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Sherilyn C. Fritz

University of Nebraska-Lincoln, sfritz2@unl.edu

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The climate of the Holocene and its landscape and biotic impacts

By SHERILYN C. FRITZ*, *Department of Earth and Atmospheric Sciences, School of Biological Sciences, University of Nebraska–Lincoln, Lincoln, NE, USA*

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ABSTRACT

The Holocene Epoch has abundant paleoclimatic archives at relatively high temporal and spatial resolution, which have helped to reveal the patterns of natural climate variation during the present interglacial period and the impacts of that variation on landscapes and biota. This article presents a personal review of some interesting insights that have emerged from analysis of Holocene paleoclimatic records from continental archives at orbital to multidecadal scales. These include how the increased density of sites in Asia, South America and Africa have revealed unforeseen spatial patterns of variation in the dynamics of the monsoon systems at orbital scales and a better characterisation of the magnitude of multidecadal and centennial variation in various parts of the globe. Among interglacial periods, the Holocene is unique as the period in which more complex human civilisations and agriculture developed, and many recent studies have evolved our understanding of the nature of the human impact relative to natural dynamics prior to large-scale population expansion.

Keywords: paleoclimate, paleohydrology, paleolimnology, interglacial, Holocene

This paper is part of a Thematic Cluster in honor of the late Professor Bert Bolin for his outstanding contributions to climate science.

1. Introduction

The Holocene, as the most recent interglacial period and as a time with an abundance of highly resolved paleoclimate archives, presents an opportunity to understand the dynamics of the Earth system during an interval when large continental ice sheets are reduced in size and as precession forcing moves through a complete half cycle. Yet, the Holocene is unique as the period in which more complex human civilisations and agriculture developed, so we have the challenge of disentangling natural dynamics and the evolving human footprint. Here I present an entirely personal view of some of the interesting insights gained from studying the climate of the Holocene and its impacts on people and environmental systems. The coverage of topics is far from comprehensive for such a vast topic, and the choice of papers is selective rather than comprehensive, although in

honour of the Royal Swedish Academy symposium that motivated this review, I tried to include European examples where appropriate. I also focus on continental archives rather than on marine records and emphasise hydrologic variation inferred from lakes and speleothems, because these are the studies that I am most familiar with.

2. Holocene climate

Considerable attention has been directed to understanding which of the past interglacials is the best analogue for the Holocene (Tzedakis et al., 2009), in part to evaluate the magnitude of the human impact on greenhouse gas concentrations in prehistory relative to natural variation (Ruddiman, 2003). Both Marine Isotope Stage (MIS) 11 and 19 have patterns of insolation variation that are similar to those of the Holocene (MIS1), but the higher greenhouse gas concentrations of MIS11 suggests that MIS19 may be the best Holocene analogue (Yin and Berger, 2012).

*Correspondence.
email: sfritz2@unl.edu

The Holocene provides the opportunity to study how the hierarchy of linked ocean–atmospheric dynamics shifts as the Earth system undergoes transition from a world dominated by massive continental ice sheets to one where ice sheet extent in the northern high latitudes and alpine regions was reduced. Orbital variation has had pronounced impacts on atmospheric circulation patterns and hence on Holocene temperature and/or precipitation patterns, although with considerable variability in magnitude and rate dependent on the inherent sensitivities of different regions and different climatic archives. At the onset of the Holocene, summer insolation was maximised in the mid to high latitudes of the Northern Hemisphere, with pronounced impacts on organisms and environments. Early Holocene summer temperatures that were warmer than those of today produced thinning at the margins of the Greenland ice sheet (Vinther et al., 2009), as well as ice melt in the Canadian Arctic and increased summer temperatures in Norway (Bradley, 2000). The migration northward of the treeline in multiple parts of Eurasia (MacDonald et al., 2000) and to higher elevations in the mountainous areas of central Sweden (Bradley, 2000) also suggests warmer early Holocene summer temperatures.

The half insolation cycle from the early to late Holocene had profound impacts throughout the globe on both climate and ecosystems. In North America, changes in insolation are associated with massive changes in the intensity and duration of drought, although the onset of extreme aridity was spatially variable, because of the interaction of insolation with the waning Laurentide ice sheet in affecting regional atmospheric dynamics (Fritz et al., 2001; Williams et al., 2010). None-the-less throughout the continental interior of North America, extreme aridity was widespread during the mid-Holocene (Fritz et al., 2001; Stone and Fritz, 2006) as a result of insolation driven enhanced anticyclonic activity aloft and reduced low-level moisture content (Diffenbaugh et al., 2006).

In regions with strong monsoon circulation, changes in summer insolation during the Holocene are associated with pronounced variability in precipitation. Early Holocene oxygen isotopic values in speleothems throughout the Asian monsoon domain show a secular trend from more depleted values in the early Holocene to more enriched values in the late Holocene (Burns et al., 2001; Fleitmann et al., 2003; Wang et al., 2005), although the relative roles of changes in precipitation amount, seasonality, source, or pathway in affecting isotopic values are debated (Dayem et al., 2010). Lacustrine stratigraphic records in regions affected by the Asian monsoon system generally show high lake levels in the early Holocene and subsequent decline, but the onset and rate of lake-level decline are variable spatially, with a possible east to west gradient in the onset of mid-Holocene drying (Morrill et al., 2003; Chawchi

et al., 2013). With continued increase in the number of Holocene paleoclimatic records from the region, discrete spatial patterns are likely to emerge, which may enable us to disentangle variation in the different components of the Asian monsoon system, whose interaction was likely highly complex in the past, as it is today (Wang, 2006).

In parts of tropical Africa, precipitation also increased in the early to mid-Holocene, which produced the well-documented greening of the Sahara and Sahel (Hoelzmann et al., 1998), the expansion of large lakes in what are now desert areas of North Africa (Gasse, 2000), and higher lake-levels throughout East Africa (Verschuren et al., 2009; Tierney et al., 2011; Berke et al., 2012) and west-central Africa (Schefuss et al., 2005; Shanahan et al., 2006). In contrast, during the Holocene, sites in south-eastern Africa ($>10^\circ$ S) were anti-phased with sites to the north (Castaneda et al., 2007). In North Africa, increased early to mid-Holocene precipitation was driven by higher insolation in boreal summer, as well as by sea-surface temperature (SST) gradients in the North Atlantic, which enhanced moisture transport into the continent (Kutzbach and Liu, 1997; Zhao et al., 2006). A variety of land-surface feedbacks likely also amplified precipitation increase (Kutzbach et al., 1996; Krinner et al., 2012). In East Africa, recent empirical studies and modelling suggest that insolation forcing influenced precipitation variation by affecting zonal moisture flux from both the Atlantic and Indian Oceans and its seasonal intensity (Tierney et al., 2011; Berke et al., 2012). The insolation-driven warm wet African Humid Period ended in the mid to late-Holocene, and the increased number of paleoclimatic records in recent years has made the variability in the timing and rate of its termination apparent (Kropelin et al., 2008; Verschuren et al., 2009; Berke et al., 2012).

Tropical South America also is influenced by a synoptic-scale monsoon circulation known as the South American Summer Monsoon (SASM) (Zhou and Lau, 1998). In the mid-Holocene, precipitation was reduced in the heart of the SASM domain (western Amazonia and tropical Andes, south-eastern Brazil) as a result of reduced insolation in the austral summer, as well as weakened tropical Atlantic SST gradients that affected the transport of moisture into the continent in low-level winds (Baker et al., 2001; Baker et al., 2005). Interestingly, recent speleothem records have demonstrated an east to west anti-phasing of precipitation on orbital scales during the Holocene, such that the Brazilian Nordeste in the eastern tropics was wet during the early to mid-Holocene, possibly because of intensification of the Nordeste low in the upper troposphere during insolation minima and the resultant reduction in subsidence (Cruz et al., 2009). On orbital scales, precipitation variation in the northern and southern tropics of South America also was anti-phased during the Holocene. In the

north, precipitation was higher in the early Holocene and decreased subsequently, because of changing seasonal insolation and its effects on the mean annual latitude of the maritime Atlantic ITCZ (Haug et al., 2001; Hodell et al., 2008).

In addition to these secular shifts in temperature and precipitation, the increasing number of high-resolution records enables higher frequency variation in climate to be reconstructed, including multidecadal and centennial variation that may be driven by SST variation, solar or volcanic activity, and other modes of ocean–atmosphere interaction. An increasing number of studies show millennial scale variation that is similar in pacing to the so-called Holocene Bond cycles (Bond et al., 2001), including temperature and precipitation reconstructions from diverse geographic regions (Wanner et al., 2011). Yet it is difficult to establish whether or not these modes of millennial variation are correlated or are a product of common forcing mechanisms, because of the difficulty of establishing firm chronological control. None-the-less, spatial networks of sites can enable us to search for common patterns of response, which are evident, for example, in continental regions bordering the North Atlantic at the time of the 8.2 ka cooling event (Seppa et al., 2007) and in the continental interior of North America near the time of collapse of the Laurentide ice sheet at 8.4 ka (Williams et al., 2010). Even if the degree of coherence in timing and forcing is uncertain, it is apparent that the magnitude of natural multidecadal to millennial scale climate variation is considerable. For example, in the tropical Andes, the magnitude of multidecadal to centennial scale precipitation variation during the last 4000 yr is $\pm 15\%$ over the long-term mean, which can have significant impacts on landscapes and humans (Baker et al., 2009).

One unrealised potential of the paleoclimatic record is to explore how the hierarchy of climate forcing varies under different mean states. Even within the instrumental record, modes of climate variation are not stationary (Garreaud et al., 2009), and the same is true of longer time scales. A classic example is the Laguna Pallcacocha record from Ecuador (Rodbell et al., 1999), which suggests that some aspect of ENSO was intensified during the last ~ 5000 yr, although more recent coral records do not show a systematic trend in ENSO variance (Cobb et al., 2013). The non-stationary nature of high-frequency dynamics is characteristic of other modes of variation; for example, there are several studies from western North America that suggest that multidecadal climate variation may have been more characteristic of the mid-Holocene than in the periods prior to or subsequent to that (Friddell et al., 2003; Stone and Fritz, 2006).

3. Impacts of climate on landscapes and people during the Holocene

Holocene stratigraphic records also provide insight into how landscapes and organisms, including humans, have responded to or been affected by climate change. Pollen records have been used to track the pattern and rate of expansion of tree populations following the retreat of continental ice sheets. These studies have provided insights into the migration rates of trees and plants in response to warming and the role of different dispersal characteristics and life-history strategies in affecting those rates (Davis and Shaw, 2001). Such studies have been integrated with climate model predictions of future climate change to evaluate whether or not major tree populations are likely to be able to disperse rapidly enough to suitable habitat in the face of global climate change. Recent studies have combined paleoecological data with analyses of the genetic composition of modern tree populations in different parts of their range (McLachlan et al., 2005; Cheddadi et al., 2006; Anderson et al., 2011). These studies suggest that many major tree species may have persisted in small isolated populations near the ice sheet margins, which then expanded as the ice sheets melted. This implies that migration rates of trees may be considerably lower than those estimated from networks of pollen data. These studies also are helping to evolve our understanding of the role of refugia in the evolution of modern biogeographic patterns and in shaping contemporary genetic diversity.

The paleoecological record also has been used to estimate the frequency and impacts of major disturbances, such as fires, wind storms (Foster and Boose, 1992), and pathogens (Peglar, 1993; Bhiri and Filion, 1996). In particular, the analysis of charcoal in lake sediments to reconstruct the history of fires has expanded greatly in the last decade or so, and a global network of charcoal studies (Power et al., 2008) has helped to evolve our understanding of the complex interactions among climate, fuel, and fires in shaping the landscape (Whitlock et al., 2008; Ohlson et al., 2011). These paleoecological data also yield a long-term perspective on the magnitude of human use of fire relative to natural background levels at both regional and global scales (Marlon et al., 2008; McWethy et al., 2010), as well as the extent to which massive 20th century wildfires may be related to 20th century climate change (Hu et al., 2010).

Certainly a defining feature of the Holocene is the development of complex human cultures that resulted in the origins of agriculture and expansions of Neolithic settlers across Europe (Thorpe, 1996; Hodder, 2006), which fundamentally transformed the landscape (Goudie, 2006). Human activities have affected biogeochemical

cycling at the Earth's surface for millennia (Martinez-Cortizas et al., 1999; Renberg et al., 2000), including hypothesised influences on atmospheric composition (Ruddiman, 2003), and it is clear that in many regions the cultural footprint has pushed environmental dynamics into states very different from those prior to population expansion (Dearing, 2008).

4. Conclusions

The Holocene Epoch has abundant paleoclimatic archives at relatively high resolution, which have helped to reveal multidecadal to multicentennial variability that is a recurrent part of the climate system. In a number of regions, a relatively high spatial density of sites has revealed new insights into the spatial patterns of climate variation that is helping us to refine our understanding of how the climate system works at long temporal scales and of the differential sensitivity and response of environmental systems to climate change (Russell et al., 2007; Fritz, 2008; Shanahan et al., 2008; Cruz et al., 2009).

In many cases, Holocene paleoecological records suggest that natural ecosystems are resilient and able to adapt to the natural variability of the climate system. But clearly in many parts of the world, humans have greatly changed the configuration of multiple aspects of the Earth system and in doing so have affected the ability of the environment to buffer the impacts of climate change. Arguably in many parts of the world, natural resources and social systems are not managed in a sustainable fashion, even given the magnitude of natural variation, let alone the potential consequences of human-induced environmental change. In any case, in recent decades, the community has generated a large number of high quality and highly resolved records of Holocene environmental variation. The time is ripe for additional large-scale syntheses of spatial and temporal patterns, which can then be linked to models to more fully evolve our understanding of both patterns of change and the mechanisms that produce it.

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