Global Land Use and Technological Evolution Simulations to Quantify Interactions Between Climate and Pre-industrial Cultures

Carsten Lemmen, Kerstin Haberkorn, Richard Blender, Klaus Fraedrich and Kai W. Wirtz

Abstract To understand the two-way interaction between past societies and Holocene climate, we conduct a series of integrated model- and data-based studies. The climate-culture feedback is investigated using a coupled Earth System Civilization Model, including a new methodology to incorporate proxy information into an Earth System Model. Our study reconstructs the transition to agriculture for Western Eurasia in the paleoclimatic context; it shows that migration is not a necessary prerequisite for this transition, which is a yet unresolved problem in European archeology. Climate variability and extreme events had no significant impact, which reflects societal resilience. Also, our simulation studies indicate a considerable range of global and regional carbon emissions by deforestation. In conclusion, we find on the one hand a lower sensitivity of past societies to changes in Holocene climate than frequently suggested, on the other hand a possibly larger influence of those societies on regional and global climate.

Keywords Neolithic transition · Preindustrial cultures · Earth system model · Sociotechnological model · Anthropocene · Proxy integration · Adaptation · Carbon emission

1 Introduction

Key questions of Holocene climate and its interaction with pre-industrial cultures are: How much did climate variability determine where and when agriculture appeared or cultures disappeared? When did humans start to interfere with and how

C. Lemmen (✉) · K.W. Wirtz
Institute for Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany
e-mail: carsten.lemmen@hzg.de

C. Lemmen
C.L. Science Consult, Lüneburg, Germany

K. Haberkorn · R. Blender · K. Fraedrich
Meteorological Institute, University of Hamburg, Hamburg, Germany

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much did they disturb global and regional carbon and hydrological cycles? When did the anthropocene begin (Kaplan et al. 2011)? To understand the two-way interaction between past societies and Holocene climate defines a challenge for transdisciplinary research and for testing controversial hypotheses of a middle Holocene influence of humans on climate.

We addressed these questions by using an interactively coupled model system composed of a cultural adaptation model [Global Land Use and technological Evolution Simulator, GLUES (Lemmen and Wirtz 2010, 2012; Lemmen et al. 2011)] and an Earth System Model [Planet Simulator, PLASIM (Haberkorn 2013; Haberkorn et al. 2012)]. Cultural feedback on climate is implemented by land surface changes. The realism of the interactive simulation of climate and culture is improved by constraining the climate model with temperature and precipitation proxies, and by constraining the cultural model with archeological data compilations and vegetation proxies indicative of human land use. Abrupt climate changes are included based on globally available time series of proxy-derived climate variability (Wirtz et al. 2010). Models and data employed in our study cover the period 11.5 thousand years (ka) before present (BP) to 3 ka BP and are global in scope. Carbon emissions are evaluated regionally, and the sociotechnological model is validated against regional archeological data for Northern Central Europe and South Asia.

We propose to integrate the dynamic anthroposphere into today's state-of-the-art Earth System Models (ESM) as a prerequisite to better understand current human-climate interaction and adaptation to ongoing climate change. Current and anticipated users of our work are paleoclimate and paleovegetation modelers, paleoclimate variability analysts, archeologists, and agricultural economists.

2 Materials and Methods

A large data set of 235 long-term (>4,000 years) and high-resolution (mostly <100 years) time series of climate information have been collected from the literature and Interdynamic partners. Based on a change-point analysis, we partitioned the Holocene into slightly overlapping periods, the early Holocene (11–5 ka BP) and late Holocene (6–0 ka BP). For each interval, we evaluated each proxy time series for statistically significant periodic signals, using very strict and data-adaptive thresholds for significance.

For simulations, we chose the PLASIM (Haberkorn 2013; Haberkorn et al. 2012) ESM which can be used to run climate simulations for multi-millennial time scales in acceptable real time while relying on a fully dynamic core; it also offers different vegetation couplers (Haberkorn 2013 and Fig. 2). We performed full Holocene transient simulations at T21 and T42 resolutions with orbital, greenhouse gas (GHG) forcing, and climatological sea-surface temperature (SST). A novel scheme was devised to reconstruct past SST from the sensitivity of land temperature to SST diagnosed from a comparison between present day climate and present day proxy climate. Socio-ecological adaptations to climate change are modeled with GLUES (Lemmen et al. 2011; Wirtz and Lemmen 2003); and the land-use feedback on population is simulated by overexploitation of land and resources. Characteristic traits of technology, substance, and economic potential exhibit adaptation and continuous innovation (Lemmen 2014).

Paleovegetation and paleoclimate forcings of GLUES, expressed as net primary production and growing degree days, are derived from PLASIM. After successfully testing vegetation fields (Haberkorn 2013), we ran GLUES to obtain socio-technological trajectories for regional subdomains, worldwide and over the entire Holocene.

3 Key Findings

The average size of regionally coherent climate variability derived from paleoclimate proxies is around 3,000 km; it significantly increased over Western South and North America, and decreased over the Arabian Sea and the Southwest Asian monsoon region. Centennial (but not millennial) scale variability decreased over the North Atlantic: this reinforced our earlier hypothesis (Wirtz and Lemmen 2003) that regional climate variability may have led to unequal probabilities for crises in early human civilizations in the Old and the New World.

The high-resolution vegetation distribution during the 6 ka BP time slice, based on the PLASIM climate, reveals generally deciduous and temperate vegetation types in Western, South and Central Europe (Fig. 1). Such a high-resolution vegetation reconstruction can improve the prediction of suitability of the land for past agricultural activities (Kaplan et al. 2011).

We successfully reconstructed a North Atlantic SST that—taken as a boundary condition for PLASIM—replicates the terrestrial temperature (i.e., the temperature relevant to societies) in Central Europe as represented by a high-resolution lake proxy. This novel method applies an inverse modeling algorithm to nudge the simulated land temperature in the climate model to a proxy-reconstructed temperature; its central element is the inverse climate sensitivity in Central Europe to North Atlantic SST anomalies (Haberkorn 2013; Haberkorn et al. 2012). We can now provide past SST fields that are in agreement with reconstructed land temperature, thus allowing the reconstruction of a dynamically consistent European climate throughout the Holocene.

We calculated the prehistoric GHG emissions from anthropogenic land use; we produced estimates for land demand for crops (Gaillard et al. 2010) and associated carbon emissions (Lemmen 2010) for the Holocene. Calculated emissions (world total 30 Gt by 4 ka BP from deforestation) could not have contributed to a significant warming. By considering past technological inefficiencies, however, we arrived at much larger emissions on the order of 340 Gt by 100 years BP (AD 1850) (Kaplan et al. 2011), consistent with the stable carbon isotope signature from ice cores. Thus, our two studies provide extreme low and high estimates of the possible

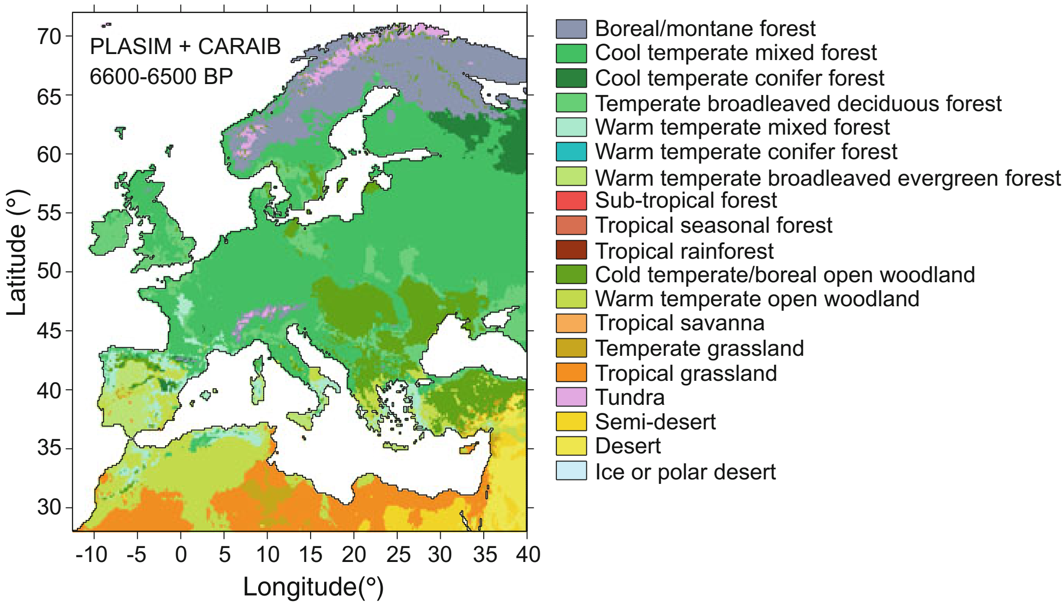

Fig. 1 European vegetation distribution for 6 ka BP, simulated by the high-resolution vegetation model CARAIB forced with PLASIM climate

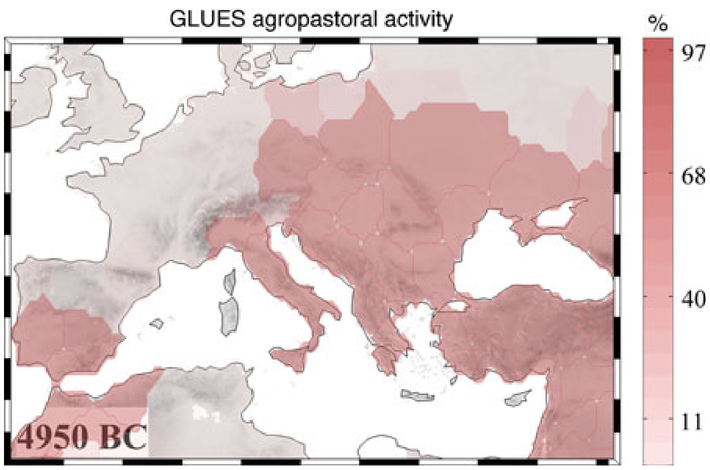

Fig. 2 Fraction of agricultural activity versus foraging subsistence at a critical transition time (6,900 years BP/4950 BC), when the GLUES-simulated frontier between farmers and foragers ran across central Europe

range of anthropogenic activities, and the Early Anthropocene hypothesis (Kaplan et al. 2011; Lemmen 2010).

Simulations of the transition to agriculture (Fig. 2) agree with archeological site data across Western Eurasia within a model uncertainty of ± 500 years (Lemmen and Wirtz 2012; Lemmen et al. 2011). Thus, GLUES is able to realistically simulate the onset of agriculture not only on a global scale as previously reported (Wirtz and

Lemmen 2003) but also within the broader region of Europe and the Mediterranean. For the first time, a numerical model shows that the transition to agriculture can also be explained by information exchange, rather than migration (Lemmen et al. 2011).

Climate events may not have been as important for early sociocultural dynamics as endogenous factors. This could be demonstrated by using idealized climate events (Wirtz et al. 2010) to disturb societies in GLUES. Time-series anomalies were spatially weighted to assess the regional impact of abrupt climate excursions (Lemmen and Wirtz 2012); climate induced population decline can lead to loss of knowledge, and could impact regional technological development. Typical observed lags between cultural complexes were simulated only by a simulation which included climate extremes (Lemmen and Wirtz 2012; Lemmen et al. 2011).

The reason for the vulnerability of several societies to climate changes is their cultural specialization, that is, the restriction to only few different subsistence economies. Continuous maintenance of a diverse pool of technologies played an important role in determining the resilience of Neolithic populations to changing climates. In conclusion, past cultural and sociotechnological changes appear much less determined by Holocene climate variability than often suggested in the literature, while the influence of past agriculture on the global carbon cycle may have been larger than previously thought.

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