Studying Africa's hydroclimate history over the last 2000 years¹

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Water-resource availability is one of the most important environmental factors on which Africa's agricultural societies are reliant. However, our knowledge of the natural background variability of rainfall and drought over Africa is currently still inadequate to allow a full grasp of the relevant climate-dynamical mechanisms and guidance of much-needed forecasts of future trends. This report presents two new efforts to improve insights into how hydroclimate has varied throughout the continent over the past two millennia. Firstly, a thorough synthesis of data from instrumental measurements, historical accounts and natural climate archives resulted in an extensive review of Africa's hydroclimate history. Secondly, the focus is narrowed to East Africa, where the sediments of hypersaline Lake Bogoria were used to reconstruct how a variable climate has driven large lake-level fluctuations over the last 1,300 years.

Key words: paleoclimatology, natural climate archive, lake-level change, sedimentology, Lake Bogoria National Reserve

Reviewing African hydroclimate change over the past two millennia

From the deserts of northern and southern Africa to the humid forests of the Congo Basin, Africa is characterized by a wide range of hydroclimate regimes (Nicholson, 2000). The livelihoods of a large part of its agricultural population are intimately linked to water-resource availability, and gravely affected by extreme events such as droughts and floods. Anticipation of future rainfall trends under anthropogenically-driven climate change is thus of utmost importance. However, whereas the mechanisms of global warming over the next century and beyond are well understood, and its expected magnitude in individual regions can be modeled with reasonable confidence, precipitation projections are inherently more uncertain (Rowell, 2012). At the moment, robust climate forecasting at spatial and temporal scales relevant to human societies is far from evident (e.g., for East Africa; see below). There is still a gap between climate science capabilities and end user needs, which needs to be closed if local governments and economies are to strategically prepare for the future (WCRP-ICPO 2011). The need for better characterizing

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(AD 900–1250), the Little Ice Age (AD 1250–1750) and the period of anthropogenic global warming during the most recent decades. A number of prominent spatial and temporal patterns of rainfall and drought are revealed, despite the limitations of a patchy geographical coverage and less-than-optimal data resolution. The resulting continent-wide synthesis of regional hydroclimate trends through time allows consideration of possible driving mechanisms and makes important suggestions for future research.

Lake Bogoria: a new hydroclimate record from the Central Kenya Rift Valley

In addition to reviewing the hydroclimate history of the entire African continent, new data on past moisture-balance changes in East Africa were produced. Much of tropical East Africa is characterized by a semi-arid or even arid climate regime, receiving relatively low amounts of total annual rainfall in combination with great inter-annual variability (fig. 1). More humid conditions are almost exclusively restricted to the interior highlands. Consequently, the ecosystems and societies of equatorial East Africa have traditionally been subject to low and irregular water-resource availability. Over the past decades, a series of droughts has highlighted the endemic vulnerability of the vast drylands of Kenya, Uganda, Ethiopia and Somalia to failing rains, with dramatic outcomes for the area's inhabitants. This was demonstrated again in 2011 by a severe famine in the Horn of Africa, affecting more than 13 million people (Hillier and Dempsey, 2012; Nicholson et al., 2014). The drought in central and eastern Ethiopia earlier this year also demanded significant humanitarian assistance (FEWS Net, 2016). The history of East African countries has been punctuated by drought-related famine for as long as historical sources are available, often with huge tolls on livestock and human life. Recorded crises

are obviously biased toward the last century, but a number of events has been traced back from written sources, most extensively for Ethiopia where limited evidence goes back to around the start of the CE (Webb and von Braun, 1994; Wolde-Georgis, 1997). Despite improvements in food-relief systems since the end of the 20th century (Graham et al. 2012), the challenge faced by these countries is to develop a sustainable agricultural economy in a future of climate change, growing demographic pressure and naturally scarce land and water resources. Severe, recurrent drought is one of the principal environmental hazards in the region. However, accu-

Figure 1: Map of Africa, with records informative of hydroclimate during the past 2,000 years. Background colouring follows the Global Aridity Index (Trabucco and Zomer, 2009), where higher values indicate more humid conditions

rately predicting 21st-century hydroclimate trends in East Africa under anthropogenic global change is still very problematic. The future of this vulnerable region is highly uncertain, as several studies have produced contradicting results in trying to delineate expected 21st-century rainfall patterns (e.g., Funk *et al.*, 2008; Shongwe *et al.*, 2011; Williams and Funk, 2011; Cook and Vizy, 2012; Niang *et al.*, 2014). The absence of a consensus on even the sign of probable future precipitation trends illustrates the need for a better understanding of the dynamics that drive East African rainfall (Rowell *et al.*, 2015). This requires additional studies on the natural variability in the region, to which newly developed paleoclimate records can make an important contribution.

Lake Bogoria is one of the few lakes in the Kenyan lowlands that have survived relatively recent intense droughts, making it one of the precious rare sites where an intact sediment archive going back further than just one or two centuries can be recovered (De Cort *et al.*, 2013). It is situated in the Central Kenya Rift Valley, 25 km north of the equator, and is classified among the ‘soda lakes’ of East Africa, characterized by high salt content (with Na⁺, CO₃²⁻, HCO₃⁻ and Cl⁻ as major ions) and high pH. Its hydrochemistry is further influenced by numerous hot springs above and below the present-day water surface (Tiercelin *et al.*, 1987). In 2014, the maximum depth of Lake Bogoria was measured to be 16 m, with lake-level elevation at c. 996 m above sea level. Along its north-south oriented longitudinal axis, the lake is divided in three depositional basins of varying area and depth (Tiercelin *et al.*, 1987; Hickley *et al.*, 2003). The shallow northern basin is connected with the largest and deepest central basin (fig. 2) by a narrow passage across the relatively high north-central sill. A similarly narrow but lower central-south sill leads to the southern basin, which is much smaller in surface area than the central basin but nearly as deep. The largest inflowing river system, the Sandai-Waseges, drains two-thirds of the lake’s catchment (Tiercelin *et al.*, 1987; Renaut and Tiercelin, 1994) and flows into Lake Bogoria from the north. The unique ecosystem of Lake Bogoria and the adjacent areas of its catchment are protected as the Lake Bogoria National Reserve, well known for the large numbers of flamingos feeding in the lake’s productive waters. The upstream drainage basin, however, is situated beyond the reserve boundaries and hence susceptible to greater human impact.

Sediment cores from five key positions in Lake Bogoria were used to reconstruct its history of depositional and hydrological changes. Cores were collected from the deepest points of the three lake basins and from the crests of the sills separating them, ranging in length from 1.2 to 3 m. Sedimentological, geochemical and mineralogical composition of the cores was determined through a range of laboratory analyses including loss-on-ignition, granulometry, X-ray diffraction, charcoal counting and high-resolution scanning of magnetic susceptibility and X-ray fluorescence. To assign ages to the observed compositional variations, radiocarbon dating of carefully isolated charcoal remains was employed, supplemented by ²¹⁰Pb dating of the most recent deposits. A detailed set of chronologically equivalent tie points between the high-resolution proxy time series of the five sequences allowed transfer of dates between the basins, enabling inter-basin comparison of sedimentation dynamics through time. The sediment-core data, which

concern past deposits and thus represent past conditions, were supplemented with information on present-day sedimentation dynamics through deployment of sediment traps, which were installed in the water column of the lake and were sampled seasonally over the period of one full year.

The obtained multiproxy data, in combination with the spatially heterogeneous distribution of consecutive sediment units at different positions in the lake, allowed a reconstruction of at least partially hydroclimate-driven variability in sedimentation dynamics and lake level over the past 1,300 years. Importantly, the results demonstrate hydrological variability over this period far beyond the fluctuations documented throughout the 20th century. Between approximately AD 690 and 950, Lake Bogoria stood almost completely dry. In the sediment record of the central basin, this resulted in episodic deposition of trona, a sodium carbonate salt that precipitates following evaporative concentration of hypersaline brines under concentrations of CO₂ in equilibrium with the atmosphere (fig. 3a; Eugster and Jones, 1979). Between c. AD 950 and 1100, slightly increased water levels allowed the build-up of high pCO₂, leading to precipitation of nahcolite instead of trona (fig. 3b). Overall, Lake Bogoria was still very low during this period, with the central and south basins containing separate brine pools and maximum inferred water level still c. 14.5 m below the 2014 position. Afterwards, Lake Bogoria experienced a pronounced highstand between c. AD 1100 and 1350, with the first connection of the three basins since the start of the record, only to recede again afterwards. For most of the time between approximately AD 1350 and 1800, the northern basin was probably disconnected from the joint central and southern basins. During the last two centuries, finely laminated sediments suggest a deep, stable water column, indicating that lake level has uninterruptedly been relatively high over this time period (fig. 3c). This has important implications for local agriculture, which already relies heavily on irrigation schemes that draw water from nearby wetlands. The sediment record of Lake Bogoria suggests that severe, decadal-scale drought greatly exceeding the 20th-century range is inherent to the area and could therefore be expected to occur again in the future. Long-term water and agricultural management plans should incorporate the accumulating knowledge on this climate-driven water-resource variability.

Figure 2: Lake Bogoria's central basin, as seen from the western shore (Photo by Gijs De Cort)

Additionally, we found evidence for substantially increased sediment supply in recent decades due to anthropogenic soil erosion around the headwaters of the Sandai-Waseges River. Problematic land degradation and its adverse effects on lake ecology have extensively been described for nearby Lake Baringo (Anderson, 2002; Hickley *et al.*, 2004), but our research presents the first evidence that similar processes are taking place in the catchment of Lake Bogoria. This is a reason for concern, and more research is needed to better document these developments and their implications for Lake Bogoria's unique ecosystem.

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Figure 3: An illustration of the variation in the sediment composition of Lake Bogoria. a: Trona deposits attest to near-complete desiccation of the lake. b: Abundant nahcolite precipitation suggests a shallow and hypersaline brine pool rich in CO₂. c: Finely laminated clays indicate a deep, stable water column during the past two centuries.

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