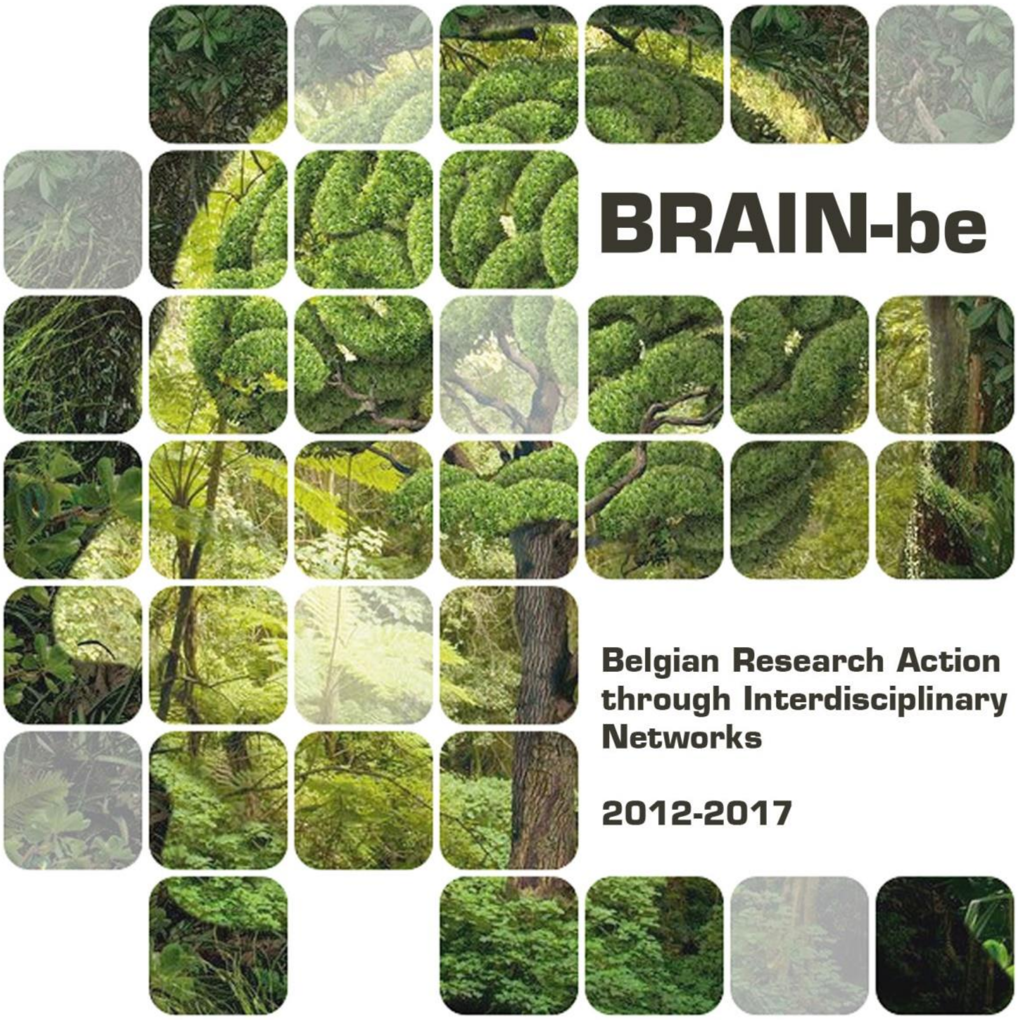

PAMEXEA

Patterns and mechanisms of climate extremes in East Africa

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BRAIN-be

Belgian Research Action through Interdisciplinary Networks

2012-2017

NETWORK PROJECT

PAMEXEA

Patterns and mechanisms of climate extremes in East Africa

Contract - BR/121/A2

FINAL REPORT

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Published in 2021 by the Belgian Science Policy Office
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Verschuren D., Goosse H., Mees F., Cocquyt C., De Cort G., Klein F., Ryken E., Van der Meeren T., Levine R., Odongo, V. O., Graham, N. E., Becht, R., ***Patterns and mechanisms of climate extremes in East Africa***. Final Report. Brussels : Belgian Science Policy Office 2020 – 33 pp. (BRAIN-be - Belgian Research Action through Interdisciplinary Networks)

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ABSTRACT

Context. Catastrophic droughts afflicting the Horn of Africa in recent years highlight the heavy impact of a variable climate on the region's vulnerable populations and socio-economic systems; and the enormous challenge to develop a sustainable agricultural economy in a future of climate change, growing demographic pressure and naturally scarce water resources. Most worrying is the uncertain impact of climate change on regional freshwater resources, due to incomplete understanding of the effects of a warming atmosphere on the region's hydro-climate. Global climate-model (GCM) simulations underpinning current IPCC prognoses for East Africa have insufficient spatial downscaling to guide the water-resource planning needed by developing economies to prepare for the future.

Objectives. Applying the powerful 'the past is the key to the (present and) future' approach, PAMEXEA aimed to improve understanding of climate trends and extremes in East Africa at multiple time scales as foundation for appropriate water-resource management in both dry and wetter regions of East Africa. Specifically, we aimed to find out how processes of natural climate variability at inter-annual, decadal and centennial time scales may interact with anthropogenic climate forcing to create future trends in rainfall and drought. In addition we aimed to place the current magnitude of human demands on East Africa's natural resources in a proper long-term context by reconstructing the history of anthropogenic impact on the region's aquatic and terrestrial environments. PAMEXEA consisted of distinct work packages (WPs) focusing on i) the quality screening and compilation of existing climate-indicator ('climate-proxy') data, ii) new hydro-climate (i.e., moisture-balance) reconstructions from carefully selected African lake-sediment records, iii) long-term hydrological and ecological monitoring of lake systems targeted for sediment-based climate reconstruction, iv) hydrological modelling of those lake systems to assess their sensitivity to hydro-climate change, and v) testing the ability of existing climate models to replicate the temporal and spatial patterns of past hydro-climate variability.

Originally focused on equatorial East Africa and on the last 2000 years, exquisite lake-sediment records obtained through international collaborations allowed expansion of the project's scope to include also the Sahara desert of North Africa and the major, century-scale climate extremes which have impacted both East and North Africa throughout the Holocene period (the last 11,650 years). These century-scale droughts epitomise how 'abrupt' climate change and climate extremes have impacted on pre-industrial societies in arid and semi-arid tropical regions worldwide, and may do so again in the future.

Results and Conclusions. Field- and lab-based PAMEXEA activities produced new high-resolution hydro-climate reconstructions from five lakes: Bogoria in central Kenya (the last 1300 years), Chala in south-eastern Kenya (2200 years), Nasiki Engida in south-western Kenya (2800 years), Ounianga Serir in northern Chad (4200 years) and Rutundu on Mt. Kenya (18,000 years). We also upgraded the existing reconstruction from Lake Naivasha in central Kenya (1650 years) using new palaeo-hydrological proxies and age-modelling. Using our hydro-climate reconstructions from lakes Naivasha, Bogoria and Chala as reference frame, we also reconstructed the history of ancient and historical human impact on the landscape of central and south-eastern Kenya in relation to the magnitude of natural aquatic and terrestrial ecosystem dynamics. The principal new insights of this part of the PAMEXEA project are that **I**) the multi-decadal events of severe drought which occurred

~8200, ~4200 and ~2900 years ago and were felt across tropical Africa were pulsed negative rainfall anomalies superimposed upon a long-term trend of gradual Holocene drying, not (as widely believed) abrupt transitions between two contrasting climate states before and after the events; **II**) when viewed over the entire Holocene period, driest climatic conditions occurred ~2900 years ago in East Africa and ~4200 years ago in North Africa; **III**) human impact on the landscape (i.e., on terrestrial vegetation) of equatorial East Africa becomes noticeable from between ~900 and ~250 years ago with early appearances mostly limited to areas with above-average population density; and **IV**) human activity has become the principal driver of terrestrial and aquatic ecosystem dynamics only within the last century, most often in the last ~50-60 years.

Integrating our new reconstructions for East Africa with published paleoclimate records produced a synthesis of hydro-climate variability across the African continent in recent millennia. To assess the magnitude of rainfall variation at this time scale, we fine-tuned an existing water-balance model for Lake Naivasha and applied it to the published lake-level reconstruction. The main conclusions of these exercises are that **V**) natural, decade-to-century scale climate variability during the last millennium has been rather uniform across the 'Horn of Africa' region of East Africa where all rainfall is sourced in the Indian Ocean; and **VI**) the full amplitude of lake-level fluctuation recorded over the past 1100 years can be explained by relatively modest rainfall variability of ~10% at decadal time scales.

PAMEXEA conducted the last five years (2013-2017) of an 11-year monitoring program on Lake Chala, thereby enabling the calibration of local phytoplankton succession against seasonal and inter-annual weather patterns for use of phytoplankton fossils (diatoms, in particular) preserved in the sediments as climate proxy. In collaboration with partners at Utrecht University this calibration was expanded to selected bacterial biomarkers to promote also their use as climate proxies. The principal new insights of this part of the work programme are that **VII)** some diatoms dominate dry-season algal productivity in Lake Chala during La Niña-type years with weak 'long' rains and a long dry season, whereas others are dominant during years with less wind, and thus more shallow water-column mixing; and **VIII)** the so-called BIT index of bacterial lipids in Lake Chala sediments, an important proxy for past rainfall variation, is controlled by the influence of rainfall on water-column stratification and oxygenation.

Improvements in long-term prediction of climate change and weather extremes in East Africa depend on climate models being capable of capturing the principal large-scale climate-dynamical processes, the mechanisms of tropical climate forcing at inter-annual to centennial time scales, and all region-specific feedbacks and land-ocean-atmosphere interactions. The principal new insights derived from PAMEXEA effort in this field are that **IX)** state-of-the-art global climate models (GCMs) simulate fairly well the unimodal annual cycle of modern-day precipitation in south-eastern Africa, while the bimodal rainfall cycle in eastern equatorial Africa is less well captured; **X)** climate-model simulations over the last 1000 years display very different temporal patterns than proxy-based reconstructions, and there is no common signal among the model time series prior to AD 1850, suggesting that simulated hydro-climate fluctuations are mostly driven by internal climate variability rather than by external (natural or anthropogenic) forcing; **XI)** the link between precipitation and Indian Ocean sea surface temperatures (SSTs) in pre-industrial time is stronger for equatorial East Africa than for south-eastern Africa, with East African rainfall being especially sensitive to an enhanced west-to-east Indian Ocean SST gradient; and **XII**) GCM simulations are unrealistic with

respect to lake hydrology, and (even after adjustment) produce no shared lake-level signal nor do they resemble the proxy-based reconstruction.

Keywords. Africa, climate change, climate modelling, climate proxies, extreme drought, Holocene, hydro-climate, lake-sediment records, last millennium, long-term ecosystem dynamics, natural climate variability

1. INTRODUCTION

The catastrophic drought which afflicted East Africa in 2011 wreaked havoc on the already precarious living conditions of pastoralists and subsistence farmers in (semi-)arid northern Kenya, eastern Uganda, southern Ethiopia and Somalia. Combined with the large-scale displacement of indigenous people fleeing political unrest, the drought put millions of people in need of emergency assistance. Coming on the heels of another severe drought in 2009, it devastated already scarce land and water resources, and further compromised the life-carrying capacity of large parts of rural East Africa. The 2011 drought is said to have been caused by persistent La Niña conditions in the Pacific Ocean, which caused failure of both the 'short' autumn rains of 2010 (October-November-December) and the 'long' rain season of 2011 (March-April-May). The climatic tele-connection between East African rainfall and the El Niño–Southern Oscillation (ENSO) is a well-established cause of the large inter-annual variation in East African rainfall (Nicholson 1996). Analysis of annually-laminated sediments in Lake Chala near Mt. Kilimanjaro (Wolff et al. 2011) showed that this tele-connection existed already during the last ice age 20,000 years ago, but with a different recurrence interval and a reduced amplitude of weather extremes compared to today. In the last few millennia the region's climate has been characterized by ENSO-type inter-annual fluctuation superimposed on pronounced (multi-) decadal rainfall variability. The natural component of this longer-term variability is partly due to variation in solar radiation and volcanic eruptions affecting the heat budgets of the Pacific Ocean and of the principal source regions of East Africa's monsoon rainfall in the Indian Ocean (Mann et al. 2005, Tierney et al. 2013).

Increasingly this long-term variability is also being forced by anthropogenic greenhouse-gas emissions, as these affect the heat budget of the global atmosphere. Over East Africa, anthropogenic climate change has thus far resulted in a warming of 0.2 °C per decade since 1960 (Christensen et al. 2007). Until recently, changes in annual rainfall across the region showed no consistent trend (Parry et al. 2007). Particularly in East Africa, naturally large temporal variability has hampered identification of the anthropogenic signature. Funk et al. (2008) were the first to report a recent trend towards less rainfall over East Africa, and identified a link with anthropogenic warming of the Indian Ocean. Rainfall during the main rain season has declined ~15% since the 1980s, coincident with very rapid warming of the (eastern) Indian Ocean as it is being encroached upon by the western Pacific Ocean's Tropical Warm Pool. Warmer air and increased humidity over the Indian Ocean generates more frequent rainfall over the ocean, such that the westward flowing air is already dry by the time it reaches the East African coast. Rain failure associated with Indian Ocean warming is most pronounced during the long rain season, which normally represents the larger fraction of total annual rainfall, and thus exacerbates the negative impact of La Niña episodes, which weaken the short rains. The frequency of severe drought over East Africa is thus likely to increase further with global warming (Funk 2011), a projection which contrasts with the earlier formulated IPCC prognosis (Parry et al. 2007; Shongwe et al. 2011) that rainfall over eastern Africa is set to increase. Williams & Funk (2011) proposed that although very wet (El Niño) years will continue to occur, they will be increasingly inadequate to recharge drought-buffering aquifers. Consequently, when rains do come the already degraded land will promote flash flooding, gully formation and large-scale soil erosion.

2. STATE OF THE ART AND OBJECTIVES

Within this alerting context of increasingly frequent weather extremes combined with a trend towards reduced rainfall, the principal research objective of PAMEXEA was to improve understanding of East African climate dynamics at inter-annual and (multi-) decadal time scales, and how processes of natural climate variability interact with anthropogenic climate forcing to create future climate trends in this vulnerable region. Availability of uniquely high-quality lake-sediment records from Mt. Kenya and the Sahara desert allowed expansion of the project's scope to include also North Africa and the major, century-scale climate extremes which have impacted both East and North Africa throughout the Holocene period (the last 11,650 years). These century-scale droughts epitomise how 'abrupt' climate change and climate extremes have impacted on pre-industrial societies in arid and semi-arid tropical regions worldwide, and may do so again in the future. The overall goal of this project was to improve the climate-impact prognosis of anthropogenic global warming at the regional level, and the capability of climate models to predict future climate change and weather extremes at inter-annual to centennial time scales. Thus, PAMEXEA aimed to produce basic knowledge and know-how crucial to develop appropriate risk management and sustainable development policies for specific areas of East Africa at different time scales, including short-term catastrophe prediction and management. The ultimate goal of this project is to contribute to more robust forecasting of seasonal and longer-term climate variability required for adequate preparation, mitigation, and risk management of weather extremes in East Africa's drylands.

Currently, robust predictions of extreme weather events such as drought are mostly limited to large spatial scales and (very) short time scales. Of course, some user needs at small spatial scales and long timescales involve unpredictable components of weather dynamics that must be dealt with through adaptive measures building resilience into the relevant socio-economic systems. However, there is considerable room for improvement in the overlap between current prediction capability and user needs (WCRP-ICPO 2011). Progress in both the observations (most crucially, long time series of high-quality climate-proxy data) and models (validated by their skill to hind-cast the multiple modes of variability in those long time series) are key to this improved prediction.

At present there are only very few world regions for which climate models reasonably agree on even the sign of predicted changes in rainfall and drought, especially over land areas. The inconsistencies are explained by the inability of global climate models (GCMs) to adequately reproduce the mechanisms driving the hydrological cycle, to account for topography, and to correctly simulate the tele-connections and feedback mechanisms responsible for spatial and temporal rainfall variability (Christensen et al. 2007). Climate scenarios developed from GCMs often fail to capture important regional variations. To reduce uncertainty in model predictions, climate models must be validated using long time series of climate-proxy data as contained in natural climate archives such as lake sediments, corals and carbonate deposits in caves. It is the spatially coherent climate modes and tele-connection patterns revealed by these archives which serve as vehicles to contrast the spatially resolved simulations of next-generation regional climate models to location-specific data on past climate change (Fischer & Wolff 2011).

Importantly, these long time series of past climate change must adequately represent both the short-term (inter-annual) and longer-term (decadal to century-scale) climate variability. High-resolution paleodata syntheses (e.g., Mann et al. 2008) are typically dominated by tree-ring data, which is problematic because suitable tree species are lacking and/or preserve poorly in major parts of the world's tropical continents. Consequently, the spatial coverage of records from those regions is at least an order of magnitude less than in Europe or North America. In equatorial East Africa, lake-sediment records are the single-most important source of climate-proxy data (Verschuren, 2004); other high-quality archives such as cave deposits and corals only occur in peripheral areas (respectively in Ethiopia and along the Kenya coast) and span only the last few hundred years. Lakes are widely distributed across East Africa, but even so only a small sub-set of them adequately balance climatic sensitivity with continuous and high-quality recording of those climatic moisture-balance changes in their sediments (Verschuren, 2003). Before PAMEXEA, well-dated climate-proxy records spanning (at least) the last 1000 years with sufficient time resolution to test the hind-casting performance of regional climate models existed from only five locations across an area the size of western Europe: Lake Naivasha (Verschuren et al. 2000) and Lake Chala (Verschuren et al. 2009; Wolff et al. 2011) in the east (both developed by UGent-Limnology), and Lake Edward (Russell & Johnson 2007), Lake Tanganyika (Stager et al. 2009; Tierney et al. 2010) and Lake Victoria (Stager et al. 2005) further west. Since these eastern and western sites already show a distinctly different history of moisture-balance variation over the last millennium (Tierney et al. 2013), better spatial resolution must be achieved to constrain the relative importance of natural and anthropogenic processes influencing regional patterns of rainfall and drought. PAMEXEA aimed to produce this spatial resolution by optimizing the yield of high-quality climate-proxy data from new and existing study sites.

3. METHODOLOGY

Applying the demonstrably powerful 'the past is the key to the (present and) future' approach, the PAMEXEA work programme consisted of four inter-connected **work packages** (WPs). First, next-generation regional climate models currently being developed must be tested against long time series of past climate trends and weather extremes which adequately represent both the frequency (recurrence interval) and intensity of such events. The small handful of such datasets from East Africa available at the start of PAMEXEA precluded meaningful analysis of spatial patterns across the region. In **WP1** we applied diverse geological, geochemical and biological methods of palaeo-hydrological reconstruction to high-quality lake-sediment records from five sites in Kenya (Bogoria, Chala, Naivasha, Nasikie Engida and Rutundu) and one in Chad (Ounianga Serir) to optimize the spatial coverage of documented climate variability in equatorial East Africa during the Holocene (the last ~11,650 years) with emphasis on the last 2000 years. **WP2** focused on the development of new climate proxies preserved in the annually laminated (varved) sediments of Lake Chala near Mt. Kilimanjaro to maximize the temporal resolution of climatic information derived from this hitherto data-sparse region. In **WP3** we integrated some of these new hydro-climate records with a quality-screened compilation of all previously existing climate-proxy data from East Africa and surrounding areas covering at least the past 2000 years to produce a spatially-resolved history of past climate change across the African continent. In addition, since all continuous climate-proxy datasets available for East Africa involve moisture-balance indicators extracted from lake-sediment records, we used inverse hydrological modelling of the upgraded dataset from Lake Naivasha to estimate the magnitude and timing of rainfall variation which caused the reconstructed sequence of past lake-level changes. The result of this exercise allows, for the first time, a direct comparison of climate-model simulations with documented African climate history at a timescale pertinent to climate change in the near future.

Improvements in the prediction of weather extremes and long-term climate change in East Africa depend on the availability of climate models which capture the principal large-scale climate-dynamical processes (in particular, the tropical hydrological cycle), the principal mechanisms of tropical climate forcing at short and medium time scales, and all region-specific feedbacks and land-ocean-atmosphere interactions. In **WP4** we tested the hind-casting performance of existing climate models, i.e. their ability to replicate the temporal and spatial patterns of past climate variability over East Africa as a guide to their relative ability to simulate future climate trends and variability under prescribed combinations of natural and anthropogenic climate forcing.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4. 1. Overview of project results

WP1: Lake-based reconstruction of East and North African climate variability

Bogoria. Sediment cores collected in July 2014 and July 2015 were used to reconstruct the history of climate-driven lake-level fluctuations in the hypersaline, alkaline Lake Bogoria (central Rift Valley, Kenya) over the past 1,300 years. Using perfectly undisturbed sediment sequences from the deepest points in each of the lake's three sub-basins as well as the sills separating them, and provided with a robust age model based on combined ^{210}Pb and ^{14}C dating, the results (De Cort et al. 2018) are an important improvement over an earlier reconstruction based on exploratory coring in 2003 (De Cort et al. 2013). Analyses included loss-on-ignition, granulometry, X-ray diffraction of authigenic minerals, charcoal counting, and high-resolution scanning of magnetic susceptibility and X-ray fluorescence. These sediment-derived data were supplemented with data on present-day sedimentation conditions through seasonal sampling of settling particles in a sediment trap deployed from July 2014 to July 2015. From AD ~690 to ~950, Lake Bogoria's central and southern basins were reduced to shallow brine pools. Between AD ~1100 and 1350 Lake Bogoria experienced a pronounced high-stand, only to recede again afterwards. For most of the time since then and until AD ~1800, the northern basin was probably cut off from the joint central and southern basins. During the last two centuries, lake level has most often been relatively high compared to the rest of the past millennium, partly climate-driven but likely enhanced by increased catchment run-off due to anthropogenic clearing of natural vegetation in the lake's catchment area (van der Plas et al. 2019).

Nasikie Engida. We exploited opportunity provided by fieldwork for the International Continental Scientific Drilling Program (ICDP) project on Lake Magadi in August 2015 to assess the potential of nearby 'Little Magadi' (Nasikie Engida) as archive of past hydroclimate variability in the southern Kenya Rift Valley, where such records are currently lacking. Lithostratigraphy and preliminary ^{14}C dating of the recovered 4.62-m long sediment sequence indicate that Nasikie Engida has accumulated finely laminated sediments continuously since ~2,850 cal yr BP, which is remarkable given its current depth of only 1.6 m. Apparently, geothermal inflow has maintained a permanent water body through past climatic episodes when many other Kenyan lakes stood dry. Although Nasikie Engida has likely been saline over the entire time span covered by the cored sequence, variation in bulk-sediment composition and in the distribution of the salt mineral nahcolite suggests multi-decadal to centennial oscillations in water-column stability and stream inflow driven by climatic moisture-balance variations (De Cort et al. 2019). Further study of this PAMEXEA-generated research material is likely to close a large geographical gap in the existing network of East African paleoclimate records.

Rutundu. Early PAMEXEA work on two sediment records from the high-alpine Hausburg and Emerald tarns on Mt. Kenya covering the last few millennia (cf. the Year 1 annual report) was halted to focus instead on the 18,000-year record of hydro-climate variability contained in the sediments of sub-alpine Lake Rutundu. This shift of attention was motivated by the finding that the Rutundu archive uniquely displays all known major Holocene episodes of severe (sub-) tropical drought (centred on ~8200, ~6500, ~5400, ~4200 and ~2900 years ago) in a chronologically well-constrained framework of East Africa's post-glacial climate history. With exception of the drought centred on 8,200 years ago (the so-called '8.2k event') the cause of these droughts is as yet unknown and a topic of hot debate in global paleoclimate research. Preliminary data on the Rutundu record were published in the context of improving the methodology for measurement of biogenic silica in volcanic settings (Barao et al. 2015). Publication of the main results (De Cort, 2016; De Cort et al. in preparation) is contingent on completion of the ^{14}C-based age model.

Ounianga Serir. Although the lakes at Ounianga Serir have long been considered stable 'relict' lakes that go back to the early-Holocene African Humid Period (Kröpelin 2007), this idea was first challenged by analyses of their fossil and modern-day mollusc assemblages (Van Boxclaer et al. 2011, Creutz et al. 2016). Partly PAMEXEA-funded research on sediment cores recovered in 2015-2016 now provides robust evidence that ~4200 years ago Lake Teli, the lowest-lying (i.e., terminal) lake in the Serir basin must have stood (nearly completely) dry. This implies that with the possible exception of local spring discharge no fresh or saline open-water habitat existed at that time in Ounianga Serir. Our sediment records also indicate that the central Sahara experienced a prominent dry episode ~1200 years ago, synchronous with a known dry spell in the North African Sahel region (Holmes et al. 1999).

WP1 results concerning lakes **Chala** and **Naivasha** are detailed under WP2 and WP3, respectively.

WP2: Development and validation of novel lake-based climate proxies

Chala. PAMEXEA conducted the last five years of an 11-year monitoring program on Lake Chala, which was ended in November 2017 to permit completion of PAMEXEA tasks involving these field data. The effort focused on calibrating seasonal and inter-annual phytoplankton dynamics in Lake Chala against seasonal and inter-annual patterns in local weather (temperature, precipitation, wind) for use of phytoplankton fossils (diatoms, in particular) preserved in the lake's sediments as climate proxy with potentially annual resolution. Dead and sinking phytoplankton intercepted by a sediment trap suspended at 35 m depth was analysed at monthly intervals throughout the 10-year period from January 2007 to February 2016. This was supplemented by analysis of pelagic (off-shore) phytoplankton collected monthly at 0, 5, 10, 15 and 20 m depth from September 2013 to January 2015, then at 0 and 15 m depth until February 2016. Additionally also littoral (near-shore) phytoplankton was analysed, collected monthly from September 2013 to February 2016. Enumeration data (from identification and counting at 1000x magnification) for each algal group (Chlorophyta, diatoms, Dinophyta, Euglenophyta, Chrysophyta, Cryptophyta) and Cyanobacteria were converted to biomass estimates based on bio-volume assessments calculated from mean cell dimensions. Since only diatom fossils in the sediment record can be identified at the species level, special attention was given to the seasonal and inter-annual succession of dominant taxa in this algal group (*Nitzschia fabiennejansseniana*, *Afrocymbella barkeri*, *Synedra* spp.). The first two of these dominant diatoms are newly described to science (Cocquyt & Ryken 2016, 2017).

Simultaneously with this proxy calibration effort we produced a 500-year reconstruction of climate-driven changes in the composition of the diatom community in Lake Chala, by sampling fossil diatom assemblages at annual resolution in its finely laminated (varved) sediment record. When published, this 500-year fossil-diatom time series will provide detailed information on the relative strength of rainy and dry seasons which reflect inter-annual variability in total rainfall over south-eastern Kenya. In the course of analysis it became clear that careful attention had to be given to correct identification of different *Nitzschia* species present in the sediment samples. We therefore performing a detailed morphometric analysis on large numbers of fossil *Nitzschia* frustules, which allowed discrimination between one large species (*N. fabiennejansseniana*) that is apparently endemic to Lake Challa (Cocquyt & Ryken 2017) and a complex group of several smaller *Nitzschia* species with less-distinct morphology. This effort allowed integration of our 500-year, annually-resolved diatom record with the lower-resolution, 25,000-year diatom record which had been produced previously (Milne 2007). Moreover it allowed to set recent changes in the diatom community of Lake Chala in a truly long-term perspective of the lake's natural ecosystem functioning. Most notably, *Synedra* s.l. spp. was not observed in the 25,000-year diatom record but appeared in sediments dated to the 1970s and since then has taken an increasingly prominent role in the diatom community of Lake Chala. Suspecting that its recent appearance may relate to the combined influence of anthropogenic warming and the impact of regional land use on the lake's nutrient budget, we further pursued this question through an MSc thesis project on sedimentary tracers of historical changes in dust input (Papadimitriou 2020).

Finally, the 500-year annual-resolution diatom record (which used a core sequence collected in 2005) was extended to 2014 by analysing diatom assemblages in the uppermost part of a gravity core collected in September 2015. Importantly, these data create temporal overlap with the lake monitoring period (2006-2017), permitting direct comparison of the fossil diatom assemblages with the corresponding diatom-community data at monthly resolution obtained from sediment-trap and live pelagic phytoplankton samples.

In collaboration with Utrecht University, we continued work on organic geochemical (biomarker) proxies for past climate variation contained in the finely laminated sediments of Lake Chala. This involved comparison of sediment-trap data (the monthly variation in diatom and biomarker fluxes) with satellite-based time series of climate variables covering the monitoring period and temperature-logger data revealing the influence of the seasonal and inter-annual weather patterns water-column mixing, oxygen distribution and nutrient recycling (van Bree et al. 2018). The reliability of the branched and isoprenoid tetraether (BIT) index of bacterial cell-wall lipids as proxy for hydroclimatic variation at decadal and longer time scales was demonstrated by clear sedimentary BIT signatures of three historically well-documented periods of prolonged drought in the past 200 years. As a whole, the high-resolution, 2200-year Chala BIT-index record (Buckles et al. 2016) provides further evidence that geographical patterns of decade-to-century variability in rainfall and drought were rather uniform across a large part of the 'Horn of Africa' region as currently defined.

Ounianga Serir. The upper section of the Lake Teli record, representing the last ~930 years, displays fine sediment lamination with high regularity ('varves'). Suspecting that these may represent a truly unique natural archive of Saharan climate variability with annual resolution, PAMEXEA applied a suite of high-resolution sedimentological and geochemical methods (X-ray radiography, CT scanning, X-ray fluorescence) to assess which climate signals these layers might contain. The complete sequence was also embedded in resin for production of thin sections which allowed microscopic examination of the laminations' structure, and in turn evaluate diversity in varve types. This work resulted in the distinction of six different varve types, each representing a distinct succession of seasonal phases in lake behaviour controlled by inter-annual and longer-term climate variability. Preliminary inferences reveal a long-term trend of increasingly pronounced seasonality which started around AD 1400.

WP3: Regional integration of hydro-climate records, and quantification of inferred climate variability

Regional integration. PAMEXEA-funded activity in this domain started with a compilation and quality-screening of all published hydro-climate records from East Africa covering the past two millennia, in the context of our contribution to the IGBP-Past Global Changes (PAGES) Africa-2k programme. The broader mission of this programme is to review and synthesize current knowledge of late-Holocene hydro-climatic patterns across the African continent. Initially our work plan differed from earlier such syntheses (e.g., Verschuren & Charman 2008; Tierney et al. 2013) in that we would not limit ourselves to the small subset of records with demonstrated continuity throughout the last 1000-2000 years, as this criterion would sacrifice the spatial coverage of reconstructions required to establish their (sub-) regional representativeness. Instead we planned to integrate all paleo-hydrological time series from East Africa, many of which are fragmentary or have a low time resolution, as long as the proxy data producing these 'time windows' on past climate change at specific locations are robust and reliably dated. Rigorous assessment of the relative quality of, and age control on, each of these 'time windows' would then have allowed to assign each of them an appropriate weight in the regional synthesis. This ambitious plan was abandoned, however, because the PAGES Africa-2k working group prioritized a synthesis of past climate variability across the African continent, focused on integrating information from all its climate-dynamically distinct regions rather than aiming for completeness in each regional compilation; the result of this Africa-wide synthesis was published by Nash et al. (2016).

Some of the methodological ambition expressed in the PAMEXEA proposal for synthesizing (mostly lake-based) African paleodata could be realised nevertheless, through the contribution of PAMEXEA staff member Dr. Gijs De Cort to a major upgrade of the African portion of the Global Lake Status Database (GLSDB), which provides a standardized synopsis of qualitative lake-status data over the past 30,000 ^{14}C years. He pursued this effort during and following a 5-month research visit to the Centre for Past Climate Change (CPCC) at the University of Reading (UK). This work resulted in an improved framework for a relational database which incorporates uncertainty in both the chronology and interpretation of paleo-environmental proxy data, and serves as a prototype for efficient lake-status data synthesis. The chronology of published reconstructions is homogenised by applying the most recent ^{14}C calibration curves and state-of-the-art Bayesian age-depth modelling to all records. Uncertainties in the proxy data are accounted for through a Monte Carlo algorithm which iteratively samples the individual lake-status histories within the confinements of their uncertainties to produce an ensemble of possible histories, and then using Recursively-Subtracted Empirical Orthogonal Function analysis to extract from this ensemble the dominant patterns of lake-status variability through time. We refer to De Cort et al. (202x) for details.

Linking lake levels to climate variability: observations. Secondly, seizing the opportunity provided by a symposium on the management of Kenya's soda lakes (Verschuren 2013) we mobilized the country's scientific and stakeholder communities to help assemble the most-complete-possible instrumental data sets of historical lake-level fluctuation. These data sets are essential to calibrate the hydrological response of individual lakes (including PAMEXEA study lakes Bogoria, Naivasha and Chala) to climatic moisture-balance variability, which in turn allows to quantify the magnitude of hydro-climate variability responsible for the lake-level fluctuations that we find recorded in our sediment records. This effort started with obtaining all relevant data for the study region hosted by Kenya's Water Resource Management Authority (WRMA) and the Tanzania Water Authority (TWA).

Unfortunately, most of these data series contain major temporal hiatuses and quality issues due to intermittent funding shortages and/or gauge breakdowns. Therefore this task necessitated supplementing these data series with data collected by i) long-lasting monitoring projects (e.g., on Lake Naivasha, run by our international partner University of Twente), ii) local scientific partners; iii) chronosequences of remote sensing data (e.g., Tebbs (2013) for lakes Bogoria and Nakuru); iv) monitoring of gauges newly installed by PAMEXEA (lakes Baringo and Bogoria, since July 2014); and v) our own local monitoring (Lake Chala, since December 2006). When complete and quality-screened, these time-series data on historical and ongoing lake-level fluctuations of all major lakes in Kenya will represent a highly valuable resource for the governments of Kenya and Tanzania, as well as a major new research tool. Achieving this objective evidently requires continuation of the lake-monitoring programmes for a number of years beyond completion of the PAMEXEA project. At this time, our efforts in this context are financed by a Global Minds project (2019-2021) funded by the Flemish Inter-University Council on Development Cooperation (VLIR-UOS). PAMEXEA activity on this theme ended with a concerted effort to quality-screen the WRMA data provided to us by the Kenyan government in digital format, by comparing them with the original data-monitoring sheets curated at the regional WRMA stations.

Linking lake levels to climate variability: inverse hydrological modelling. Conversion of historical records and sediment-based reconstructions of lake-level fluctuation into time series of past rainfall variability can also be accomplished through inverse hydrological modelling. PAMEXEA pursued this method by turning the relationship between lake level (or volume) and rainfall variability for Lake Naivasha in the historical period (post-1900; Becht & Harper 2002) into a conceptual water-balance model that could be applied to the existing, semi-quantitative lake-level reconstruction covering the last 1100 years (Verschuren et al. 2000). Simultaneously we updated both the Naivasha lake-level reconstruction itself and its chronology using state-of-the-art methods (Van der Meeren et al. 2019). The major outcome of this modelling is that the full amplitude of lake-level variation recorded over the past 1100 years (>30 m) can be explained by relatively modest rainfall variability of +/- 10% at decadal time scales. This is due to an amplifying mechanism which translates modest rainfall variability into large variability of the river inflows to Lake Naivasha, most likely related to the lake's characteristic situation of a very large ratio between catchment area (3200 km^2) and lake surface area (varying between 100 and 180 km^2), and wet headwater regions on the rift shoulders draining towards a semi-arid rift-valley floor.

WP4: Modelling long-term variability in East Africa's hydro-climate

Comparing modelled climate with lake-based paleodata. PAMEXEA focused on testing the ability of existing climate models to replicate the temporal and spatial patterns of past climate variability, as a guide to their relative ability to simulate future climate trends under prescribed combinations of natural and anthropogenic climate forcing. We first conducted a data-model comparison by analysing the simulated and proxy-based reconstructions of multi-decadal to century-scale East African hydro-climate variability over the last 1000 years (Klein et al. 2016). The paleodata in this study originated from the four East African lakes where high-resolution sediment-based reconstructions have been achieved: Chala, Naivasha, Masoko and Malawi. The simulations considered were those performed within the framework of the PMIP3/CMIP5 projects, using an ensemble of the most sophisticated general circulation models (GCMs) available. We found that all GCMs simulate fairly well the unimodal annual cycle of precipitation in the Masoko-Malawi region of south-eastern Africa, while the bimodal annual cycle characterizing the Chala-Naivasha region in equatorial East Africa is generally less well captured by most models. Model results and lake-based hydro-climate reconstructions display very different temporal patterns over the last millennium. Additionally, there is no common signal among the model time series, at least prior to AD 1850. This suggests that simulated hydro-climate fluctuations are mostly driven by internal climate variability rather than by common external forcing, such as solar-activity variation or volcanic eruptions. After AD 1850, half of the models simulate a relatively clear response to forcing, but this response is different between the models. Overall, the link between precipitation and tropical sea surface temperatures (SSTs) over the pre-industrial portion of the last millennium is stronger and more robust for the Chala-Naivasha region than for the Masoko-Malawi region. At the inter-annual (ENSO) timescale, last-millennium Chala-Naivasha precipitation is positively correlated with western Indian Ocean SST and negatively with eastern Indian Ocean SST, while a direct influence of the Pacific Ocean appears weak and unclear. The same pattern of correlations occurs at the centennial timescale, but only in fixed-forcing simulations, meaning that at this time scale the effects of (natural or anthropogenic) climate forcing starts overriding the imprint of internal climate variability on large-scale, long-distance tele-connections.

Data assimilation. We then directed our attention to the mechanisms driving East African hydroclimate variability in GCM simulations. This study started from hypotheses formulated previously in literature (for an overview, see Klein & Goosse 2018), with emphasis on the potential role of temporal variation in Indian Ocean sea surface temperature (SST). The hypotheses had been based on relatively simple statistical diagnostics such as correlation coefficients, and consequently did not allow identifying whether or not the link between East African rainfall and Indian Ocean SST is based on physical processes. Two different methods were used to achieve greater insight into this link. The first method was a data assimilation scheme based on a particle filter, using hydro-climate reconstructions from the four East African sites mentioned above (Naivasha, Chala, Malawi, Masoko) and SST reconstructions at six oceanic sites spread across the Indian Ocean to constrain the Last Millennium Ensemble of simulations performed by the GCM CESM1 (Otto-Bliesner et al. 2016). This is, to our knowledge, the first time that this method is used to reconstruct simultaneously these two variables over such a long period. While this gave satisfactory results, they mainly emphasised two limitations that tend to alter the skill of the reconstructions, namely the biases of the climate models and the uncertainties of proxy-based reconstructions. Skilful reconstructions of Indian SSTs and East African rainfall can be obtained based on assimilation of only one of these variables, in the form of pseudo-proxy data deduced from the CESM1 model (Klein & Goosse 2018). Reconstruction skill increases with the number of particles selected in the particle filter, with improvements levelling off beyond 99 particles. When considering a more realistic framework, model biases and the inherent uncertainties of the proxy-based reconstructions strongly deteriorate reconstruction skill. However, it is still possible to obtain a skilful reconstruction of SSTs over most of the Indian Ocean only based on assimilation of the six SST-related proxy records selected, as far as a local calibration is applied at all individual sites. This underlines the critical importance of adequately integrating the proxy-inferred signal into the climate models used for reconstructions based on data assimilation.

Sensitivity experiments. In a second step, the existing hypotheses about the mechanisms responsible for simulated rainfall variability in East Africa were tested by making new simulations with the GCM EC-EARTH, one of the most sophisticated climate models available at present. Using sensitivity experiments, we assessed the impact of two different patterns of Indian Ocean SST anomalies, known to often coincide with enhanced 'short rains' over East Africa, on simulated East African rainfall. The first pattern consists in higher SSTs in the western tropical Indian Ocean, and the second in a high SST contrast between a warmer western and cooler eastern tropical Indian Ocean (e.g., Ogallo et al. 1988; Goddard & Graham 1999; Webster et al. 1999; Nicholson & Selato 2000; Schubert et al. 2016). The principal result of this test is that elevated western Indian Ocean SST can cause a slight increase in East African rainfall, but the impact of an enhanced west-to-east SST gradient across the Indian Ocean is much stronger (Klein 2016). This result is related to physical processes: reorganization of the surface winds is indeed observed with low-level easterly anomalies over the tropical Indian Ocean and weak westerly anomalies over central and eastern equatorial Africa, but present only in the simulation with a prescribed enhanced west-to-east SST gradient. These wind anomalies create a convergence zone over the East African region, associated with ascending motion and increased convective activity.

Simulating lake-level history using GCMs. Finally we assessed the performance of current climate models by combining GCM simulations of the past millennium with the catchment-runoff / water-balance model ('lake system model', LSM) developed by PAMEXEA for Lake Naivasha in Kenya (see under 'inverse hydrological modelling in WP3) to produce simulated 1000-year lake-level histories that were then compared with the proxy-based reconstruction. Strictly speaking, we examined Naivasha's lake-level response to meteorological forcing (precipitation and temperature) as simulated by a set of six GCMs each prescribed by known variation in radiative forcing (principally solar variability and volcanic eruptions) over the past 1000 years. A first pertinent observation in this exercise was that GCM-derived values of modern-day mean annual temperatures for the Naivasha region were too high in all six models, by amounts ranging from 2.3 to 7 °C, and five of the six models underestimate mean annual rainfall by a factor ranging from 1.76 to 7.00. These mismatches were compensated by applying multiplicative (rainfall) and additive (temperature) adjustments to bring the GCM-derived and observed annual means into agreement. Secondly, neither the temporal trends of the simulated lake-level histories from any one of the six model runs nor the averaged result of those runs bear any notable resemblance to the proxy-based lake-level history. In particular, none of the simulated histories attained the remarkable amplitude (>30 m) of climate-driven lake-level variation in the past millennium demonstrated by the proxy data.

4.2. Principal new insights and conclusions

Results of the various topical studies made possible by the PAMEXEA project, as described above, have produced significant new scientific insight which can be summarized in 12 principal conclusions:

I) The multi-decadal events of severe drought which occurred ~8200, ~4200 and ~2900 years ago and were felt across tropical Africa were pulsed negative rainfall anomalies superimposed upon a long-term trend of gradual Holocene drying, not (as widely believed) abrupt transitions between two contrasting climate states before and after these extreme events.

II) When viewed over the entire Holocene period, driest climatic conditions occurred ~2900 years ago in East Africa and ~4200 years ago in North Africa.

III) Human impact on the landscape (i.e., on terrestrial vegetation) of equatorial East Africa becomes noticeable from between ~900 and ~250 years ago with early appearances likely limited to relatively few and/or small areas with historically above-average population density due the attractiveness of the local landscape with regard to life-supporting land and water resources.

IV) Human activity has become the principal driver of terrestrial and aquatic ecosystem dynamics only within the last century, most often in the last ~50-60 years and not uniformly distributed in space.

V) Natural, decade-to-century scale climate variability during the last millennium has been rather uniform across the 'Horn of Africa' region of East Africa where all rainfall is sourced in the Indian Ocean.

VI) The full amplitude of lake-level fluctuation recorded over the past 1100 years can be explained by relatively modest rainfall variability of ~10% at decadal time scales.

VII) Some diatoms dominate dry-season algal productivity in Lake Chala during La Niña-type years with weak 'long' rains and a long dry season, whereas others are dominant during El Niño years with less wind, and thus more shallow water-column mixing. This calibration permits the use of fossil diatom assemblages recovered from the Chala sediment record as proxy to trace past changes in local weather patterns at the all-important inter-annual timescale.

VIII) The BIT index of bacterial lipids in Lake Chala sediments, an important proxy for past rainfall variation, is controlled by the influence of rainfall on water-column stratification and oxygenation.

IX) Current state-of-the-art global climate models (GCMs) simulate fairly well the unimodal annual cycle of modern-day precipitation in south-eastern Africa, while the bimodal annual rainfall cycle characterizing eastern equatorial Africa is generally less well captured by most models.

X) Climate-model simulations display very different temporal patterns over the last millennium than proxy-based hydro-climate reconstructions, and there is no common signal among the model time series prior to AD 1850, suggesting that simulated hydro-climate fluctuations are mostly driven by internal climate variability rather than by common external forcings such as solar-activity variation, volcanic eruptions or (since AD 1850) increasing atmospheric CO_2 concentration.

XI) The link between continental precipitation and Indian Ocean sea surface temperatures (SSTs) over the pre-industrial portion of the last millennium is stronger and more robust for equatorial East Africa than for south-eastern tropical Africa. Elevated western Indian Ocean SST can cause a slight increase in East African rainfall, but the impact of an enhanced west-to-east SST gradient across the Indian Ocean is much stronger.

XII) Unadjusted simulations from modern coupled ocean-atmosphere GCMs forced with estimates of past radiative forcing are unrealistic with respect to lake hydrology, and (even after adjustment) produce no clear shared lake-level signal nor do they resemble the proxy-based lake-level reconstruction.

4.3. Contributions to policy and decision-making

Priorities in sustainable-development science must reflect user needs. The societal relevance of the research accomplished by PAMEXEA follows from the fact that severe and recurrent drought is the principal weather-related hazard in the vast (semi-) arid regions of East and North Africa, and because the currently poor quality of long-term climate prediction is a major bottleneck hampering successful drought mitigation and adaptation. Indeed, the devastating impact of the 2009 and 2011 droughts resulted primarily because negative rain anomalies in many areas moved well outside typical ENSO-type variability, and because the back-to-back occurrence of rain failure compromised the resilience of both natural and human systems to recover from the first crisis.

On the other hand, improved climate prediction is not the only factor which will determine the quality of life for East Africa's pastoralists and farmers. With World Bank and EU support, Kenya has since 1996 developed a multi-faceted drought management system as part of its national arid lands programme. Compared to several decades ago, the average loss of human life during droughts has been reduced by an order of magnitude. After each new crisis this system, and similar drought-management systems established in Tanzania, Ethiopia and Sudan, are reviewed and upgraded to better cope with a future crisis. At the same time, some negative impacts of the recent droughts could have been avoided by better regulation of agricultural economy. The harsh reality is that without (non-sustainable) irrigation from deep wells or endorheic lakes, only 20% of Kenya's land is suitable for arable crop production; in the vast (semi-) arid lands that constitute the other 80%, rain-fed livestock herding is the most productive economic activity. Unfortunately, drylands and the pastoral livelihoods they support suffer from underinvestment and ineffective government policies encouraging formerly mobile herders to transit into settled ways of life. With high population growth putting pressure on available farmland, drylands have lately become a target for new agricultural expansion involving non-sustainable, water-intensive development of communal lands formerly dedicated to livestock grazing. As under-grazed pasture is now largely restricted to national parks and other protected areas, pastoralists opportunistically establish temporary camps inside national parks. In the Serengeti, thousands of cattle are now allowed to graze inside the park at night, and during the 2009 drought, substantial numbers of livestock crossed through the forest zone on Mt. Kenya to graze on fragile Afro-alpine grasslands above 3200 m altitude. Schemes which pay herders for wildlife and ecosystem conservation can help stabilize pastoralist communities living near protected ecosystems. In one successful programme, payments to herders living near Masai Mara and Nairobi National Parks provide them with a reliable source of income that reduces poverty and protects precious grazing areas for both livestock and wildlife.

In regions where crop cultivation is ecologically sustainable, structural adaptation to endemic climate instability is compromised by deforestation and land degradation. On many marginal lands currently under agriculture, scarce precipitation already routinely causes crops to fail in one out of every six (or fewer) growing seasons. A major concern is that further rainfall decline due to global warming could by 2050 make vast areas of this marginal African farmland unable to support even a subsistence-level production of staple foods such as maize and millet (Jones & Thornton 2009). In those circumstances, also poor subsistence farmers will increasingly rely on livestock to buffer the risk of climate change. Of course, livestock as a bulwark against challenging environmental conditions is not a novel idea: it explains the development of pastoralism as the lifestyle most suitable for survival in a landscape offering few and unpredictable resources.

In this multifaceted context, the real challenge is to make climate-change and weather-hazard projections sufficiently robust to allow delineating the specific areas in East Africa where management effort should focus on promoting either the cultivation of drought-tolerant varieties of commercial and food crops, on livestock ownership by subsistence farmers, or on pure and mobile livestock herding; and with each of these economic activities adopting measures to prevent soil loss and land degradation. Kenya is a natural laboratory for this purpose, because the strong climatic moisture-balance gradient associated with its mixed topography creates a mosaic of landscapes covering the full range of ecological and economic carrying capacity. This requires the government to adopt a diversified strategy of rural land and water-resource development.

From the above it is clear that sustainable policy strategies do exist, but would benefit greatly from obtaining better projections of the future amount and seasonal pattern of precipitation at the sub-regional scale. Climate-model simulations informing the 4th IPCC assessment report (Parry et al. 2007) were never intended to provide rainfall trend projections for every region (Funk 2011). Yet these models' majority consensus that East Africa would become wetter during the 21st century has stimulated several agencies to create long-term plans of economic development which rely on higher rainfall, and to promote agricultural expansion in areas that may in fact become drier. Echoing Funk (2011), we hope that climate science based on local/regional observations and climate models may eventually produce the robust long-term climate projections which can increase the precision and efficiency of government and foreign aid programs focused on alleviating poverty among East and North Africa's rural poor.

On the scientific level, the considerable success of PAMEXEA mostly derives from its combination, and strong integration, of advanced expertise in lake-based climate reconstruction, lake hydrology and climate modelling. Although the new knowledge it has produced is by no means complete, it allows concrete recommendations on where future scientific effort should be directed. PAMEXEA project results drive home the message that also the currently most advanced climate models still struggle to capture the full complexity of monsoonal climate dynamics in equatorial East Africa. Developing better models partly hinges on achieving more complete and accurate documentation of past climate variability at the most relevant time scales (i.e., inter-annual to century-scale) with adequate geographical resolution across the East African Plateau. Given the semi-arid tropical climate conditions characterising a large areal fraction of the plateau, and hence the natural scarcity of permanent surface waters, closing all geographical gaps with robust paleodata requires continued effort to identify and develop the sub-continent's most promising (or rather, the handful of continuous) lake-based climate archives.

In this context, one major scientific outcome of PAMEXEA may be that it has 'seeded' the DeepCHALLA project of the International Continental Scientific Drilling Program (http://challa.icdp-online.org), which succeeded in November 2016 to recover the continuous and highly resolved sediment archive from Lake Chala near Mt. Kilimanjaro. Covering two glacial-interglacial cycles (~250,000 years), this record enables direct assessment of rainfall amount and variability in East Africa during warm climate episodes in the distant past, which for climate modelling can serve as closest analogues to the climatic conditions expected to be realized by the late 21st century.

5. DISSEMINATION AND VALORISATION

5.1. Formal knowledge transfer

PAMEXEA project activities have been communicated through 10 oral and 14 poster presentations at international or national symposia, and 3 invited seminars. In the combined listing below, PAMEXEA project members are indicated in **bold** type.

Cocquyt C, **Ryken E** (2015). *Afrocymbella* sp., a new diatom from a small deep East African crater lake. 9th Ghent Africa Platform Symposium, Gent, Belgium, 17/12/2015. Poster.

Cocquyt C, **Ryken E** (2016). A new *Afrocymbella* species (Bacillariophyta) from a small deep East African crater lake. 10th Central European Diatom Meeting, Budapest, Hungary, 20-23/04/2016. Poster.

Cocquyt C, **Ryken E** (2016). *Afrocymbella* sp., a new diatom from a small deep East African crater lake. 3rd Annual Meeting on Plant Ecology and Evolution, Ghent, Belgium, 5/02/2016. Poster.

Cocquyt C, **Ryken E** (2016). Diatom dynamics in the phytoplankton of a small deep crater lake in East Africa. 24th International Diatom Symposium, Québec, Canada, 21-26/08/2016. Oral presentation.

De Cort G (2018). Lake-based Holocene hydroclimate reconstruction in equatorial East Africa. Ocean and Climate Physics Seminar Series, Lamont-Doherty Earth Observatory of Columbia University, New York, USA., 27/04/2018. Invited seminar.

De Cort G (2018). Lake-based late-Holocene environmental reconstruction in equatorial East Africa, using sediment mineralogy and geochemistry. Geochemistry Seminar Series, Free University of Brussels, Brussels, Belgium, 31/05/2018. Invited seminar.

De Cort G (2018). Late-Holocene sediment records of East-African soda lakes: indicators of environmental change. Department of Geological Sciences and Environmental Studies Seminar Series, Binghamton University, Binghamton, USA, 19/10/2018. Invited seminar.

De Cort G, Barao L, Conley D, Haug G, Blaauw M, Engstrom D, **Verschuren D** (2015). Early- to mid-Holocene hydroclimate change in tropical East Africa: the multi-proxy sediment record from Lake Rutundu, Kenya. European Geosciences Union (EGU) general assembly, Vienna, Austria, 16/04/2015. Oral presentation.

De Cort G, Barao L, Conley D, Haug G, Blaauw M, Engstrom D, **Verschuren D** (2016). Early- to mid-Holocene hydroclimate change in tropical East Africa: the multi-proxy sediment record from Lake Rutundu, Kenya. Geologica Belgica conference, University of Mons, Belgium, 29/01/2016. Oral presentation.

De Cort G, Bessems I, Keppens E, **Mees F**, Cumming B, **Verschuren D** (2013) Late-Holocene and recent hydroclimatic variability in the central Kenya Rift Valley: the sediment record of hypersaline lake Bogoria. International investigator/stakeholder conference *Kenya's Soda Lakes: conservation status and management*, Naivasha, Kenya, 4-7/12/2013. Poster.

De Cort G, Burrough S, Chevalier M, Chen CY, McGee D, Shuman BN, Harrison S (2018) Studying eastern and southern African late-Pleistocene and Holocene hydroclimate history through the Global Lake Status Data Base. Poster presentation at the African Quaternary (AFQUA) conference, Nairobi, Kenya, 14-22/07/2018. Poster.

De Cort G, Mees F, Renaut RW, Sinnesael M, **Van der Meeren T**, Goderis S, Keppens E, Mbuthia A, **Verschuren D** (2018) Late-Holocene sedimentation and sodium-carbonate deposition in the hypersaline alkaline lake Nasikie Engida, southern Kenya Rift Valley. American Geophysical Union Fall Meeting, Washington DC, USA, 10-14/12/2018. Poster.

De Cort G, Verschuren D, Renaut RW, Sinnesael M, **Van der Meeren T**, Mbuthia A, Keppens E, Goderis S, **Mees F** (2018) Late-Holocene sedimentation and sodium-carbonate deposition in saline alkaline Nasikie Engida, southern Kenya Rift Valley. International Paleolimnology Association (IPA) - International Association of Limnogeology (IAL) Joint Meeting, Stockholm, Sweden18-21/06/2018. Poster.

Klein F, **Goosse H**, **Graham NE** (2014) East African climate dynamics over the past millennium in PMIP3/CMIP5 simulations. Second general PMIP3 meeting, Namur, Belgium, 05/2014. Poster.

Klein F, **Goosse H**, **Graham NE** (2014) East African climate dynamics over the past millennium in PMIP3/CMIP5 simulations. EGU General Assembly, Vienna, Austria, 04/2014. Poster.

Klein F, Goosse H, Graham NE, Verschuren D (2014). Assessing the performance of climate models in East Africa over the last millennium. Royal Academy of Oversea Sciences Young Scientists Day, Brussels, Belgium, 27/12/2014. Poster.

Klein F, **Goosse H**, **Graham NE**, **Verschuren D** (2015). Comparing East African climate model results with lake records over the last 1000 years. AfQUA, Cape Town, South Africa, 03/02/2015. Oral presentation.

Klein F, **Goosse H**, **Graham NE**, **Verschuren D** (2016). Comparison of Simulated and Reconstructed Variations in East African Hydroclimate over the Last Millennium. AMS, New Orleans, USA, 13/01/2016. Oral presentation.

Nash DJ, **De Cort G**, Chase BM, **Verschuren D**, Nicholson SE, Shanahan TM, Asrat A, Lézine AM, Grab SW. (2016). African hydroclimate during the last 2000 years. INQUA early career researcher conference and summer school, University of Reading, UK, 5-9/09/2016: Poster.

Owen RB, Renaut RW, Lowenstein T, Muiruri V, McNulty EP, Rabideaux N, Leet K, Deocampo D, Cohen A, Campisano C, Billingsley A, Sier MJ, Luo S, Deino A, **De Cort G**, Shen C, Mbuthia A. (2018) Quaternary outcrop and core stratigraphy of the Magadi Basin, South Kenya Rift. Oral presentation at the International Paleolimnology Association (IPA) - International Association of Limnogeology (IAL) Joint Meeting, Stockholm, Sweden, 18-21/06/2018. Poster.

Ryken E, **Cocquyt C**, **Verschuren D** (2015). Reconstructing 500 years of inter-annual and decade-scale climate variability in southeastern Kenya, using diatoms in annually laminated lake sediments. BELQUA 2015 Annual Scientific Workshop, Brussels, Belgium, 3/03/2015. Oral presentation.

Ryken E, **Cocquyt C**, Milne I, **Verschuren D** (2016). Fossiele diatomeeëngemeenschappen als venster op klimaat-gerelateerd mengregime in het Oost-Afrikaanse kratermeer Challa(Kenya/Tanzania). Studiedagen Nederlands Vlaamse Kring van Diatomisten, Utrecht, The Netherlands, 20/05/2016. Oral presentation.

Ryken E, **Cocquyt C**, **Verschuren D** (2016). Fossil diatom communities of Lake Challa (Kenya/Tanzania) reveal secrets of recent and historical climate change in East Africa. 33th International Society of Limnology congress, Torino, Italy, 31/07-5/08/2016. Oral presentation.

Ryken E, **Cocquyt C**, **Verschuren D** (2014). Reconstructing climate variability and extremes in East Africa over the past 500 years, based on freshwater diatom community changes recorded in the sediments of Lake Challa (Kenya). 8th Ghent Africa Platform Symposium, Gent, Belgium, 27/11/2014. Poster.

Ryken E, **Cocquyt C**, **Verschuren D** (2014). Reconstructing historical and recent climate changes in East Africa, based on Diatom community changes in Lake Challa (Kenya/Tanzania). Royal Academy of Oversea Sciences Young Scientists Day, Brussels, Belgium, 27/12/2014. Poster.

Van der Meeren T, Verschuren D, Sylvestre F, Nassour YA, Naudts E, Aguilar Ortiz LE, Deschamps P, Tachikawa K, Garcia-Molina M, Schuster M, Abderamane M (2018). Late-Holocene hydrological variability of iconic oasis lakes at Ounianga in the central Sahara (Chad). International Paleolimnology Association (IPA) – International Association for Limnogeology (IAL) Joint Meeeting, Stockholm, Sweden, 18-21/06/2018. Oral presentation.

Verschuren D (2013). Long-term dynamics of Kenya's soda lakes. International investigator and stakeholder conference *Kenya's Soda Lakes: current conservation status and management*, Naivasha, Kenya, 4-7/12/2013. Invited oral presentation.

5.2. Outreach

Throughout the duration of the project we have taken advantage of every opportunity to communicate project results to stakeholder groups in Kenya, most recently in July 2017 and December 2018. Two PAMEXEA presentations were made during the combined investigator/stakeholder meeting '*Kenya's soda lakes: conservation status and management*' in December 2013, organised by the lead promoter on behalf of the Kenya Wildlife Service (KWS) and the National Environmental Management Authority (NEMA) to address the societal impacts of flooding due to the major transgression of Kenya's rift-valley lakes since 2011. This meeting revealed widespread misconceptions about the probable cause of this rising lake level, both among the general public and Kenyan authorities. It offered PAMEXEA staff a platform to debunk various myths, and explain why its true cause is most probably related to the recently changing seasonality in the region's monsoon rainfall. It also strengthened our mandate from the Kenya government to conduct the research needed to improve long-term climate prediction at the regional scale, eventually paving the way for government permission to develop the ICDP project DeepCHALLA (http://challa.icdp-online.org), which called for major, and thus unavoidably intrusive, deep drilling into the bottom of a crater lake bridging the border between Kenya and Tanzania near Mt. Kilimanjaro.

6. PUBLICATIONS

PAMEXEA project activities have thus far produced 16 publications in international research journals (A1), two other research publications (A2), one book chapter (B2), one publication in meeting proceedings (C1), two PhD dissertations (C2) and one MSc thesis (C4). In the combined listing below, PAMEXEA project members are indicated in **bold** type.

Buckles LK, **Verschuren D**, Weijers JWH, **Cocquyt C**, Blaauw M, Sinninghe Damsté JS (2016). Interannual and (multi-)decadal variability in the sedimentary BIT index of Lake Challa, East Africa, over the past 2200 years: assessment of the precipitation proxy. *Climate of the Past* 12: 1243-1262. (A1)

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7. ACKNOWLEDGEMENTS

Fieldwork on lakes Bogoria and Rutundu was executed with permits from the National Commission for Science, Technology and Innovation of Kenya (RRI/12/1/BS011/44; RCD/14/012/14) and the National Environmental Monitoring Authority (AGR/7/2010/0029). The research materials from these two sites were exported under Material Transfer Agreement A11/TT/1040 between the Kenya Wildlife Service, the University of Nairobi and Ghent University. The fieldwork on Nasikie Engida benefited from Research Foundation Flanders (FWO) grant no. K215514N, and permits obtained for the ICDP Hominin Sites and Paleolakes Drilling Project. Fieldwork and original analyses on the Lake Naivasha sediment record were supported by NSF-DEB 93-20324, NSF-ATM 95-31222, NSF-RTG 90-14277 and the Quaternary Paleoecology program at the University of Minnesota (USA). Fieldwork on the Ounianga lakes was conducted with permission of the Centre National d'Appui à la Recherche of Chad, and with funding from the 'Grands Ecosystèmes Lacustres de Tchad' (GELT) project and National Geographic Society (USA) exploration grant NGEF186-16.

We thank the World Climate Research Programme's Working Group on Coupled Modelling, and the climate-modelling groups listed in Table 1 of Klein et al. (2016) for producing and making available their model output. We further acknowledge the US Department of Energy's Program for Climate Model Diagnosis and Inter-comparison for coordinating support to the Coupled Model Inter-comparison Project (CMIP) and development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

We thank all field-work participants and all staff from our own and partnering institutes who provided laboratory or administrative assistance which furthered the research results reported here.

Finally we thank the members of the PAMEXEA follow-up committee, listed below, for their interest in the realisation of this multi-faceted project and their constructive advice, both formally at project annual meetings and informally through contacts with individual project partners.

Dr. Heinz Wanner
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Claire Collin
Federal Public Service of Belgium for health, food chain safety and environment (DG environment, climate change section)

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