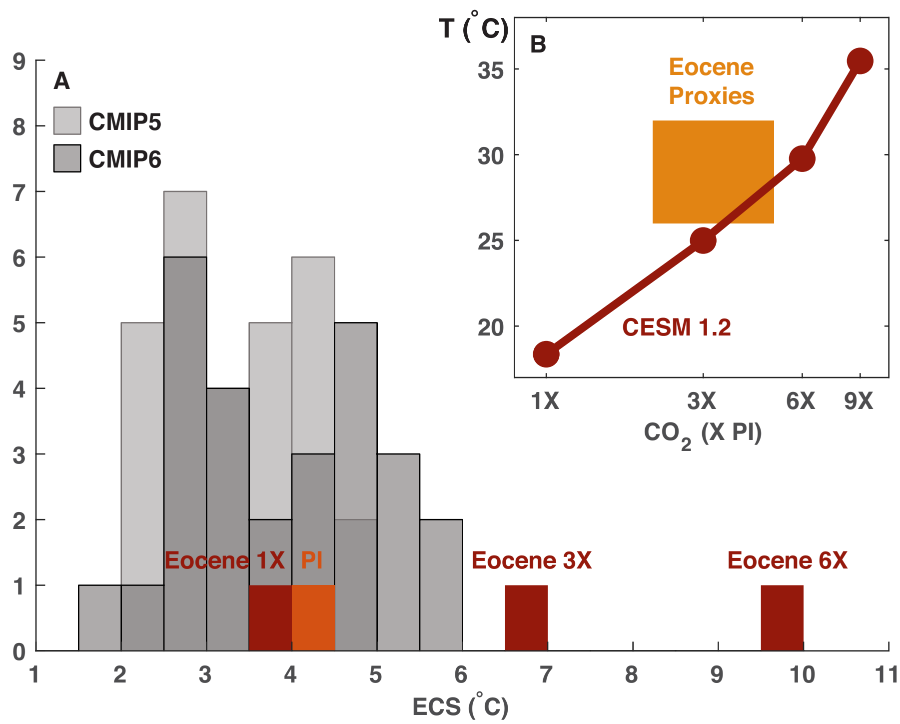

Figure 2: **Constraining equilibrium climate sensitivity (ECS) through simulation of the early Eocene.** a. ECS in CMIP5 and CMIP6 models (grey bars; (*15*)) compared to ECS in the CESM1.2 preindustrial (PI, orange bar) and Eocene simulations with 1X, 3X and 6X preindustrial CO_2 levels (red bars). b. CO_2 concentrations (times preindustrial level) vs. global mean temperature according to early Eocene proxies (yellow patch) compared to the results from the CESM1.2 Eocene simulations. Proxy CO_2 estimates are a 2σ range derived from the collection plotted in Figure 1. Readers are referred to (*19*) for details of the Eocene climate simulations and proxy global mean temperature estimation.

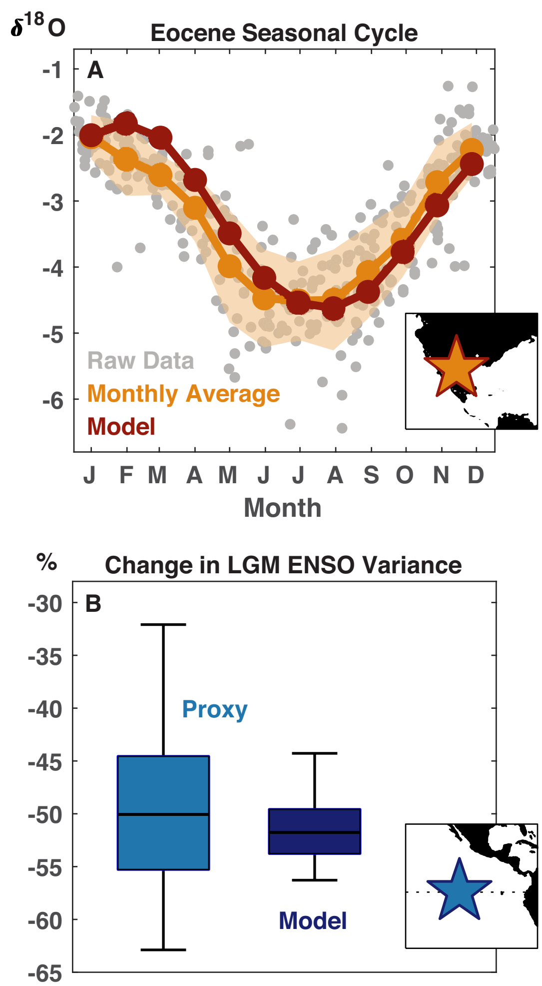

Figure 3: **Examples of seasonal and interannual paleoclimate data and comparison to models.** (a) Seasonally-resolved δ^{18}O carbonate from the shells of a fossil bivalve, *Venericardia hatcheplata*, from the early Eocene Hatchetigbee Formation (orange star in inset) (*43, 44*). Monthly averaged data (orange, with 1σ uncertainty bounds) are compared with predicted δ^{18}O-carbonate seasonality at the same grid-point from an isotope-enabled Eocene model simulation (*19*) (red) (using modeled δ^{18}O of seawater and SST, and the calibration of ref. (*110*)). (b) Mg/Ca measurements of individual planktic foraminifera *Trilobatus sacculifer* from an eastern equatorial site (blue star in inset) provide proxy evidence of a reduction in ENSO variability during the Last Glacial Maximum (LGM) relative to pre-industrial conditions (*46*) (lighter blue). The magnitude of reduction agrees with simulations using CESM1.2 (darker blue) (*111*).

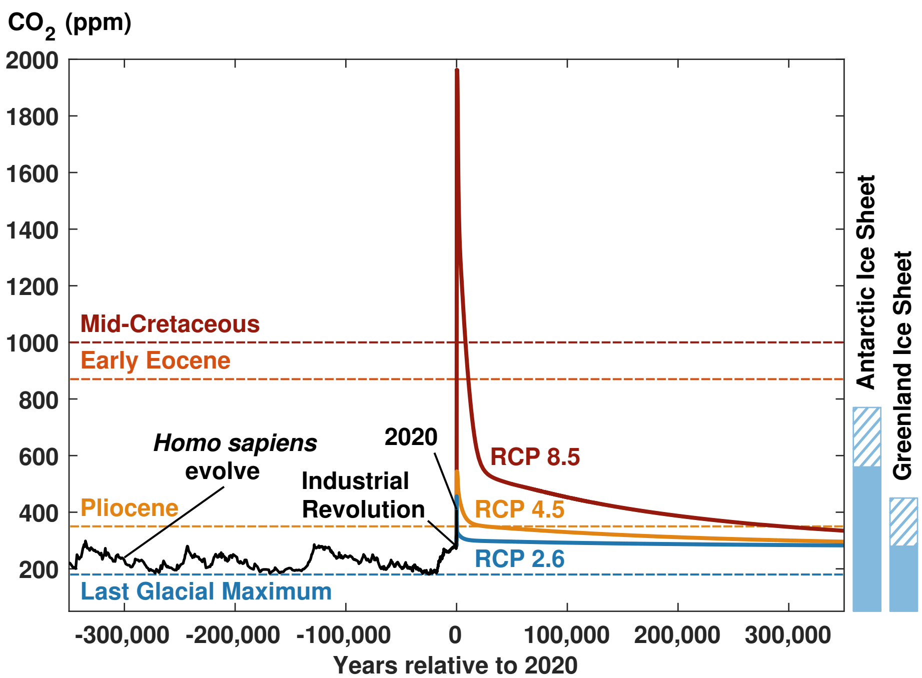

Figure 4: **The anthropogenic climate aberration.** Black line shows CO_2 measured in ice cores for the past 350,000 years (*9*). Solid colored lines show future CO_2 concentrations for the IPCC AR5 Representative Concentration Pathways, run out to 350,000 years in the future with the cGENIE model. Dotted lines indicate average CO_2 for key time periods in the geologic past. Bars at right indicate CO_2 concentrations under which there are well-developed ice sheets (solid areas) and intermittent ice sheets (hatched areas), based on geologic evidence and ice sheet modeling (*112*).

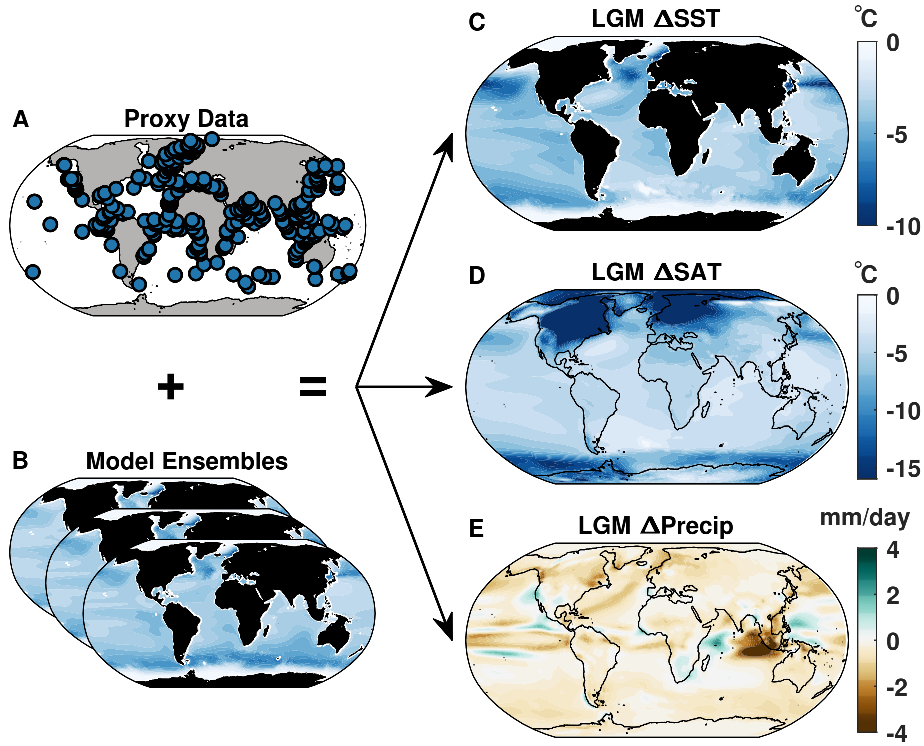

Figure 5: **An example of paleoclimate data assimilation.** Marine sea-surface temperature (SST) proxy data from the Last Glacial Maximum (LGM) and the Late Holocene (a) are combined with an ensemble of model simulations (b) which contain multiple climatic variables. The results (c-e; LGM - Late Holocene differences for sea-surface temperature (ΔSST), surface air temperature (ΔSAT), and mean annual precipitation (ΔPrecip)) include all the variables in the model prior, which are influenced by the assimilated SST proxy data. Proxy data, model fields, and assimilated results are from ref. (*91*).