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ORIGINAL ARTICLE

What can Palaeoclimate Modelling do for you?

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Abstract

In modern environmental and climate science it is necessary to assimilate observational datasets collected over decades with outputs from numerical models, to enable a full understanding of natural systems and their sensitivities. During the twentieth and twenty-first centuries, numerical modelling became central to many areas of science from the Bohr model of the atom to the Lorenz model of the atmosphere. In modern science, a great deal of time and effort is devoted to developing, evaluating, comparing and modifying numerical models that help us synthesise our understanding of complex natural systems. Here we provide an assessment of the contribution of past (palaeo) climate modelling to multidisciplinary science and to society by answering the following question: What can palaeoclimate modelling do for you? We provide an assessment of how palaeoclimate modelling can develop in the future to further enhance multidisciplinary research that aims to understand Earth's evolution, and what this may tell us about the resilience of natural and social systems as we enter the Anthropocene.

Keywords Climate · Model · Palaeoclimate · Global change · Environmental change · Earth history

1 Introduction

Complex climate models, and latterly Earth System Models (ESMs), are in the vanguard of attempts to assess the effects, risks and potential impacts associated with the anthropogenic emission of greenhouse gases (GHG: IPCC 2013). Climate predictions underpin scientific assessments of mitigation and societal adaptation pathways (IPCC 2013).

The use of models to understand the evolution of our planet's climate, environment and life (Fig. 1), collectively known as past (palaeo) climate modelling, has matured in its capacity and capability since the first simulations using a General Circulation Model (GCM) were published in the 1970s for the Last Glacial Maximum (e.g., Gates 1976). Since then it has become apparent that to fully appreciate the complex interactions between climate and the environment, and to use this knowledge to address societal challenges, it is necessary to adopt multidisciplinary scientific approaches capable of robustly testing long-standing hypotheses that describe the sensitivity/resilience of our planet and the life forms that inhabit it. Multidisciplinary studies have provided unique ways of evaluating the efficacy of climate and ESM predictions in reproducing large-scale climate changes that occurred in the past (Haywood et al. 2013), and this has

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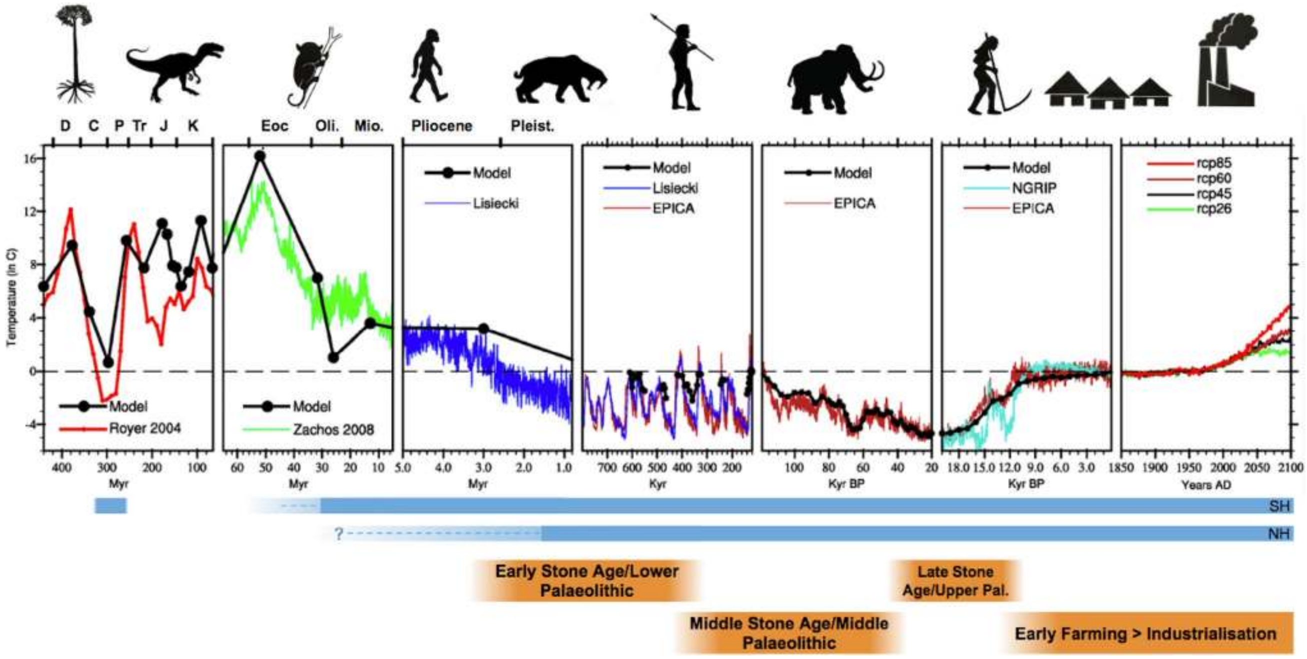

Fig. 1 Global annual mean temperature variation of the Earth through time (last 400 million years) predicted by the Hadley Centre Coupled Climate Model version 3 (HadCM3), compared with geologically derived estimates of temperature variability over the same period [the Royer et al. 2004 temperature record, the Zachos et al. 2008; Lisiecki and Raymo 2005 benthic oxygen isotope stack, as well as the EPICA and NGRIP ice core records; Jouzel et al. 2007 and NGRIP Members 2004. Geological epochs include the Devonian (D), Carboniferous (C) Permian (P), Triassic (Tr), Jurassic (J) Cretaceous (K), Eocene (Eoc), Oligocene (Oli.), Miocene (Mio), Pliocene and Pleistocene (Pleist.)] Future predictions of temperature change are based on HadCM3 simulations using different Representative Concentration Pathways (RCPs). Horizontal blue lines represent geological evidence for ice sheets in the northern (NH) and southern (SH) hemispheres. Major evolutionary characteristics and events over the last 400 million years represented by cartoon silhouettes

provided valuable out-of-sample tests for the tools used to predict future climate and environmental change.

The march towards multidisciplinary assessment of past climate and environmental states has accelerated through the construction of models that have more complete representations of the Earth system at higher spatial resolution. From relatively simple three-dimensional representations of the atmosphere, models have developed to include representations of the oceans and land cover, and incorporate the interactions between atmosphere, oceans, and the land and ice sheets. They have developed to enable dynamic simulation of the distribution of past vegetation cover, ice sheet distribution and variability, and ocean/terrestrial biogeochemical cycles (Prinn 2013). Each development has brought with it opportunities to form new research collaborations with observational-based scientists to test hypotheses for Earth evolution in novel and exciting ways, and to relate this knowledge towards addressing societal challenges.

Whilst some of the contributions made by palaeoclimate modelling to wider research efforts are obvious, the utility of, and access to, model simulations has grown to such a degree that many of the connections between palaeoclimate modelling and other disciplines are not appreciated. Unsurprisingly, the way in which palaeoclimate modelling addresses societal needs, as generally expressed through UN SDGs and scientific grand challenges, is not fully appreciated either. Here we address this issue through the exploration of palaeoclimate modelling' s (using complex numerical models) contribution to the better understanding of climate sensitivity, data-model comparison and geological proxy interpretation, life and its resiliency, glacial and sea-level history, hydrology, anthropology and natural resource exploration as well as energy-based research. We also discuss potential avenues for the future that have the capability to enhance the contribution of palaeoclimate modelling to other disciplines and to better address societal needs.

2 The Climate Sensitivity Grand Challenge

Studies of climate sensitivity quantify changes in global mean temperature in response to variations in atmospheric CO_2 concentration. The concept of equilibrium climate states has been crucial in this respect. Equilibrium Climate Sensitivity (ECS) is the temperature difference in response to a doubling of CO_2, where the climate is assumed to be in equilibrium before and after the CO_2 perturbation (e.g., Von der Heydt et al. 2016). An important aim of quantifying

ECS has always been to predict future climate change, where ECS plays a role in quantifying the expected warming in the year 2100. Moreover, in view of recent plans to limit future global warming to between 1.5 and 2 °C (Paris Agreement), establishing ECS is crucial to determining how to cap greenhouse gas emissions to limit warming to within this range and contribute to objectives described under the climate action SDG.

In addition to the direct radiative effect caused by a change in CO_2 concentration, surface temperature responds to feedbacks operating in the climate system. These feedbacks can act on different timescales and amplify (or dampen) the initial temperature change as a result of CO_2 forcing. Certain fast(er) feedback processes, such as surface albedo-temperature feedbacks, tend to lead to an amplified climate response to CO_2-induced radiative forcing. ECS estimates have mostly been derived using climate models that represent fast(er) feedbacks, where fast means fast enough to approach an equilibrium climate state within a century. Together with observations of the instrumental period, ECS incorporating fast(er) feedbacks is estimated to range between 1.5 and 4.5 °C (Solomon 2007). This range has changed little since the first estimates of ECS (Charney et al. 1979).

However, since 1979 our scientific understanding of the stability of ECS, and how slow(er) feedbacks may alter it, has grown substantially. This is in no small part due to palaeoclimate modelling. The concept of longer term climate sensitivity, or Earth system sensitivity, emerged from studying the way climate varied in response to variations in atmospheric CO_2 concentration (Hansen et al. 2008). One of the most salient observations made by palaeoclimatology is that the magnitude of reconstructed climate change in the past can be hard to reconcile with the absolute CO_2 forcing at a given time, and from fast(er) climate feedbacks alone. This draws attention to an important limitation of a scientific focus that is restricted to modern and recent climate states, as it is incapable of providing the kind of broader perspective needed to determine how climate responds to CO_2 forcing in the longer term (multi-centennial to millennial timescales). It has been possible to reconcile the magnitude of past climate change to direct CO_2 forcing, in part by considering the contribution to temperature change that can be derived from slower responding components of the Earth system, such as the response of ice sheets and vegetation cover (Hansen et al. 2008; Lunt et al. 2010a; Rohling et al. 2012; Haywood et al. 2013). In addition, palaeoclimate modelling has highlighted that ECS itself may not be a constant. The nature of the climate system, which can affect feedback processes, may influence how the surface temperature responds to CO_2-based forcing. However, the degree to which ECS variations according to base state are influenced by the specific model chosen remains unknown. As such, palaeoclimate modelling has made an important contribution towards understanding the complexity of deriving ECS. More broadly, it is helping us to understand how the sensitivity of global temperature to CO_2 variation may have changed in the past in response to the first order controls of palaeogeography (see Fig. 2).

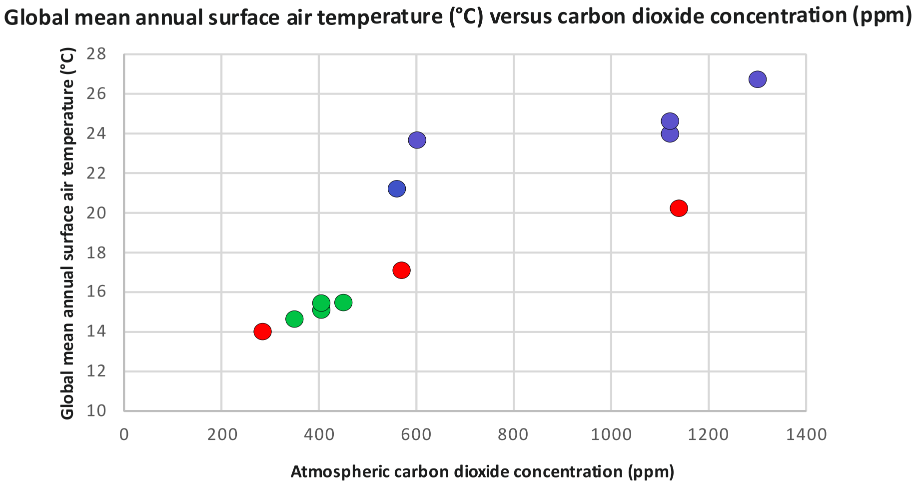

Fig. 2 Global mean annual surface air temperature as a function of atmospheric CO_2 simulated by the Community Climate Model Version 4 (CCSM4) at the National Center for Atmospheric Research. Red dots show the simulated global temperature response to rising CO_2 concentration based when using modern geography, ice sheets and vegetation in the model. Green dots show the simulated global temperature response to rising CO_2 concentration when using modern geography, Pliocene ice sheets and vegetation in the model. Blue dots show the simulated global temperature response to rising CO_2 concentration when using Eocene or Cretaceous geography, no ice sheets and prescribed palaeo vegetation (Bitz et al. 2012; Brady et al. 2013; Baatsen et al. 2018; Tabor et al. 2016; Feng et al. 2017)

3 Model/Data Comparison: Veracities, Uncertainties and Synergies

Proxy data-based environmental reconstructions play a central role in evaluating the ability of climate models to simulate past, present and future climate change. Over the last few decades, several paleoclimate modelling intercomparison projects have provided compilations of terrestrial and marine biological and geochemical data to facilitate global data-model comparisons for different time intervals in Earth history (e.g., Kageyama et al. 2018). For qualitative and quantitative comparison, climate models are either used in "forward mode" (i.e., models are capable of simulating proxy systems, such as biomes or isotopes) or "inverse mode" where proxy data measurements are translated into the same climatological values produced by climate models (temperature/precipitation, etc.). One of the greatest strengths of palaeoclimate simulations is their ability to provide process-based explanations for past environmental change. Testing the importance of feedback mechanisms through palaeoclimate modelling was a major step towards identifying and understanding non-linear responses of the environment to climate change. A prominent example includes the analysis of vegetation, ocean and soil feedbacks simulated in palaeoclimate models to understand the strong response of the African monsoon and associated rapid "greening" of the Sahara during the Holocene African Humid Period (AHP). The AHP is recorded in multiple archaeological and geological records, but cannot be explained by orbital forcing alone (Claussen et al. 1999; Tjallingii et al. 2008; Tierney et al. 2017).

The majority of data-model comparison studies have focused on the most recent geological past (such as the AHP), and their outcomes and benefits for the understanding of Holocene and Pleistocene environments have been discussed elsewhere (Braconnot et al. 2012; Harrison et al. 2016). However, palaeoclimate modelling has also improved our understanding of warm climates in the deeper geological past, which were primarily controlled by elevated greenhouse gas concentrations, providing an additional framework for understanding future climate change. Whilst pre-Quaternary warm climates hold the key to understanding how environments respond to CO_2-induced warming in the long term, the uncertainties in defining geological boundary conditions and reconstructing past environments increase with geological age. Furthermore, disagreements between climate model simulations and available geological data in the polar regions remain, with models underestimating the degree of warming (e.g., Masson-Delmotte et al. 2006; Haywood et al. 2013; Huber and Caballero 2011; Dowsett 2013).

The analysis of congruence between proxy data and model simulations is of mutual benefit in that it has the potential to improve the assessment of model performance, and the robustness of proxy data-based environmental reconstructions. Data assimilation, which incorporates observations into numerical modelling, have been shown to be a promising new technique in pre-Quaternary global biome mapping projects to regionally improve model simulations and to increase the spatial and temporal resolution of data-based vegetation reconstructions (Salzmann et al. 2008; Pound et al. 2012). In addition, the resolution of the so-called "cool tropics paradox" is a prominent example where palaeoclimate model outputs challenged sea surface temperature (SST) estimates (e.g., D'Hondt and Arthur 1996). Early estimates of tropical SSTs for the Cretaceous were far cooler than climate model simulations. However, newer exceptionally well-preserved Palaeogene microfossils (Sexton et al. 2006) led to a revision to higher estimated SSTs bringing greater agreement between the data and model estimates of tropical SSTs (Pearson et al. 2001). Furthermore, a long-standing discrepancy between model simulations of atmospheric CO_2 (pCO_2), ice sheet extent and the geological record of ice sheet and sea-level variability during the icehouse of the Palaeozoic (330 Ma) prompted the generation of new high-resolution proxy records of pCO_2 that reconcile the geological archives and model outputs (Montanez et al. 2016).

The spatial and temporal resolution, and accuracy of deep time, pre-Quaternary reconstructions, have significantly improved as science has progressed. The outputs from various new international pre-Quaternary model intercomparison initiatives, for example, PlioMIP (Haywood et al. 2016) and DeepMIP (Lunt et al. 2017) and proxy data syntheses, for example, PlioVar PAGES (McClymont et al. 2015) and PRISM3 (Dowsett et al. 2016) now enable reconstructions of terrestrial and marine environmental change over multiple time intervals during the last 65 million years at a global scale (see Fig. 3). Coincidentally, an increasing number of exceptionally dated, high-resolution deep-time geological records spanning several millions of years are becoming available (Brigham-Grette et al. 2013; Herbert et al. 2015; Panitz et al. 2018). These allow, for the first time, combined model-data approaches to analyse the role and importance of climate extremes, astronomical cycles, nonlinear responses and feedback mechanisms, and non-modern analogue environments.

4 Palaeoclimate Modelling and Understanding Life on Earth: Past, Present and Future

There is increasing concern over how Earth's biota will respond to the rapid climatic changes already underway (Urban 2015; Thomas et al. 2004; Barnosky et al. 2011).

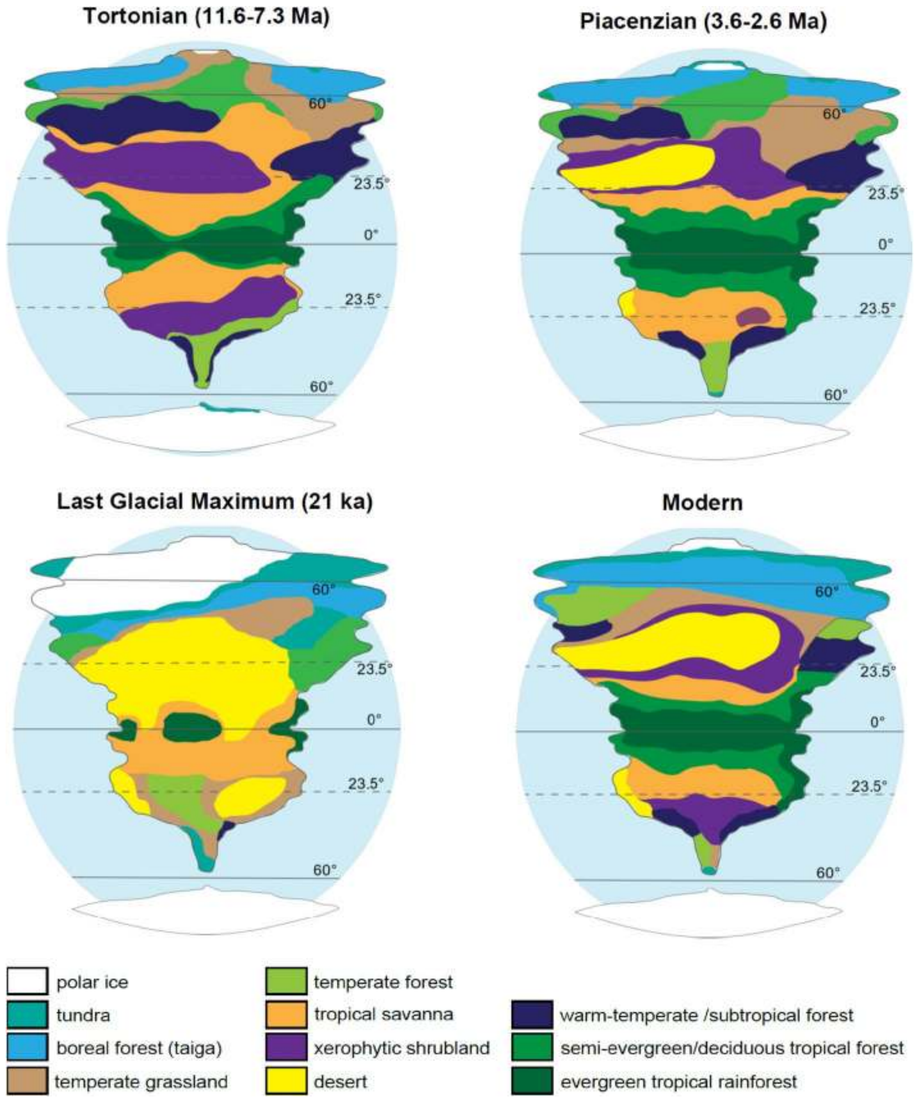

Fig. 3 Distribution of biomes as displayed on a hypothetical "supercontinent" (after Troll 1948) for present-day (after Klink 2008) and the geological past. The distribution was created through combination of vegetation simulation informed by palaeoclimate simulations as well as palaeobotanical data to create a spatial reconstruction of global vegetation for the Miocene (Tortonian; Pound et al. 2011), the Pliocene (Piacenzian; Salzmann et al. 2008) and the Last Glacial Maximum; Kageyama et al. 2012; Tarasov et al. 2000)

These concerns are highlighted in the UN Sustainability Goals of preserving and protecting biodiversity for the maintenance of ecosystem goods and services, both on land and in the water. However, preservation and maintenance of biodiversity rely on accurate understanding and predictions of climate-life dynamics on both short and long time scales (Finnegan et al. 2015; McKinney 1997; Dawson et al. 2011). Species' interactions with climate on longer time scales provide necessary insights into biotic responses to differing rates of environmental change, non-analogue climate scenarios, and extreme warmth (Barnosky et al. 2011; Finnegan et al. 2015; Williams and Jackson 2007), all of which have relevance to changes that are occurring today (Williams et al. 2007).

Predictive models of biotic responses to climate change can be sourced from the integration of fossils and palaeoclimate data. Palaeoclimate models are essential to disentangle biotic responses to climate change, because they provide a spatially explicit framework in which to test hypotheses. In a perfect world, science would have access to palaeo-proxy data that provide accurate estimates of past environmental conditions for every point on Earth throughout Earth history. In reality, palaeo-proxy data are spatially discontinuous, and while it can provide robust palaeoenvironmental constraints on local scales, it is often temporally limited. To generate longer term environmental records, data are compiled such that they represent globally averaged signals (e.g., Zachos et al. 2008), and thus it can be challenging to disentangle the causal processes responsible for regional biological patterns from such global compilations.

Palaeoclimate models fill proxy data-deficient gaps, providing higher resolution spatial and temporal constraints on the biotic responses to climate. When coupled with ecological niche modelling (ENM: Myers et al. 2015; Peterson et al. 2011; Svenning et al. 2011), palaeoclimate models also provide critical insight on both the rate at which species are able to respond to changing conditions, and on those species most vulnerable to them. The record of responses to differing rates of environmental change in the past is capable of elucidating whether a given species can survive the rapid and unprecedented rate of present-day climate change via either adaptation and/or environmental range shifts (Dawson et al. 2011; Harrison and Prentice 2003; Davis and Shaw 2001; Parmesan and Yohe 2003; Chen et al. 2011; Saupe et al. 2014; Lawing and Polly 2011). Palaeoclimate models can also be used to estimate a species' traits, such as their abiotic niches, to examine whether these traits result in differential extinction risk (Saupe et al. 2015) and to question the role of climate in influencing evolutionary, ecological and biogeochemical processes at varying spatial and temporal scales (e.g., Svenning et al. 2015). Such models have been used to study the co-evolution of Earth and life, with focus on how climate regulates the tempo and mode of speciation, extinction and adaptation. Examples in the latter category include work that aims to quantify rates of within-lineage abiotic niche evolution (Saupe et al. 2014; Jackson and Blois 2015; Stigall 2014; Veloz et al. 2012), also of relevance to the UN goal of conserving biodiversity.

Palaeoclimate models have the ability to contribute to debates regarding the role of climate in regulating past biotic events, particularly major extinctions. For example, the late Pleistocene and early Holocene witnessed the extinction of more than 97 genera of megafauna (animals > 44 kg; Barnosky et al. 2004), but the kill mechanism(s) for this event are debated. Over hunting by humans and climate change have been proposed as the two primary mechanisms (Svenning et al. 2011), and the latter hypothesis has been tested by climate models, helping to produce estimates of the degree to which suitable habitats for various taxa changed as climate warmed. Results are variable, with some studies finding available habitat increased for taxa (Martinez-Meyer et al. 2004; Varela et al. 2010) and others finding that it decreased (Nogués-Bravo et al. 2008), potentially reflecting where each taxa was distributed latitudinally (Svenning et al. 2011).

Ecological patterns and processes may also be influenced by climate, and palaeoclimate models can test the extent to which climate controls patterns of distribution, dispersal, community composition and assembly (Lawing and Polly 2011; Gavin et al. 2014). Moritz et al. (2009), for example, used palaeoclimate models to examine the origins of a suture zone—shared regions of secondary contact between long-isolated lineages—in the Australian Wet Tropics rainforest. The authors found that the zones of contact were clustered in a corridor between two major Quaternary refugia, suggesting it was unsuitable for the species during the mid-Holocene, and that the current suture zone was established only within the last few 1000 years.

Understanding how climate regulates the biological controls of major element cycling, in particular carbon, is of critical importance for accurate estimations of the effects of elevated atmospheric CO_2 on global temperatures, natural carbon sources and sinks, future ocean chemistry and ecosystem responses (e.g., Cox et al. 2000; Le Quéré et al. 2009; Sarmiento et al. 2004). The palaeontological perspective allows us to ground truth our understanding of these systems. At the broadest scale Earth System Models of Intermediate Complexity (EMICs), or even simpler models, have been used to investigate the impact major biological innovations such as evolution of photosynthesis ~ 2.5 billion years ago on ocean chemistry (Lenton and Daines 2017), and the colonisation of the land by plants and its effect on weathering and atmospheric CO_2 (Berner 1998). The integration of biogeochemical processes into palaeoclimate models also allows us to reconstruct the influence of changing climate and biogeochemistry on shorter timescales and gain a greater understanding of thresholds, sensitivity and tipping points. More temporally constrained work allows us to investigate the impact of glacial–interglacial climates on ocean chemistry and carbon cycling on timescales relevant to humans (Buchanan et al. 2016; Adloff et al. 2018).

The geological record provides a direct source of information about biological processes against a backdrop of varying climate, allowing us to investigate system/species baselines, resiliencies and failure points in different climate states. To use this rich resource from a modelling perspective, we require higher spatial resolution transient climate simulations that will provide greater spatial and temporal constraints on speciation, extinction dynamics, niche evolution through time, and dispersal corridors and refugia in the face of rapidly changing environments. This will facilitate fundamental knowledge capable of informing strategies for the management of future biodiversity. Where transient simulations with high spatial resolution are computationally prohibitive, running snapshots over geologically and evolutionarily meaningful timescales, particularly around periods with major climate transitions and aberrations, provide highly valuable initial benchmarks.

5 Melting Ice Sheets and Sea-Level Change

A major scientific and societal challenge is understanding the response of ice sheets to warming, and the resulting rates, magnitudes and impacts of regional sea-level change in the next 100 years and beyond (Church et al. 2013). By reconstructing past ice sheet variability, changes over centennial to millennial (and longer timescales) can be understood. This is central to understanding societal impacts and risks associated with future climate change.

The palaeo record helps constrain the drivers of ice-sheet change, and therefore, associated sea-level change, during differing climate states. Over the last 65 million years, major climate transitions associated with growth and decay of ice sheets were superimposed upon a gradual trend of atmospheric cooling (Zachos et al. 2008). Due to the sparse nature of geological evidence for ice sheet extent and sea-level history, ice sheet and palaeoclimate models have fundamentally changed our understanding of ice-sheet growth in both hemispheres, disentangling the role of CO_2 versus the role of tectonics in driving ice sheet expansion over major climate transitions. For example, DeConto and Pollard (2003) found that Antarctic Ice Sheet growth at the Eocene Oligocene Transition (~ 34 Ma) was driven by decreasing atmospheric CO_2, countering the prevailing view that the opening of the Drake Passage and subsequent thermal isolation of the continent was responsible (Kennett 1977). Tectonics and mountain building have also been implicated in the gradual onset of northern hemisphere glaciation between 3.6 and 2.4 Ma (e.g., Mudelsee and Raymo 2005). Lunt et al. (2008) established that decreasing atmospheric CO_2, rather than tectonics, was the dominant control on Greenland ice sheet growth. Models also highlight that the scale of growth is sensitive to whether the ice sheet was growing from an entirely ice-free state or not (Contoux et al. 2015).

Whilst palaeoclimate modelling has been informative in understanding the growth of ice sheets, of more pressing concern is the scale and rate of future ice sheet mass loss in a higher CO_2 world. Instrumental records (e.g., satellite data) of glacier extent only systematically capture the last 4 decades of change and, therefore, limit our capability to understand large-scale, long-term changes in ice volume. Global mean sea level (GMSL) rise from 1901 to 2010 has been 1.7 mm/year (Church et al. 2013). However, during the last deglaciation (ca. 21–7 ka) magnitudes and rates of GMSL rise were significantly larger. Combined palaeoclimate and ice sheet modelling has identified an acceleration in ice mass loss at 14.5 ka, triggered by abrupt warming, driving separation of the North American Ice Sheet into regional ice domes (a process termed saddle collapse) and contributing 5–6 m to GMSL at a rate of ~ 14.7 to 17.6 mm/year (Gregoire et al. 2016; Gregoire et al. 2012). This provides a mechanism to explain a significant proportion of the rise in GMSL at 14.5 ka. Given that sea level is projected to rise well beyond 2100 (Clark et al. 2016) assessing the ability of models to reproduce rates of sea-level change on centennial to millennial timescales, and potential mechanisms for rapid collapse, is central to have confidence when applying them to long-term future projections.

Models have helped refine our understanding of potential rates and scales of sea-level rise, which can be attributed to specific processes during previous climatically warm periods. During the last interglacial (LIG) (ca. 129–116 ka), GMSL is thought to have been 6–9 m above present (Dutton et al. 2015) when the climate was 3–5 °C warmer at polar latitude (Capron et al. 2014). Moreover, it is likely that there was a period during the LIG in which GMSL rose at a 1000-year average rate exceeding 3 mm/year (Kopp et al. 2010), but it is important to understand which ice sheet(s) contributed to this rapid rate. Coupled palaeoclimate-ice sheet simulations, consistent with geologic data, indicate a retreat of ice in Greenland during the LIG (Fig. 4) leading to a GMSL rise of ca. 1.4 m. Models also suggest that Antarctica could have also contributed 3–4 m to the LIG highstand (Goelzer et al. 2016), with one study suggesting that with > 2–3 °C of Southern Ocean warming there is the potential for complete collapse of the West Antarctic ice sheet (Sutter et al. 2016), the recurrence of which is a key concern in the context of future climate change.

The LIG, and the even warmer mid-Pliocene Warm Period (mPWP, 3–3.3 Ma), have been used as analogues to understand future Earth system responses to warming at the poles. DeConto and Pollard (2016) calibrated a palaeoclimate and ice sheet-modelling framework against the geological record of sea-level change during these time periods to predict future ice mass loss from Antarctica. To reconcile past records of GMSL with modelled ice mass loss, they invoked a new mechanism that enhances the sensitivity of the ice sheet where it meets the ocean. If this is applied under future climate scenarios, Antarctica has the potential to contribute more than 1 m to GMSL by 2100 and more than 15 m by 2500. A challenge to these future predictions is that we require supporting empirical evidence that these processes operated in the past (Ritz et al. 2015).

Palaeoclimate modelling has been critical in improving understanding of how ice sheets, and thus sea level, respond to increasing greenhouse gases. Progress towards addressing the UN SDGs and the WCRP grand challenges will come from fully coupling palaeoclimate and ice sheet models to perform transient simulations at higher resolutions than previously possible so that feedbacks between these components of the Earth system can be better quantified. Current modelling efforts focus largely on ice-sheet contributions to GMSL, but in the future regional sea level will significantly deviate from the global mean. Incorporation of other controls on sea level such as ocean-density changes, glacio-isostatic adjustment, dynamic topography and erosion and sediment transport (Church et al. 2013) will help reduce uncertainty in long-term (centennial to millennial) projections.

6 Palaeoclimate Models and Hydrology

Much of the climate change debate, particularly when discussing the past, is focussed on changes in temperature. However, the WCRP grand challenges highlight the

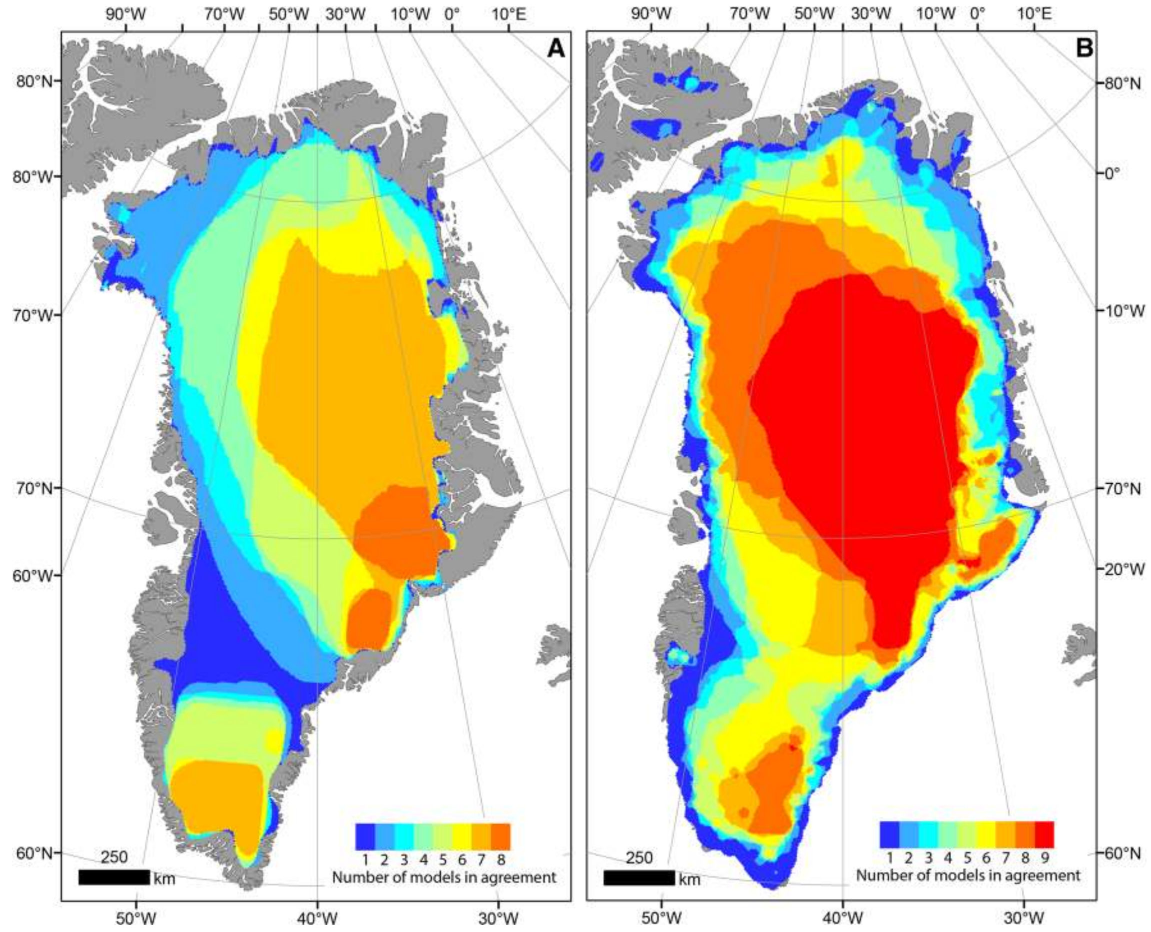

Fig. 4 Simulated Greenland Ice Sheet minimum extent for **a** the mid-Pliocene warm period (mPWP ~ 3 to 3.3 Ma) and **b** the Last Interglacial (LIG ~ 125 Ka) simulated by ice sheet models with multiple climate model forcings for each period. The shading indicates the number of model simulations that predict ice being present at a given location. Nine models simulations are included for the LIG (Otto-Bliesner et al. 2006; Solomon 2007; IPCC 2013; Yau et al. 2016) and eight models are included for the mPWP (Dolan et al. 2015). The combination of climate and ice sheet modelling can lead to new insights regarding ice sheet extent and variability for time periods where direct geological evidence is sparse or entirely missing

importance of water supply for food production as well as the role of extreme hydrological events (floods and droughts). Both of these aspects are also closely linked to the UN Sustainability Goals of ending hunger and improving food security as well as delivering clean water and sanitation.

Until recently, most palaeoclimate modelling has focussed on improving our understanding and ability to model the mean changes in temperature/precipitation. This type of modelling includes long timescale changes, such as the role of Tibetan uplift in enhancing the South Asian monsoon system (e.g., Manabe and Terpstra 1974; Ramstein et al. 1997; Lunt et al. 2010b) or evaluation of simulated monsoon changes resulting from orbital changes in the late Quaternary and their impact on lake levels (e.g., Kutzbach and Street-Perrott 1985). In addition to orbital enhancement of summer monsoons, recent advances in computing power allow palaeoclimate modelling of transient changes, indicating the importance of changes in CO_2 and meltwater during the Quaternary as having affected the evolution of rainfall patterns (Otto-Bliesner et al. 2014). Thus, the late Quaternary provides a challenging test for models for forcings relevant to the present.

Providing a clean water supply can also be facilitated by learning from the past. For instance, there is considerable concern about the recent decreases in the area of Lake Chad (e.g., Lemoalle et al. 2012). However, in the Holocene and Pliocene Lake Chad was much larger (the so-called Mega-Chad). Palaeoclimate modelling (e.g., Sepulchre et al. 2008; Contoux et al. 2013; Haywood et al. 2004) has shown that this is a result of modest shifts in the position of the ITCZ and hence implies that communities must expect and adapt to high variability in Lake Chad on decadal and longer timescales. Considerably more work is needed to expand these studies to other hydrological systems. Similarly, many areas of Africa rely on groundwater sources, and some of these reservoirs still contain water accumulated many thousands of years ago. We have a poor understanding of many of these systems and future work must target improvements in this area.

Palaeoclimate modelling that directly targets the grand challenge areas of hydrological extremes and water supply are at an early stage of development, but should become one of the major priorities for research. Until recently, extreme events were hard to simulate but improvements in the spatial resolution of models are allowing palaeoclimate models to tackle such issues (see outlook section). Initial work (e.g., Haywood et al. 2004) used regional models to show that the hydrological cycle associated with extreme warm periods operated very differently, and this affected the interpretation of the sedimentary structures found for such periods. More recent work is increasingly focussing directly on the science of palaeo-tempestology and extreme events. For instance, Peng et al. (2014) modelled severe and persistent droughts in China during the last millennium and suggested that these droughts (and the East Asian monsoon system) could have been modulated by variations in solar output.

7 Palaeoclimate Modelling and Human Systems

Palaeoanthropologists and archaeologists have a long history of collaboration with climate modellers. From a modelling perspective, palaeoclimate proxies (e.g., pollen data, microfauna, malacofauna) obtained from dated archaeological deposits allow climatologists to test model performance in non-analogue situations (Braconnot et al. 2012). From an archaeological perspective, palaeoenvironmental reconstruction and palaeoclimate modelling provide essential context for understanding past human adaptations. Palaeoanthropology, firmly rooted in evolutionary ecology, has long recognised that climate change has an impact on hominin evolution (Vrba 1995) and palaeoclimate models feature prominently in palaeoanthropological debates. Palaeoclimate models are also increasingly integrated into archaeological models that seek to understand the pattern of hominin dispersals out of Africa, for example, or to explore how past climate conditions affected the spatial distribution and structure of human populations, altering the course of cultural evolution. The pioneering ‘Stage 3 Project’ (Van Andel and Davies 2003) is an example of the interdisciplinary nature of archaeological research, demonstrating the integration of palaeoclimate models and archaeological data to design research that sheds light on the dynamics of human populations in the past.

Early human evolution is currently framed as a series of adaptive responses to environmental changes linked to orbital forcing mechanisms. Within this framework, climate models are used in conjunction with palaeoenvironmental data to interpret the paleontological record (Grove 2011). For example, although the origins of bipedalism (which defines the hominin lineage) extend further back in time, the evolution of obligate bipedalism during the Pliocene is linked to transformations of the African landscape and the expansion of C4-dominated grasslands. This event and others like it (e.g., the emergence of the genus Homo) are thought to have been triggered ultimately by orbital forcing (Maslin and Christensen 2007). Climate models have also been used to assess the impact of climate variability on hominin populations. The variability selection hypothesis, for example, suggests that trends in variability during the Plio-Pleistocene resulted in a selection for plasticity that characterises our lineage (Potts and Faith 2015), which could explain why humans have dispersed more widely than any other primate species.

Our understanding of the mechanisms shaping the pattern of hominin dispersals, which are major events in the history of our species, is framed in terms of environmental change. The earliest hominin dispersals, for example, likely coincided with climate events that reshaped the biogeographical map of Africa (Larrasoaña et al. 2013). Later dispersals, such as the dispersal of modern humans into Eurasia during the late Pleistocene, are also best understood from a climate perspective (Hughes et al. 2007; Timmermann and Friedrich 2016; Eriksson et al. 2012). Modern human dispersals to Australia and the New World coincide with megafaunal extinctions and climate models provide us with the data we need to contextualise this information, attributing causality where it is due (Prescott et al. 2012). If climate change shaped the pattern of human dispersals in the past, climate variability has been shown to affect modern societies too, increasing conflict (O’Loughlin et al. 2014), which is linked to modern population displacements.

High-resolution palaeoclimate models have been used to study the response of human systems to climate instability (Banks et al. 2013), to assess the impact of climate events such as the Last Glacial Maximum on population structure and demography (Tallavaara et al. 2015), and test the sensitivity of human systems to climate predictors such as ecological risk (Burke et al. 2017). Modelling the complex interactions between human systems and the environment allows us to appreciate how demographic patterns such as population size and connectivity, which are affected by climate change, can drive technological innovation and cultural complexity. By developing spatially explicit models that incorporate climate models or simply make use of model outputs, archaeologists gain a richer and more dynamic appreciation of the environmental response to climate change and the various mechanisms that allow human systems to adapt. These archaeological models, in turn, hold lessons for the future as we attempt to gauge the resilience of small-scale, or "traditional" societies and judge what is required to preserve human cultural diversity.

Collaborations between palaeoclimate modellers, archaeologists and palaeoanthropologists have provided rich opportunities for modelling human/environment interactions as well as contributing to improving climate model design. However, difficulties arise because of differences in the resolution of model outputs and signals from the palaeoclimate record that limits the application of palaeoclimate models to the study of early human evolution, for example. Furthermore, human populations perceive and respond to environmental change at a wide range of temporal and spatial scales. Increased capability and capacity in palaeoclimate research and improvements to the scale of resolution of model outputs, as well as greater efforts towards improving the accessibility of climate model outputs for non-specialists, will improve this situation in the future.

8 Palaeoclimate Modelling, Industry and Innovation

There is a strong focus on the impact of contemporary climate change on various aspects of industry. However, the fact that many important aspects of society's requirements need a longer term perspective either for the future or of the deep past is often overlooked.

One of the most challenging demands of modern society is the use of the Earth's geological resources and reserves. The growth of the world economy is demanding greater supplies of many metals such as aluminium, as well as ever increasing demands for fossil fuels. The geographical distribution of aluminium's chief ore (bauxite) and organic-rich source rocks for hydrocarbons both depend on past climates. Hence prediction (or retrodiction) of past climates can help in frontier exploration for these resources. Since the earliest days of palaeoclimate modelling, efforts have been made to retrodict source rocks. Parrish and Curtis (1982) and Scotese and Summerhayes (1986) developed a conceptual and a computer model of atmospheric circulation patterns to predict where oceanic upwelling occurs. Such regions are typically associated with high organic productivity that subsequently is buried and potentially becomes source rocks. Further work with palaeoclimate models extended these predictions by quantifying them (e.g., Barron 1985). More recent work (Harris et al. 2017) continues this research with full ESMs, making use of simulated atmospheric and ocean circulation (including aspects such as storminess and solar radiation) as well as aspects of the modelled carbon cycle to make very specific regional predictions of source rocks. These are used for frontier exploration.

Palaeoclimate modelling also plays a major role in risk assessment of the long-term storage of nuclear waste. Any site proposed as a nuclear waste repository requires a risk assessment measured up to 100,000 years into the future. On such long time scales, future orbitally forced climate change becomes as important as anthropogenic forcing. Early studies (e.g., Goodess et al. 1990) simply extrapolated past long-term changes into the future, but more recent work has made extensive use of more detailed palaeoclimate models. The latest approaches (e.g., Lindborg et al. 2005) use a combination of simple and full complexity climate models to provide detailed predictions of site-specific climate up to 200,000 years into the future, using methodologies identical to many palaeoclimate modelling studies.

The methodologies of palaeoclimate modelling have been utilised in some aspects of geoengineering research. This is because palaeoclimate modelling has often pioneered the use of ESMs, including detailed representations of the carbon cycle. Hence, many ideas of carbon sequestration have used palaeoclimate modelling tools to evaluate their efficacy. For example, Taylor et al. (2016) discussed the artificial acceleration of rock weathering as a potential method for enhanced drawdown of CO_2 and reduced ocean acidification.

Many aspects of society are also vulnerable to extreme events. Almost by definition (e.g., 100 year return period), these extreme events are beyond the observational record and palaeoclimate studies are required to give context to any event. Palaeoclimate proxy observations of storm events have frequently been used in infrastructure planning (such as flooding events and the location of nuclear power stations), but more recently palaeoclimate modelling of extreme events has also helped in planning process. For instance, model predictions of storm events during the last millennium (Kozar et al. 2013) were considered as a part of the evidence based in the New York City Panel on Climate Change 2015 Report (Horton et al. 2015). These include estimating the frequency of extreme events for flood protection, the risk assessment for nuclear power stations and long-term storage of nuclear waste.

9 Outlook

9.1 Overcoming Current Methodological/Technological Limitations

A thorough understanding of physical processes, the robust application of mathematics and statistical techniques, the availability of accurate geological boundary conditions and forcing estimates, combined with the required research-intensive computer facilities and appropriate computational and software engineering support, are central to the overall capability of palaeoclimate modelling (Fig. 5).

One of the most fundamental strengths of palaeoclimate modelling is that it provides a unique way to examine the response of the Earth system to forcing mechanisms in an integrated way. Key uncertainties associated with future climate change projection stem from the strength of positive feedbacks associated with components of the climate system that respond to forcing over medium to long timescales (e.g., ocean circulation and ice sheets; IPCC 2013), and the geological record is uniquely capable of preserving signals of change associated with slower responding components of the Earth system (Haywood et al. 2013). ESMs that incorporate the representation of many earth system processes, and their associated feedbacks on climate, are now available and can be run at higher and higher spatial resolutions (Peng et al. 2014). Such models are capable of simulating the response and longer term climate feedbacks stemming from a wide array of earth system processes, and from climate-relevant processes that operate over medium to long timescales.

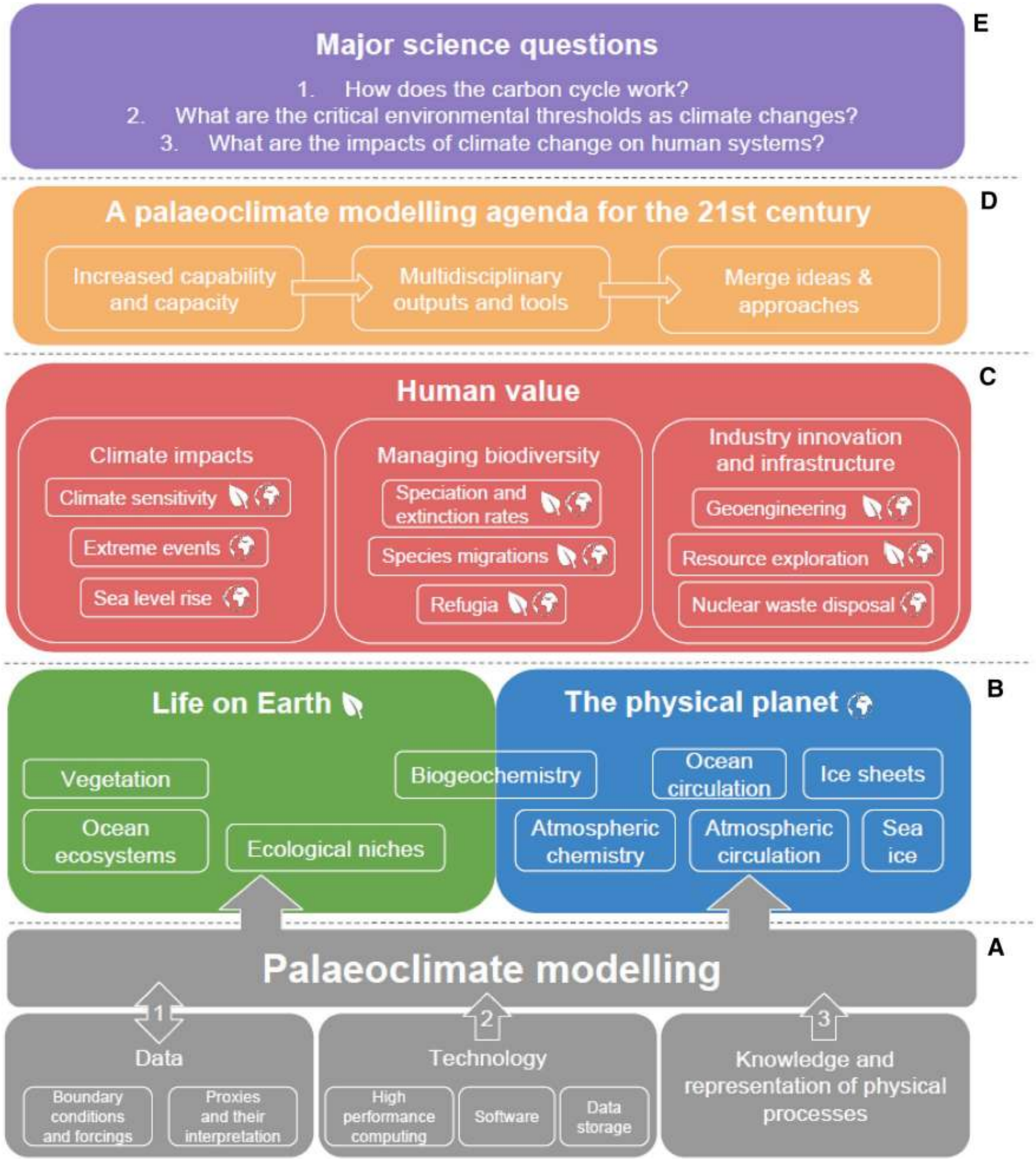

Fig. 5 Summary illustration showing **a** key data and technological/knowledge requirements that underpin palaeoclimate modelling, **b** key areas of contribution to understanding different physical systems and life on Earth, **c** the human value components of the contributions shown in **b**, and **d**, **e** the direction of travel required to address outstanding critical research questions with significant human importance

However, with increasing resolution and model complexity comes increasing computational demand and cost. In addition, using high-resolution ESMs to simulate the past comes with its own unique scientific and technological challenges that can dramatically increase the computational expense and time associated with producing simulations.

For example, uncertainties in geological boundary conditions often necessitate the production of an ensemble of climate simulations for a specific interval of time (Haywood et al. 2013). In addition, reconfiguring ESMs so that they can simulate the deeper past successfully is extremely challenging. Such models are not developed with the specific needs of palaeoclimate modellers in mind. As such, the reconfiguration of the land/sea mask, land elevation, ocean bathymetry, land cover, etc., creates challenges that require dedicated software engineering support to overcome, which is difficult to resource adequately. In addition, with increasing model capability comes increasing demand for appropriate boundary conditions and forcing datasets so that the potential of these new models can be fully realised. For instance, models that incorporate complex representations of atmospheric chemistry and/or atmospheric dust/aerosol-climate interactions may require information on the initial concentration of CH_4 in the atmosphere, or dust emission sources and emissions of Volatile Organic Compounds (VOC's). Unless ESMs are developed so that the model dynamically predicts such parameters, rather than requiring their initial prescription, it may lead to increased uncertainty in boundary conditions and forcings within palaeoclimate simulations, as these parameters may be poorly constrained geologically. Also given the radically different (from modern) climates such models are applied to, and the major changes to boundary conditions that are necessary, palaeoclimate simulations require substantial spin-up time insofar as they include a dynamic ocean, which can require several thousand simulated years to fully adjust, though atmospheric spin-up time is much faster (several decades to a century of simulation). Here computational efficiency and scalability of the model code (across computer processors) become paramount. Any model that cannot reliably achieve at least 10–30 model years per wall clock day with a reasonable total CPU demand/cost will be very challenging, if not practically impossible, to apply effectively to palaeoclimate applications and the assessment of uncertainty in past climate simulation.

The majority of latest generation full complexity ESMs do not meet the requirements for palaeoclimate modelling. Model development is carried out in isolation from the palaeoclimate community's specific requirements. There seems little scope that will change, meaning that the palaeoclimate modelling community's future interests could be best served by adopting a more tailored strategy towards model development. Examples of the development of EMICs (Earth System Models of Intermediate complexity) as well as other current large-scale research initiatives such as the climate modelling initiative called PalMod (Paleo Modelling), which is funded by the German Federal Ministry of Education and Science to understand climate system dynamics and variability during the last glacial cycle. Fundamentally, more considered and flexible strategies will be required to determine what spatial and vertical resolution and model complexity is actually needed to answer specific challenges in palaeoclimate science.

9.2 Enhanced Integration of Statistical Methodologies to Assess Uncertainty

While current climate models seek to optimally represent physical processes that determine weather and climate, this representation is not perfect and models have been tuned to provide acceptable simulations of modern climate regime. For palaeoclimate simulations, where boundary conditions such as atmospheric CO_2 concentration differ from modern climate simulations, the approaches used to ensure that models deliver the best possible simulation for the modern (observed) climate may no longer hold. A commonly employed solution to this problem is to consider ensembles of models to understand the commonalities and differences between possible model outputs. Statistical techniques such as Bayesian Model Averaging (Hoeting et al. 1999) can be used to compute ensemble averages where greater weight is given to models that are most compatible with the available data.

In addition, the impacts associated with global warming cannot be fully characterised by a change in the spatial and temporal averages of specific climate variables. To capture such changes it is necessary to model how the distribution of a climate variable (instead of just the mean) depends on changing boundary conditions (such as GHG concentrations). A variety of statistical techniques have been used for this purpose: quantile regression is a generalisation of linear regression, which allows for the estimation of arbitrary quantiles of the distribution of a climate variable instead of just the mean (e.g., Janson and Rajaratnam 2014). For example, extreme value theory describes the tails of a distribution, with the aim of predicting extremes beyond what has been observed in the available time series of data (e.g., Mannshardt et al. 2013). Some authors have also used specialised techniques to simultaneously capture the correlations between proxy variables and climate variables across space and time (e.g., the GraphEM method; Guillot et al. 2015), although such beneficial approaches are not commonly used, and this highlights the need for further integration between palaeoclimate modellers and applied statisticians.

9.3 Removing Barriers to Data Sharing and Multidisciplinary Collaboration

Access to appropriate palaeoclimate model outputs is a significant limitation for other research disciplines. The progress already made towards widening access can be attributed in part to research council requirements to make publicly funded science widely available in national data repositories (e.g., the British Atmospheric Data Centre). In addition, journal requirements for the uploading of data sets associated with specific publications have had a positive impact, as well as internationally promoted output standards and software libraries such as those adopted by the Coupled Model Intercomparison Project (i.e., CMOR: the Climate Model Output Rewriter). CMOR ensures that a standard set of model variables for different climate model experiments are available on Earth System Grid Federation repositories (https://esgf.llnl.gov).

New community-based efforts are underway to support data sharing across disciplines. For example, the PaleoClim database provides pre-processed climate data to support ecological niche studies (Brown et al. 2018). These community-led initiatives are important because the approach towards processing model outputs can be application specific, and scientists in the disciplines requiring climate outputs may not have the required programming skills and experience to successfully deal with unprocessed palaeoclimate model data. Initiatives such as PaleoClim provide a template of how communities can come together to discuss the removal of barriers and enhance awareness of, and access to, palaeoclimate modelling data.

Whilst the initiatives described above can improve access to palaeoclimate model output by other communities, they will not fully resolve the issue of rigorously embedding palaeoclimate model outputs into other disciplines. There is an underlying concern as to whether model outputs used in specific applications contain an adequate appreciation and expression of uncertainty. The obvious solution is to embed palaeoclimate modellers within multidisciplinary teams. However, the global pool of available palaeoclimate modellers is small, and thus collaborative capacity is limited. A complementary solution promoted more generally in efforts to foster multi-disciplinarity is the development of T-shaped researchers (e.g., Palmer 1990). The development of T-shaped skills is a concept promoted for more than 20 years, with the T representing the range of research expertise an individual develops, and the foundation/depth of individual understanding represented by the vertical bar (Palmer 1990). Using this philosophy a researcher first develops an expertise in their own discipline before subsequently developing their skills base in a way that facilitates the deployment of their knowledge in a wider array of scientific disciplines. The development of T-shaped researchers is essential to the success of multi-disciplinarity, but it is unclear how conducive academic environments currently are to those wishing to adopt a T-shaped research skills base. The required investment of time versus immediate scientific return is of paramount consideration for early career scientists, with the requirement to demonstrate sustained levels of high research performance very clear.

9.4 Developing an Enhanced Focus on Past for Future Relevant Science

The potential contribution of different types of palaeoclimate modelling to the generation of science underpinning UN SDGs or global scientific grand challenges is not equal. This is also the case for the support palaeoclimate modelling can provide to multidisciplinary research. For the science to grow its influence in these regards, more targeted and co-ordinated approaches will be required that maximise the utility of palaeoclimate modelling. We highlight this need and opportunity by reference to specific examples.

Mitigation and adaptation strategies for global climate change are informed by studies that seek to better constrain the extremes of natural variability in climate and weather phenomena from the past (beyond the observed climate period). However, a weakness of approaches that consider only the very recent past, for example the last millennium, is that the effect of the warming trend since the onset of the industrial revolution is omitted from the assessment of the behaviour of weather and climate extremes. Given the current and projected rates of GHG emission, and the associated rapid warming trend, palaeoclimate modelling is paying increasing attention to warmer (than the pre-industrial) intervals, and also to intervals when CO_2 concentrations in the atmosphere were analogous to current and near future concentrations (e.g., Haywood et al. 2013). Given the current rapid rate of temperature increase, it is necessary to go back in time as far as the Pliocene epoch (~ 3 million years ago) to find the estimated 3 °C global annual mean surface temperature change that we are on track to achieve by the end of this century (Haywood et al. 2013). This rapid progress towards analogous past warm climates was recently highlighted by Burke et al. (2018) who used different climate model simulations for future GHG scenarios, and then compared these to different simulated climates of the past including the Last Glacial Maximum, the Mid-Holocene, the Last Interglacial, the Pliocene and the early Eocene. Statistically, the climate state that they considered to be most similar to what models predict will be reality by 2030–2050 AD was the mid-Pliocene Warm Period (~ 3 million years ago), and by ~ 2200 AD the early Eocene (Burke et al. 2018). This provides a sobering assessment of the rate of climate change currently occurring, and underlines the importance of an increasing focus on past warm intervals.

However, even a general concentration of community efforts on warm epochs may not be sufficient to guarantee the maximum utility of palaeo science in informing UN SDGs and global scientific grand challenges. Climate variability is driven by variations in Earth's orbit around the sun with predictable periodicities (the Milankovitch cycles). Orbital forcing has acted as a natural pacemaker for insolation since our planets formation. Therefore, while epochs in the past may be analogous in the sense of different conceivable CO_2 stabilisation scenarios for the future, at any point in time within these epochs the surface expression of climate (i.e., difference compared to the pre-industrial baseline) will not solely be a response to GHG forcing (Haywood et al. 2016). While this does not matter greatly in terms of the global annual mean temperature response, it is important for the time-specific expression of climate change locally, regionally and seasonally. Orbital parameters, and the resulting insolation pattern at the top of the atmosphere, are reliably calculable for the Cenozoic (Laskar et al. 2011). It is possible to isolate specific intervals within a warmer than pre-industrial epoch with the same, or very similar, insolation forcing (e.g., Haywood et al. 2016). Such an approach provides an obvious benefit of studying a mean state climate that is more influenced by a carbon cycle perturbation and less influenced by other forcing agents. This approach has been adopted within the scientific strategy underpinning the second phase of the Pliocene Model Intercomparison Project[36], whereby a specific interglacial within the Pliocene has been identified for study. Such a methodology differs from more classical approaches in palaeoclimatology where the most concentrated effort tends to focus on the most rapid and/or largest transitions in Earth system behaviour, but that does not necessarily mean those intervals are the most relevant in the context of the future. The judgement is dependent upon the scientific question which is asked. Nevertheless, it is important to recognise that warm (and warming) intervals in the past characterised by very different orbital forcing compared to present-day (e.g., the Last Interglacial and the Last Deglaciation) will remain very important to study. For example, they are important for the assessment of regional and seasonal variations in climate (past and future), and for understanding how the Greenland and Antarctic Ice Sheets respond to a warmer (and warming) atmosphere and oceans (Otto-Bliesner et al. 2006).

Palaeoclimate modelling studies have focussed a great deal on large-scale mean state climate changes. Within such a context, numerous studies have examined modes of natural climate variability, but very few have examined the nature of extreme weather and climate events during warm episodes of the deeper past. Given that society is likely to experience the worst initial effects of anthropogenic climate change through a change in the frequency and/or magnitude of extreme events (IPCC 2013), a more concerted effort in this regard is required. Whilst geological data may not always be available to assess the quality of model results in this regard, data are available for the climatic mean state. This mean state is a product of the average weather and climate variability at any given time and place. Therefore, if models demonstrably simulate the mean climate faithfully, this may add credence to their simulation of higher order climate and weather variability, even if geological data to assess the model predictions of extreme weather and climate events are absent.

10 Conclusion

In conclusion, palaeoclimate modelling over the last 4 decades has provided a broad and deep contribution to multidisciplinary science, and to the science underpinning global grand challenges and SDGs. First-order questions about the operation of climate and environmentally relevant processes, and our planet's limits in terms of sustaining life during periods of rapid change remain unanswered. This includes the fundamental understanding of the carbon cycle, identification of critical environmental thresholds for species distribution and life, and what are the longer term implications of climate and ecosystem change on human adaptability and vulnerability. The great strides made in the development of more and more compete and capable models provide a wealth of opportunity for further discovery, but only if the unique challenges associated with simulating climate of the past are properly appreciated and understood.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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