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Global palaeoclimate modelling approaches: some considerations for archaeologists

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21.1 Introduction

Palaeoclimate reconstruction is an important complement to archaeological research on ancient environments. Climate interacts with vegetation and geologic features in the production of what we characterise as the environment, and climate, in turn, is affected by that environment. Computer modelling of the climate system is one powerful way to estimate past and future climates.

21.2 General Circulation Models

General Circulation Models (GCMs) are a prominent tool in use at the present for studying past climates. While the output of these models is potentially helpful to archaeologists, it is important to be aware of their limitations. Complex, global-scale, three-dimensional mathematical models, GCMs attempt to represent Earth's atmosphere or oceans. Recent efforts have concentrated on linking the atmospheric/oceanic modelled systems and on developing global databases for surface variables such as biome distribution or soils, and their interactions with atmospheric circulation (e.g. Foley 1993; Gallimore & Kutzbach 1989).

These models are based on quantitative expressions of physical laws, not generally on observed field data. GCM runs begin with information about the amount of energy arriving at the top of the atmosphere, fuelling the climate system. Variations in the earth's orbit and properties of land and the atmosphere affect how and where that energy gets used or if it is reflected back to space. Factors such as carbon dioxide levels in the atmosphere, the reflectivity of the ground surface (albedo), volcanic and other aerosols, the sea surface temperature, the amount of sea ice, the extent of ice sheets on continents, and other forcing variables are considered. Forcing variables are those parameters that seem to drive climate change on earth.

After setting initial values in the model, researchers can experiment with hypothetical future global climate scenarios. Examples include 'what if' models assuming CO_2 increases of 1% per year or CO_2 doubling over the next seventy years. Researchers can model past climates as well. The GCM computes the effects of past solar radiation on temperature and moisture circulation as far as the model and inputs are correct.

Model simulations are dynamic – after inputting the initial forcing values the model is allowed to run until it comes to some kind of equilibrium. An example of the large number of calculations that are required to produce one of these models is provided by Ruddiman and Kutzbach (1991) (see Table 21.1).

Groups of researchers work together to create such models and then team together to fund the phenomenal amounts of computer resources required to implement a GCM run. These models are so computer intensive that the newer coupled atmospheric/oceanic versions have pushed the limits of available technology. An Atmospheric GCM alone may take two minutes of Cray supercomputer time to advance one model day (e.g. Pitcher *et al.* 1983). For the example provided by Ruddiman and Kutzbach, this would translate to roughly 120 hours per GCM run.

Discrepancies between simulations and field data can point to areas of weakness in the models. The models work best in the Northern Hemisphere, especially in the area of the North Atlantic. This is partly due to the greater concentration of land mass in the northern hemisphere (land temperature responds more quickly to changes in incoming radiation than does ocean temperature), the greater amount of research that has been done on northern high latitude areas, and the greater quality and quantity of input records. See Kalkstein (1991) for one comparison of GCM output with observed modern climate data.

GCM simulations of past global climates are being tested against the existing archaeological, geological, palaeobotanical, palaeozoological, and other records by an innovative multi-disciplinary group known as COHMAP (the Co-operative Holocene Mapping Group) working with National Center for Atmospheric Research (NCAR) GCMs (COHMAP 1988). This systematic comparison of model output with real field observations can be extremely useful for fine-tuning, and may help researchers to better predict the effects anthropogenic-induced greenhouse warming will have on the earth.

21.3 Comparison of GCMs and GIS

For those familiar with GIS systems, there are interesting differences between that type of modelling and the modelling done in GCMs. First, GCMs truly are quantitative. Little consideration is paid to visual representation of data. GCMs divide the world into three dimensional cells, much like three dimensional raster cells

Horizontal Grid	5° latitude by 5° longitude	= 2500 squares
Vertical Grid	40 layers (20 in atmosphere, 20 in ocean)	= 40 levels
		Total: 100,000 cells
Variables	Temperature Radiation Motion Water Vapor Clouds Rain Snow Evaporation Soil Moisture Albedo	
For a 100 year model, with calculations every hour:	24 hr/day × 365 days/year × 100	= 100,000 steps
	Total number of equations to be solved:	$10^5 \times 10^1 \times 10^5 = \mathbf{10^{11}}$

Table 21.1: Example showing number of calculations required to create a GCM.

in a 3-D GIS (see Figure 21.1). Cell values are determined by complex physical interactions with all adjacent cells. Without going into a detailed discussion of climatology, some of the processes that are used to determine cell values include the effect of earth's rotation on the movement of air parcels (the coriolis effect), movement due to pressure and temperature gradients in the atmosphere or oceans (created by differential heating of the earth's equator and poles), and movement due to friction of air parcels against the earth's surface (due primarily to North/South running mountain ranges). Values are not computed for cells themselves but for each intersection of a three dimensional cell's corner with any of its neighbours. In other words there are 8 points around each cell for which values are calculated.

Those doing GIS analyses are accustomed to struggling to have the topography in their computer models resemble reality adequately. Decisions of scale are made carefully, whether it is to use 1:10,000 DEMs, 1:50,000 DEMs, etc. The global scale of GCMs, and the very real need to simplify as much as possible to make them manageable, requires that topography be oversimplified. The Rockies, Himalayas, and Andes are the only surface undulations that show up enough in one of these models to be recognisable. Even these mountain ranges are drastically simplified and reduced. The Rockies, for instance, are sometimes limited to a height of less than 2000 m and are treated as a smooth dome. In reality they are almost twice as high and are craggy rather than smooth. Smaller scale topography has an important impact on weather, and these sub-grid scale effects are just *not* picked up in GCM models.

21.4 Scale in Palaeoclimatic Changes

Scale is a very important issue when determining how GCMs can be useful to archaeologists. GCMs are really not useful for determining what the climate was like at a particular spot on the ground in a particular century of the past. The map output created by GCM runs are difficult to relate to ground truth precisely. GCMs are not going to replace detailed pollen core, palaeo-lake level reconstruction and other proxies for specific archaeological locales for a long time to come. Rather, GCMs can clarify some of the large scale reasons *why* climates changed across regions in the past. They also provide information for what past climates may have been like in those areas lacking proxy data. GCMs can also provide important information on the seasonality and magnitude of past climate states. Changes from winter to summer precipitation regimes, for instance, are likely to be apparent from careful examination of GCM runs.

It is important to clearly draw the distinction between weather and climate. Day to day variations are called weather and are studied by meteorologists. The atmosphere's status globally, regionally, or locally on a temporal scale of seasons or longer is defined as climate and is studied by climatologists. The underlying physical mechanisms used in GCMs to model atmospheric circulation are those which underlie both weather and climate. The restraints imposed by computing limitations, however, generally prevent GCM runs being sufficiently detailed for confidence in generated weather output. For archaeologists who are interested in past human behaviour, the detail of day to day weather or seasonal weather regimes may be more informative than long time-

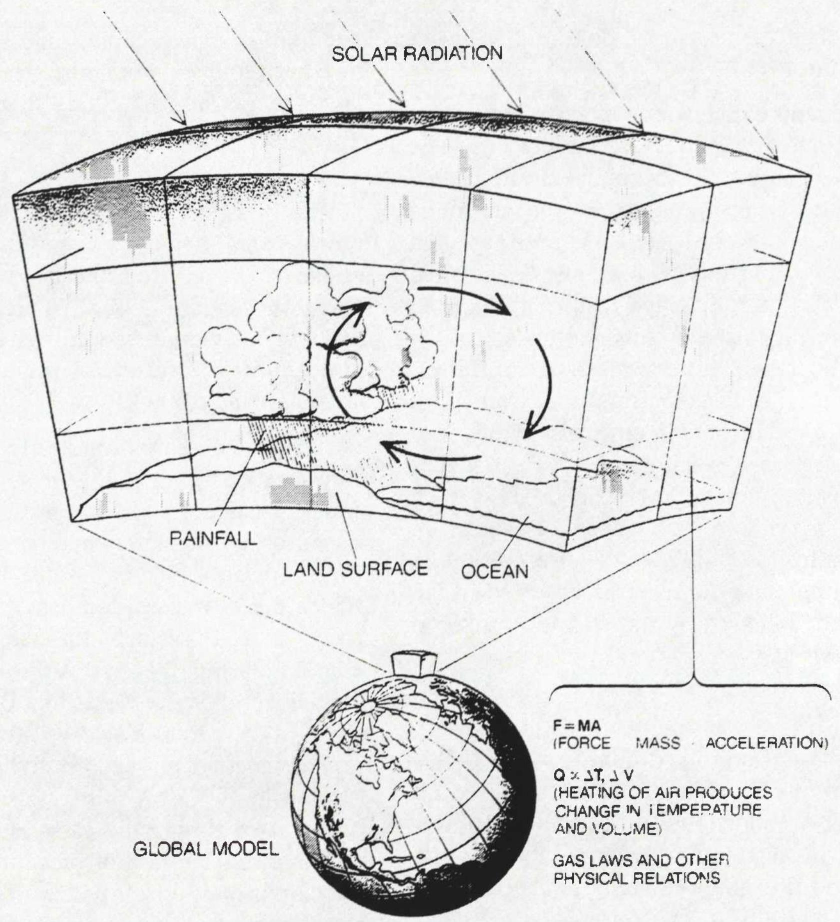

Figure 21.1: GCM Climate Models. Reprinted with permission from Ruddiman and Kutzbach (1991).

span trends on the scale of hundreds or thousands of years. Long-term trends can, however, help us visualise the long-term variation people living in an area had to contend with. Climatologists who are interested in past weather systems are few and far between, as are meteorologists who are interested in past climate systems, yet it is in this interface that information most useful to archaeology is likely to come. Archaeologists need to articulate their need and desire for finer time resolution in palaeoclimate reconstructions. Finer time resolution is an area where we can expect to see great improvement in GCMs over the next few years. These finer scales may be obtainable by using other types of climate models in conjunction with GCM output (e.g. Energy Budget Models or EBMs) or by discovering relationships between weather and climate patterns using statistical techniques.

A short time scale climatic change can have serious consequences for people, even if it is *only* two or three years of sequential flooding or drought. Field data show that climatic change was as common in the past as it is now, and may have had more dire consequences for people with different tool kits (Harding 1982). These short time scales are exceedingly difficult to learn about through GCM models, but some sense of the range of variance, the frequency and magnitude of extremes, and the rates of change can be obtained. GCMs can provide a 'reality check' or an internal consistency check for explanatory theories suggested by archaeologists and involving climatic components. An example of this is provided for the early Holocene period in North Africa.

21.5 Modelling the Holocene in North Africa

Much work has been done on the palaeoenvironments, palaeoclimatology, and archaeology of North Africa making it a useful region in which to explore the archaeology/climate modelling interface. North Africa today is dominated by the vast Sahara Desert where virtually no rain falls. Vast sand seas and rocky, lifeless terrain are the images that come to mind. But 9,000 years ago North Africa was a very different place. The early to mid-Holocene was associated with wetter than present conditions in many parts of the northern hemisphere. Large lakes spread across the North African landscape (Hastenrath & Kutzbach 1983; Street-Perrott & Perrott 1993). Changes in flow carved parts of the Nile valley into a deep uninhabitable channel (Close & Wendorf 1992; Stanley & Warne 1993). Rivers drained water from the southern Sahara into the Nile River (Pachur & Kropelin 1987). Most strikingly, the Sahara seems to have been much more widely covered by Sahelian-type grasslands at the time (Neumann & Schulz 1987; Petit-Maire *et al.* 1991; Ritchie & Haynes 1987). Palaeozoological and botanical evidence indicate the nowbarren landscape once teemed with diverse life forms (Gautier 1987; Hassan 1986).

Both descriptions and explanations of early cultivation and domestication in North Africa are closely entwined with tales of climate change. This is not unexpected given the restrictive climate and environment that people living in North Africa today face. It is interesting that archaeologists who work in this region have been called upon to do double-duty as landscape historians, turning their skills to discovering the environmental history of the region in order to understand cultural history (e.g. Butzer, Hassan, & Wendorf). Archaeologists have worked in close association with researchers in other disciplines who have the same dual role (e.g. Haynes; Petit-Maire; Ritchie). An exhaustive summary of the decades of such work is not in the purview of this paper. Readers are referred to Hastenrath (1991, 437–442). We present in this paper a brief introduction to patterns observed in the archaeological record, followed by the climatic backdrop as elucidated by GCMs.

21.5.1 Archaeology

At the time of the last glacial maximum (c. 18,000 BP) the area now covered by the Sahara desert supported no human life (Close & Wendorf 1990). The Nile in lower Egypt was also not hospitable for living creatures as its channel was deep and floodplain limited. Archaeological evidence of those who lived in North Africa shows settlement concentrations in the Nile Valley of Upper Egypt and areas further south. Subsistence activities focused on fishing, hunting, and gathering a variety of small, quickly reproducing, r-adapted creatures (Close & Wendorf 1990; Gautier 1987).

Archaeological evidence for renewed occupation of the Saharan region by 9,500 BP has been found (Close & Wendorf 1992). People in what is now the central Sahara hunted hare, porcupine, hedgehog, birds, wild sheep, gazelle, and possibly wild cattle. They caught fish in the lakes that then dotted the southern Saharan landscape, gathered wild plants and processed them on grinding stones, utilised blade technologies, and decorated their pottery with a dotted wavy line pattern (Barich 1987). This lifeway seems to have been typical throughout North Africa in the early Holocene (McDonald 1992; Smith 1980) and is known as the 'Early Khartoum' tradition. After gaps in occupation at many sites (variably dated, but generally falling between 8500 and 6000 BP) people reoccupied the Sahara for a second time. In the intervening period their subsistence behaviours seem to have changed from fishing/hunting/gathering to cattle pastoralism. The material culture assemblage associated with reoccupation by pastoralists is known as the 'Shaheinab' tradition.

The earliest actual evidence for domesticated cattle comes from the site of Bir Kiseiba in Southeast Egypt (Close & Wendorf 1992). This is deduced not from skeletal evidence, as domesticated status is morphologically unclear, but the ecological context of faunal remains. In archaeological assemblages large quantities of small animals and small quantities of cattle have been found. No middle-sized or other large animals have been found, suggesting that the environment could not support cattle-sized creatures without human intervention.

There is some evidence for cultivation and perhaps a trend toward domestication of sorghum and millet by around 8,500 BP from the Egyptian site of Nabta Playa (Close & Wendorf 1992). No archaeological evidence for a full agricultural economy has been found prior to the introduction of Near Eastern domesticates (wheat and barley) around 6,000 BP.

Current consensus on early North African cattle domestication suggests that it had something to do with climate change. Some suggest that pastoralism was an adaptation of hunter/gatherers across North Africa to climatic deterioration in the mid-Holocene (Barich 1987). Others agree that pastoralism developed across North Africa at approximately the same time, but argue this occurred during the wet early Holocene. During the following arid phase, places like Dahkla Oasis are thought to have become cultural centres from which pastoralism was transmitted to people living in the Nile Valley (McDonald 1992). A third suggestion is that cattle were domesticated during the early Holocene re-settlement of the Sahara in the face of precarious environments. The idea here is the cattle provided a reliable source of protein in the form of milk and blood (Close & Wendorf 1992). Another scenario is that of mutualism. After early Holocene wet conditions led to a northward spread of Sahel-type grasslands, the climate began to decline and water became scarce forcing human, animal, and plant populations to cluster around remaining bodies of water. Here proximity instigated the long process of cultivation and selection that subsequently ended in domestication. In the 'mutualism' scenario, arid conditions in the mid-Holocene are either thought to lead to domestication, or alternatively to end the first steps in that direction. Climate plays an important role in each of these domestication theories, but they are often in conflict with one another about the direction of climate change and its importance for human populations.

21.5.2 GCMs and North African Monsoons

GCMs can not give us detailed, site-specific information. We are unable to use them to reconstruct the early to mid-Holocene climates of Bir Kiseiba, Nabta Playa, Dahkla Oasis, or anywhere else. They can provide insight into the regional climatic patterns that were prominent in the past and can offer helpful insights into the seasonality, magnitude, and tempo of past climate changes.

GCM runs done with forcing variables set for the amount of solar radiation reaching the earth 9,000 years ago paint a very interesting picture. The main difference between modern and early Holocene solar radiation rests with the date of perihelion, or day earth is closest to the sun, although obliquity of earth's axis and the eccentricity of its orbit were also different (Kutzbach 1981). Currently perihelion falls in Northern hemisphere winter. 9,000

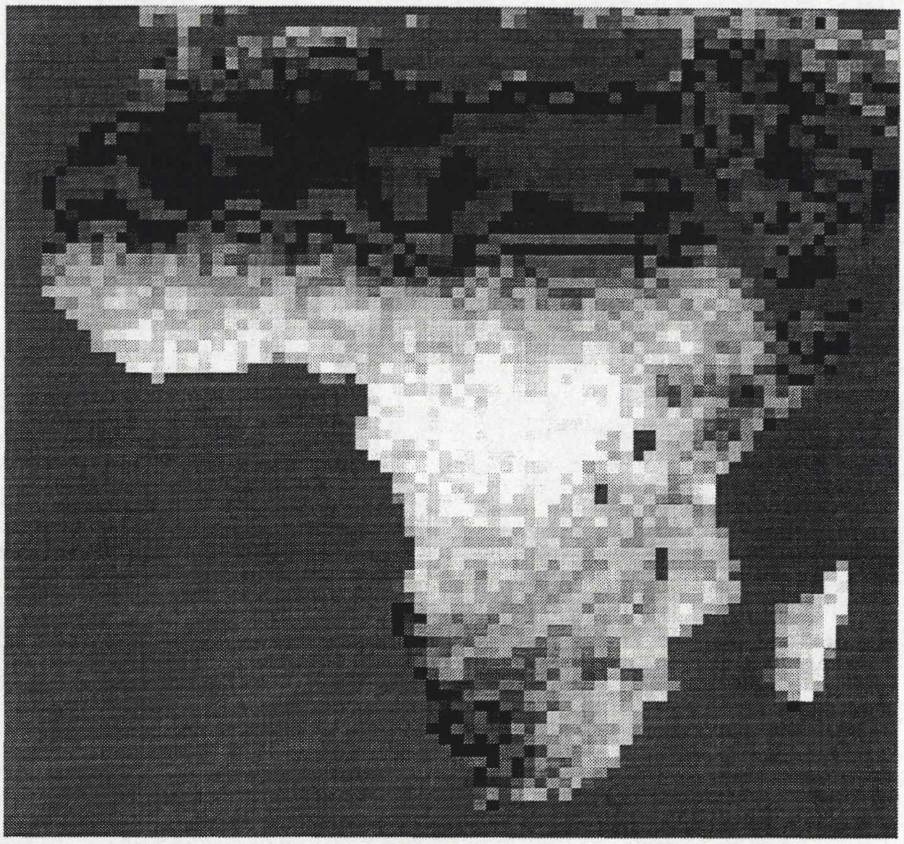

Figure 21.2: Modern Annual Average Evapo-Transpiration in Africa. Lighter areas are more moist and darker areas are more dry (with the exception of the surrounding oceans which unfortunately are dark as well!). Notice hyper-arid core of the eastern Sahara

years ago perihelion was in Northern hemisphere summer, resulting in 7% increased solar radiation reaching the earth in boreal summer and 7% decreased solar radiation reaching the earth in boreal winter. These seasonal variations do not play out the same way on all parts of the globe.

In North Africa, the major climatic control today, like 9,000 years ago, is differential heating of the continental land mass and the Atlantic and Indian oceans. The oceans have a greater thermal capacity than land, and sea surface temperatures respond more conservatively to changes in incoming radiation than do land surface temperatures. In winter the land quickly loses heat while oceans remain relatively warm. In summer, the land heats relatively quickly while the oceans remain relatively cool. These differences in response time underlie the timing and distribution of monsoon rains. The result 9,000 years ago, simulated in GCM runs, is greater precipitation across North Africa in summer as the monsoon rain belt moved northwards, and locally cooler conditions due to increased cloudiness. GCMs tell us that large portions of North Africa probably experienced improved climates at the same time (roughly 12,000–6,000 BP) and for the same global reasons (orbital geometry changes). GCMs have the potential of offering fine enough resolution to address the possibility of a brief mid-Holocene arid phase, but to date computer resource limitations have made such fine-scale modelling runs impractical.

The first advance of people into the eastern Sahara during the Holocene occurred approximately in the centre of the cool, wet climate period c. 9,500 BP (Close & Wendorf 1992). Humans and cattle seem to have been developing the mutually interdependent patterns which result in domestication by this time in the Eastern Sahara. Could several thousand years of improving climates have caused this change? Perhaps so, but it is important to stress that this was a period of improving environment. This contradicts the idea that cattle pastoralism was a response by humans in the early Holocene to increasing aridification. As the earliest evidence for cattle domestication comes from the eastern Sahara, and not from across the entire Saharan region, this suggests that there were important socio-cultural reasons for the adoption of a pastoral subsistence strategy at this time. It should be kept in mind, however, that the eastern Sahara is more arid today than the western Sahara at similar latitudes (see Figure 21.2). If pastoralism spread northwards in Africa with the northward extension of the monsoon rain belt, it could be expected that early pastoral sites would be found farther south than south-western Egypt. This has not been found to be the case. The oldest pastoral sites in the Sudan, for instance, only date back to 9,000 BP (Close & Wendorf 1992).

21.6 Conclusions

GCMs can provide information about why very large scale environmental changes occurred in the past. They can be used to check the consistency of climate-based theories to explain evidence collected from the archaeological record. In areas for which no palaeoenvironmental proxy data are available, GCMs can fill in puzzle pieces. The scalar resolution of current GCMs is not perfect for archaeological applications, but we can look forward to continuing improvement in this area. Also improving is the degree of realism with which natural processes are modelled (e.g. much of the underlying mathematics is presently linear, but refinements are being made).

Change is difficult to incorporate in archaeological computer analyses. The temporal dimension is very elusive. We locate sites in landscapes, noting the elevation at which they sit or their distance from water. If interested in human movement on these landscapes we model friction surfaces or cost surface analyses. We treat landscapes as static backdrops against which humans act and feel and think. If we are truly interested in change through time, we must be willing to look for that change in human behaviour *and* in human surroundings. We need to challenge ourselves to treat the complexities of past landscapes with as much respect as we attempt to treat the complexities of past humans. GCMs provide an example of dynamic computer modelling focused on understanding the scale, timing, and tempo of change.

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