Injecting Climate Modeling Into Deep Time Studies: Ideas for Nearly Every Project

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ABSTRACT

Global climate models (GCMs) primarily exist to describe the present-day climate system and simulate its response to inputs in order to attribute observed change to its causes and predict the future of climate. It has been proposed to enable GCMs to simulate potentially large future climate transitions by testing their ability to attribute climate change against new and existing data concerning past transitions in Earth's history. These proposals emphasize the technical challenges and large uncertainties of climate modeling in deep time as well as the need for substantial culture change to bring modelers and observers together to solve challenges like the climate dynamics of icehouse–greenhouse transitions. This essay proposes that the creation or just the use of climate model output could bring added value to many deep time studies, even those small in scale; and thus should be considered in project design. Examples are mainly provided from studies of Carboniferous and Permian strata that suggest potential in areas such as macrogeological databases, high-resolution depositional records, and uncertainties in atmospheric composition and paleogeography.

INTRODUCTION

Studies of present and future climate change and of the connected issues of energy, pollution, and mineral resources strongly connect the geosciences with society. Global climate models (GCMs) have become an important tool in the study of climate. Their development since the late 1980s has been shaped by two needs: (1) to attribute the rapid rise in global mean temperature in the 20th and 21st centuries to its causes (2) to predict how climate will change in the future, particularly because much of recent climate change is attributed to human activities, as described in the reports of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 1990, 1996, 2001, 2007, 2014).

Modeling contributions to the IPCC have mostly focused on the very recent past and near future of climate (1850–2100) (e.g., Taylor et al., 2012). However, it was soon recognized that models that could simulate a wider range of climates than during the instrumental record might simulate future climate better. Therefore, standardized GCM simulations of the middle Holocene (6 ka) and Last Glacial Maximum (LGM, 21 ka) were undertaken soon after the first IPCC Report in 1990. They are now considered valuable enough to merit an entire chapter in IPCC's (2007) Report (Joussaume et al., 1998; Crucifix et al., 2005).

Geoscientists interested in the deep past, the history of the Earth solely recorded in the rock record (prior to the Pleistocene, 2.588 Ma), have suggested that climate change throughout Earth history is also relevant to the direction of climate today. They propose studying icehouse–greenhouse transitions during Earth's history and designing standardized global climate model (GCM) experiments to understand them (NRC, 2011). Comparing these experiments with the geological record would (among other things) test the ability of GCMs to simulate the response of climate to large, rapid changes in greenhouse gases (Valdes, 2011; Zeebe, 2011; NRC, 2011).

GCM simulations of the Earth's deep past are nothing new (e.g., Kutzbach and Gallimore, 1989), but, to borrow from medical parlance, they long have been an off-label use. However, there are at least three reasons why observers of deep time (geologists, geochemists, paleobiologists, etc.) should continue to engage with the broader climate science enterprise represented by the IPCC by further integration of observational studies with GCM simulations.

First, deep time climate studies relevant to present day climate could open new funding opportunities for the academic sedimentary geology and paleobiology community, which has significantly contracted in recent years in the U.S. (Parrish et al., 2011). Second, many GCMs do not just model the atmosphere but consider the ocean, the land surface, and the cryosphere in their abiotic and (increasingly) biotic characteristics (see Heavens et al., 2013 for an overview). These new capabilities may allow more direct simulation of some aspects of the geological record. Finally, the expanding capabilities of GCMs can pose new technical challenges for modeling deep time climates, which also would merit more attention from GCM developers and funding agencies if deep time grew in relevance (e.g., Heavens et al., 2012).

Yet modelers and observers of deep time face difficult technical challenges, including uncertainties in how to set up and test simulations. They also may face cultural challenges, which may be broadly summarized as obstacles to finding the time, financial support, tools, and collaborators to solve those technical challenges (NRC, 2011).

In the remainder of this essay, I will argue that a closer relationship between climate modeling and observational studies of deep time does not need to be a daunting prospect. Indeed, current developments in sedimentary geology can encourage closer collaboration between observers of deep time, modelers of deep time climates, and perhaps the community that focuses on the changing climate of the Earth today. In addition, I will show how observational uncertainties in deep time can stimulate climate modeling.

The opportunities are already here to build the scientific culture and research infrastructure that can make the past of Earth's climate relevant to predicting its future. Indeed, seizing those opportunities may help prioritize what technical and cultural problems need to be solved. My examples mostly focus on my own research interests in late Paleozoic continental climate. Nevertheless, the points I make should be broadly relevant and perhaps could be better supported by examples from other parts of Earth history.

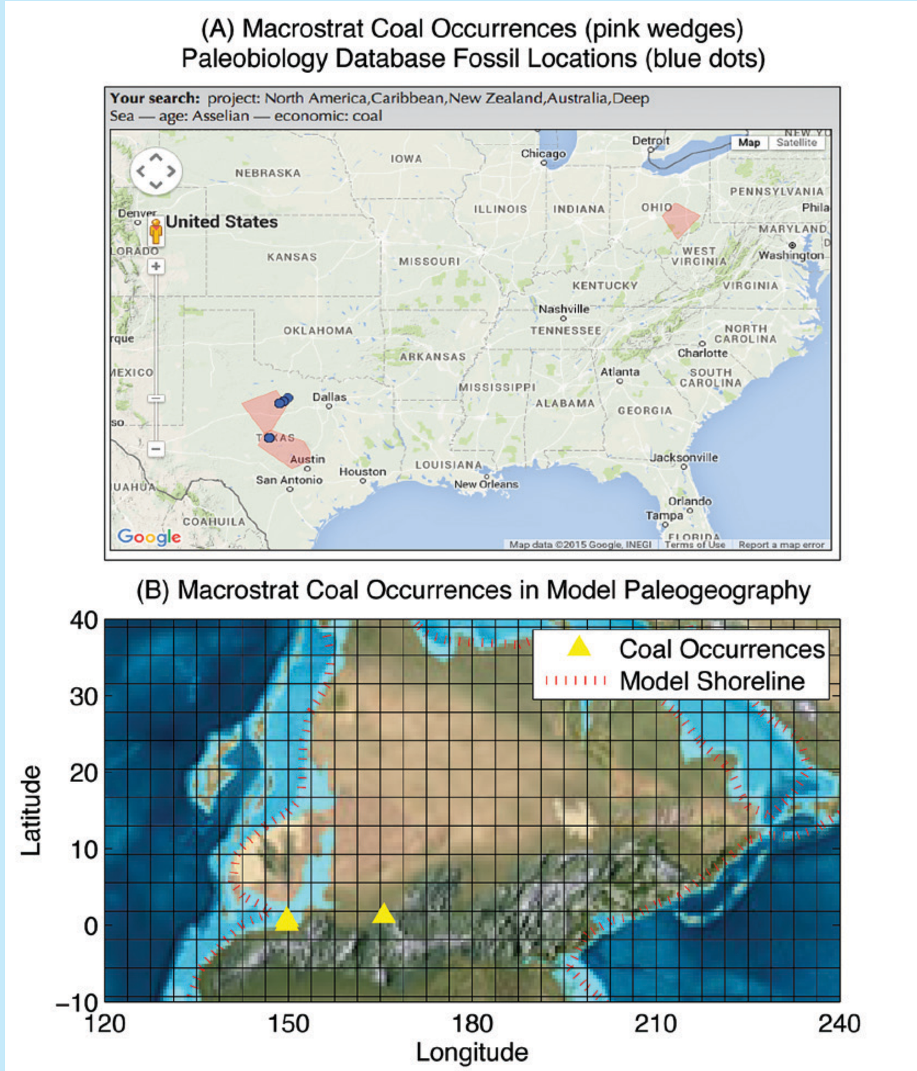

Figure 1: (A) Asselian coal occurrences in Macrostrat; (B) Asselian coal occurrences from (A) in model paleogeography of Heavens et al. (2015) overlaid on the Blakey (2015) paleogeographic map on which it was based, whose uncertainties are not known. The intersections between gridlines indicate model gridpoints, so the square size is indicative of model resolution but does not correspond to the true gridboxes.

CLIMATE MODELING OPPORTUNITIES

Using Digital Macrogeological Databases To Test GCM Simulations

Compiling and organizing geological data over scales much greater than outcrops is at least as old as Smith's (1815) map of Great Britain. Digital computers and the Internet can make compilation faster, cheaper, and easier to query. One result is digital databases like the Paleobiology Database and Macrostrat, which have been developed to quantitatively test hypotheses that span large geographic scales and/or wide swathes of the Earth's history.

Peters and Heim (2011) classifies the purpose behind quantitative analyses of these databases under the head of "macrostratigraphy" and "macroevolution", reviving the concept of "macrogeology," in historical studies of geology (Schneer, 1981; Bretsky, 1983). These studies contrast deriving broad general principles analogous to the laws of physics (macrogeology) with incremental exploration and accurate description of individual rock units (microgeology). Databases like Macrostrat therefore are macrogeological in vision (and in name) but synthesize abundant, high-quality microgeological studies in the form of existing syntheses (Childs, 1985) or data mining of the peer-reviewed literature (Zhang et al., 2013). It soon may be possible to make direct data queries about the distribution of facies in seconds that previously would have required months of bibliographic research.

Macrogeological databases also enable GCM simulations to be compared

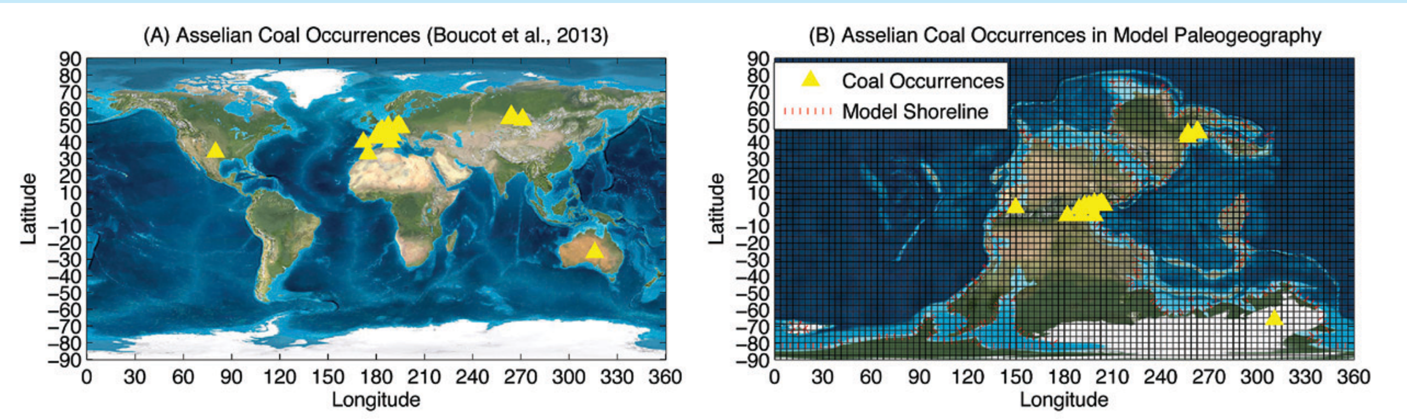

Figure 2: (A) Asselian coal occurrences in Boucot et al. (2013); (B) Asselian coal occurrences from (A) plotted as in Figure 1B. "Very earliest Wolfcampian" and Autunian are considered to be equivalent to Asselian.

with the distribution of facies restricted to particular climatic conditions (e.g., coals, bauxites, evaporites, tillites). The distribution of such sediments has been used to reconstruct past climate and/or geography (Patzkowsky et al., 1991; Ziegler et al., 1997; Tabor and Poulsen, 2008). GCM simulations are fully quantitative climate reconstructions, so it is reasonable to ask whether climate-sensitive facies occur within the expected climate conditions.

As a concrete illustration, I use coal occurrence during the Asselian (295.0–298.9 Ma) to test climate simulations by Heavens et al. (2015) that are focused on tropical climate dynamics during this time. The test is whether precipitation and evaporative balance in the simulations at the location of coal occurrence is consistent with the conditions under which peat deposition is thought to be possible (Patzkowsky et al., 1991; Cecil et al., 2003).

Because most of its continental data is concentrated in North America, Macrostrat currently contains minimal Asselian coal data (Figures 1A and 1B). So I have used a more expansive, non-digitized global compilation of climate-sensitive facies (Boucot et al., 2013) to demonstrate Macrostrat's future potential. Nevertheless, there is room for improvement in characterizing the record even at this temporal resolution. Most of the Asselian coal occurrences are in Europe and Eurasian Russia (Figure 2A). Early Permian coal occurrences from China are abundant, but age control to Age/Stage level is lacking (Boucot et al., 2013). The full set of occurrences covers equatorial Pangaea as well as parts of both the northern and southern extratropics (Figure 2B).

Three of the Heavens et al. (2015) simulations, which span low pCO_2 icehouse climates similar to today as well as high pCO_2 greenhouse climate conditions, are broadly consistent with peat deposition at tropical coal occurrences (Figure 3). Most of the exceptions are in southern tropical Pangaea, where all simulations overestimate climate seasonality/evaporation and the icehouse simulations are overly dry (Figure 3). The greenhouse simulation *(greenhouse.noglaciation)* is similarly incorrect with respect to the Texas occurrence (Figure 3). All simulations appear overly dry in the extratropics, but the greenhouse simulation is wet enough for peat deposition in some extratropical locations (Figure 3). Peat deposition where Asselian coals occur is inconsistent with a simulation in which there is glaciation at the equator at altitudes of 500–1000 m *(icehouse.glaciation.equatorial)*. Climate conditions of this extremity would have interrupted peat deposition globally (Figure 3).

In all simulations, the amount and seasonality in precipitation in tropical Pangaea is affected by the monsoon over Pangaea (Heavens et al., 2015). This monsoon is stronger under greenhouse conditions. Under icehouse conditions and when the Earth's orbit is eccentric, the monsoon is strong when the longitude of perihelion is in phase with the summer solstice. However, the effects of orbital variability on this coal occurrence test are minor (Figure 4). A strong northern summer monsoon *(ih.g.orb4)* dries most areas of coal occurrence near the equator and a strong southern summer monsoon moistens the same areas. But these changes are not sufficient to move any location in or out of the zone of peat deposition (Figure 4).

Fully interpreting the results of this experiment is beyond the scope of this essay. Nevertheless, using digital macrogeological databases to test models in this way could help separate and attack discipline-spanning uncertainties that have so far proven difficult to separate (Heavens et al., 2015; Soreghan et al., 2015). Such an error could come from the model itself, due to poorly resolved or poorly represented processes and could be isolated by model intercomparison tests along the lines proposed in this section. This error could be the result of incorrect dating or paleogeographic assignment, which could be assessed by geological and geochemical techniques. Or the coals all could be Asselian but were deposited in different climates within Asselian time, which could be assessed geologically as well. Or the systematic errors could arise from errors that directly bridge observations and modeling, such as those related to greenhouse gas inputs or paleogeography.

Climate model tests like this do not need to be limited to lithology. Fossils themselves can be analogous to a climate-sensitive facies. Biophysical analysis and simulations of plants and animals can estimate the environmental tolerance of extinct species and/or properties from which such tolerances can be estimated (e.g., Head et al., 2009; Wilson and Knoll, 2010). Indeed, at least one attempt at paleobiological validation of GCM simulations predates the Paleobiology Database (Rees et al., 1999).

Climate model tests of this kind only will be common when climate modelers provide output in ways that interface well with macrogeological databases. For the experiment described above, I relied on direct inspection of the source maps for the paleogeographic model of Heavens et al. (2015) to match the modern location of the facies with its location in the simulations. This is not a scientifically reproducible technique. Archiving output will require more rigorous definition of the translation between paleo-space and present space.

GCM Investigations of Hypothetical High-Resolution Climate Signals

One uncertainty in predicting future climate is the relationship between change in the mean state and higher order moments of climate (e.g., Schneider, 2004). Put another way: does climate change gradually and linearly or non-linearly and abruptly? One approach has been to investigate and/or model climate variability in the recent or deep past at a variety of timescales, even those approaching the annual or seasonal (Alley, 2000; Zachos et al., 2001; Crowley and Hyde, 2008). However, as global temperatures warm, the climates recorded by deep ocean or ice core oxygen isotope records become poorer analogs for the future. High-resolution data during icehouse–greenhouse climate transitions throughout Earth history could be valuable.

Fortuitous high-resolution data of at least one sort is known in the stratigraphic record. Length of day in Proterozoic time can be inferred from laminar tidal rhythmite deposits, some of which have diurnal resolution (Williams, 1997). Perhaps more common and more climatologically useful are potential speleothems from

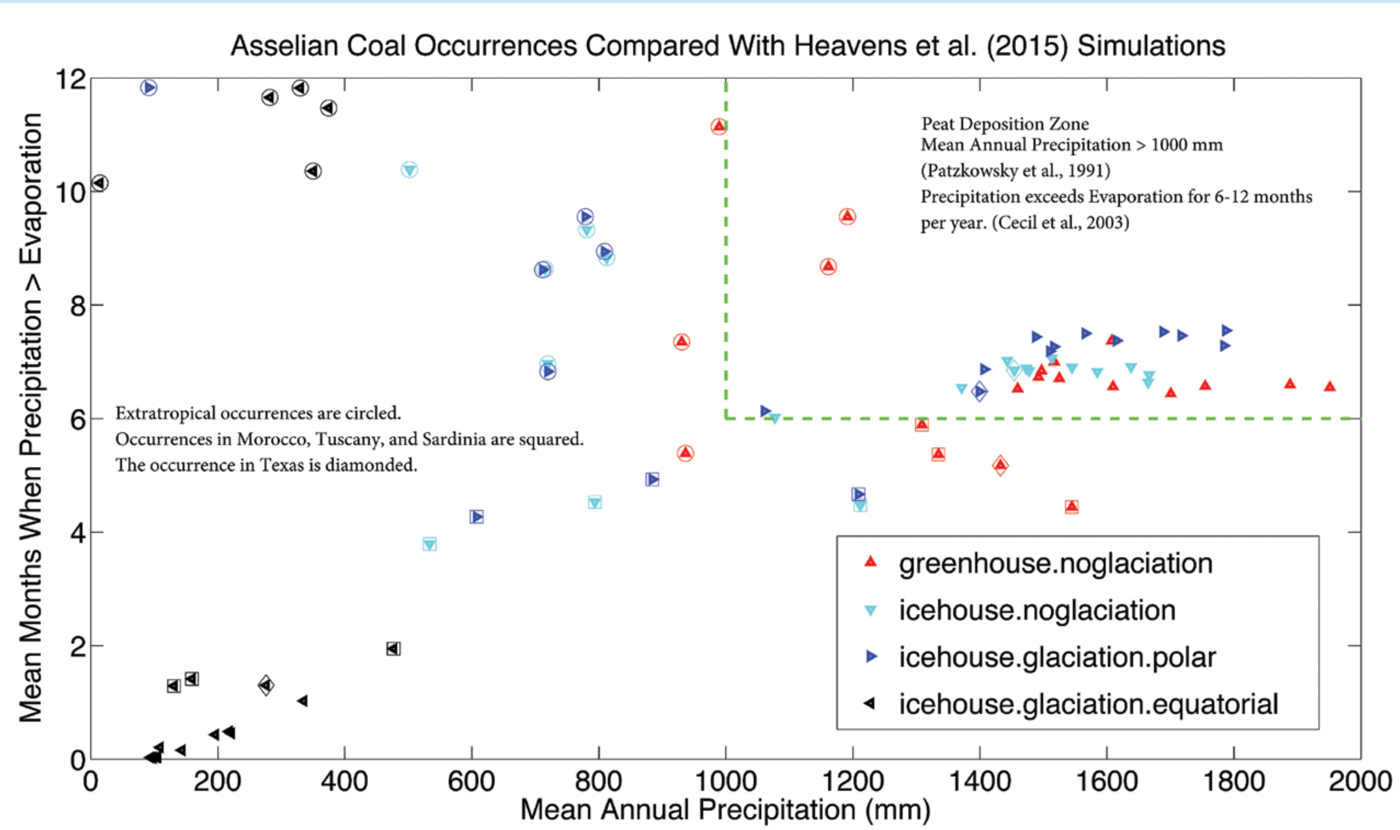

Figure 3: Predicted conditions critical for peat deposition at the locations of Asselian coal occurrences for four climate model simulations of Heavens et al. (2015), as labeled. The chosen simulations sample a range from extreme icehouse to extreme greenhouse conditions. See text for discussion.

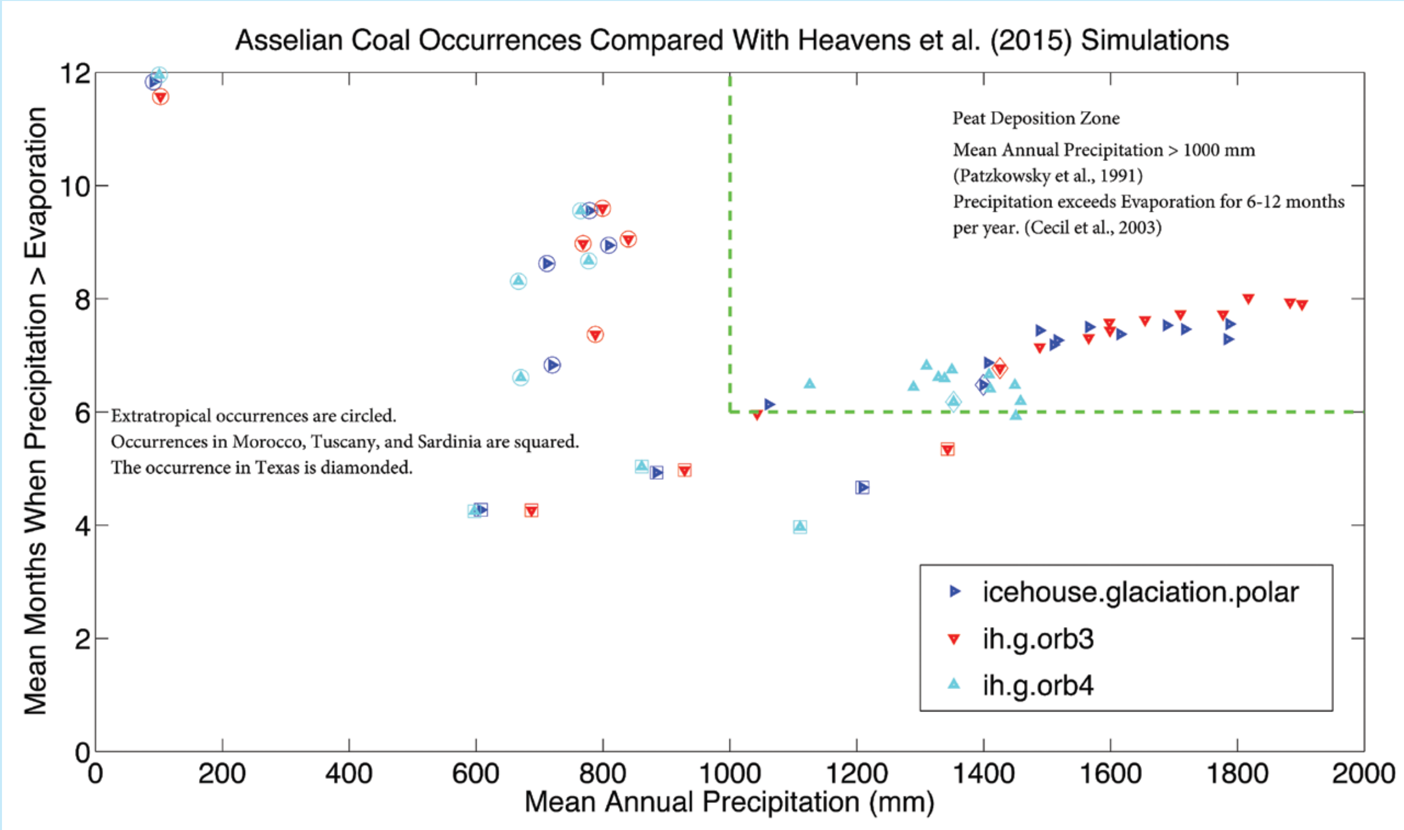

Figure 4: Predicted conditions critical for peat deposition at the locations of Asselian coal occurrences for three climate model simulations of Heavens et al. (2015), as labeled. The chosen simulations sample different monsoonal conditions over Pangaea. See text for discussion.

deep time, which may sample annual or even seasonal variability in the chemical and isotopic composition of precipitation influx to the cave (Woodhead et al., 2010).

Woodhead et al. (2010) qualitatively attribute the variability in their speleothem record to climate dynamics. Yet GCMs now are capable of simulating the isotopic composition of water in precipitation as well as the deposition of sea salt and/or particular elements such as P (e.g., Risi et al., 2010; Mahowald et al., 2006, 2008; Vet et al., 2014). Simulations could strengthen Woodhead et al. (2010)'s case by estimating the sensitivity of speleothem signals to climate variability, enabling comparisons with the potential effects of internal cave dynamics and/or post-burial diagenesis as well as the quantification of the higher order moments of climate variability from a suite of proxies. And this potential does not stop with speleothems but might apply to a variety of strata encountered by future continental drilling projects, such as varved lakes.

Uncertainties In Atmospheric Composition Are Opportunities In Disguise…

Observations of deep time come with uncertainty. One may identify them. One may list them. One may bemoan them. But one motivation for studying the Earth's history is to reduce them. In many cases, GCMs can help.

Oxygen has obvious significance for biology and biogeochemistry. Its role in climate is less obvious. It absorbs poorly in the infrared and so is not a greenhouse gas (IPCC, 2013). However, it currently makes up 21% of the atmosphere by volume. Oxygen molecules frequently collide with greenhouse gas molecules, enabling greenhouse gases to absorb wider bands of infrared radiation (Goody and Yung, 1989). In addition, oxygen scatters incoming solar radiation (Trenberth et al., 2009). However, recent reconstructions of atmospheric oxygen disagree, particularly for the Late Mesozoic, e.g., the Cenomanian (93.9–100.5 Ma), where estimates range from 11–24% and are inconsistent within the published uncertainties (Falkowski et al., 2005; Glasspool and Scott, 2010; Tappert et al., 2013).

GCM simulations of the Cenomanian by Poulsen et al. (2015) have shown that a Cenomanian climate with higher oxygen levels would be cooler and drier. The uncertainty quoted above was found to be equivalent to ~3° C in surface temperature. Poulsen et al. (2015) propose that the lower estimates for Cenomanian oxygen levels are correct and could explain why GCMs have trouble simulating the warmth of Late Mesozoic climate, a time in which carbon dioxide levels are much better constrained than oxygen.

…And So Are Paleogeographic Uncertainties

A frustrating aspect of simulating the Earth's climate in deep time is uncertainty in inputs related to the setup of model experiments such as the placement of continents, the heights of mountains, and greenhouse gas and aerosol levels. For geologists interested in paleogeography, this uncertainty is an opportunity: an opportunity to quantify the impact of these uncertainties on climate.

One realized example is reconstruction of the altitude and spatial extent of the Central Pangean Mountains (CPM). Slingerland and Furlong (1989) modeled the CPM as a wedge limited by the Coulomb strength of the rocks. It then used the structure of sedimentary basins to estimate crustal loading by the CPM, a partial constraint on the wedge model. Due to uncertainty in erosion rate (a climatically controlled parameter) and wedge basal slope (a tectonically controlled parameter), a range of solutions was obtained. The favored solution was of a mountain range comparable in width and altitude to the Andes.

The significance of this problem to climate was first illustrated by Otto-Bliesner (1993), who showed that a Himalayas-like CPM during the Kasimovian restricted the northward progression of the Intertropical Convergence Zone greatly enhanced precipitation rates over the CPM, which would impact the CPM's possible structural characteristics within Slingerland and Furlong's (1989) model. A direct test was undertaken by Fluteau et al. (2001) which varied the altitudes of the Appalachian and Variscan sections of the CPM to obtain the best agreement with a variety of observations about Late Permian climate. The conclusion: the CPM was closer in height to the Andes than to the Himalayas.

CONCLUSIONS

Observers of the Earth's deep past and climate modelers have found opportunities for collaboration and intellectual engagement in the past. The rise of global climate change as a defining paradigm for the earth sciences presents an opportunity to deepen and widen those collaborations. I have underlined the importance of: (1) using GCMs as a tool for constructing new hypotheses about the geological record and synthesizing many different types of geological information; (2) making geological data and GCM model output accessible and convenient to analyze. Doing so will not only help maintain the relevance of geology and paleobiology to society but also will expand our knowledge of the Earth's deep past for its own sake.

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