Valley formation aridifies East Africa and elevates Congo Basin rainfall

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Abstract

East African aridification during the last 8 million years is frequently invoked as a driver of large-scale shifts in vegetation[1] and the evolution of new animal lineages, including hominins[2–4]. However, evidence for increasing aridity is debated[5] and, crucially, the mechanisms leading to dry conditions are unclear[6]. Here, numerical model experiments show that valleys punctuating the 6,000 km-long East African Rift System are central to the development of dry conditions in East Africa. These valleys, including the Turkana Basin in Kenya, cause East Africa to dry by channeling water vapour towards the Central Africa, a process that simultaneously enhances rainfall in the Congo Basin rainforest. Without the valleys, the uplift of the Rift System leads to a wetter climate in East Africa and a drier climate in the Congo Basin. Results from climate model experiments demonstrate that the detailed tectonic development of Africa has shaped the rainfall distribution, with profound implications for the evolution of African plant and animal lineages.

Main

East Africa is the driest equatorial landmass on the planet - an unexplained quirk in the classic Hadley model of tropical circulation[7]. Owing to the relatively low annual precipitation (mainly <800mm.yr^{-1} in recent decades)[8], and propensity to drought[9], much of East Africa is unable to support dense forest. This is in contrast to the widespread rainforests of central and western equatorial Africa, where annual rainfall is higher, by 150-300%[10]. Over the last 8 Ma, the reduction in East African dense forest, and associated expansion of mixed and grassland habitats[1], has been linked to the evolution of new animal lineages[1], including hominins[2–4]. There is no convincing climatic mechanism explaining this transition, and which accounts for continued presence of dense forest in Central Africa. One hypothesis is that drier conditions in East Africa evolved with the uplift of the 6,000 km-long East African Rift System (EARS)[11,12], however, mechanisms that relate uplift to rainfall deficits are problematical. In this paper, we demonstrate that the formation of valleys, rather than the uplift alone, is crucial to the low rainfall totals in East Africa. The valleys cause East Africa to dry by channeling water vapor towards Central Africa, a process that simultaneously favors rainfall in the Congo Basin rainforest. Without the valleys, the uplift of the Rift System would lead to a wetter climate in East Africa and a drier climate in the Congo Basin.

The East African Rift System separates relatively dry regions of eastern Africa from wetter central Africa. It is a leaky barrier to moisture laden tropical easterly winds, which have been present from at least the middle-Miocene[13]. A series of fault-bounded valleys, orientated east-to-west, punctuate uplifted topographic domes along EARS, including the Ethiopian and Kenyan Highlands. The valleys are key conduits for water vapor transport from the Indian Ocean to Central Africa, with transport occurring via five major easterly low-level jets (LLJs), which accelerate as they are constrained by the valley sides[14,15] (Extended Data Figure 1). Strong LLJs lead to enhanced water vapor export from East Africa, resulting in low rainfall[15–17]. The valleys - and associated water vapour pathways - likely reached their present day morphology in the latter stages of EARS development (after 10 Ma[18]). We hypothesise that they are central to the present day rainfall distribution.

To test this hypothesis, we alter the valleys in a series of 20-year climate model experiments using a 25 km-resolution Pan-African regional climate model from the UK Met Office (See details of the model setup, evaluation and experiments in Methods). The model performs well in its simulation of present day rainfall and circulation (Extended Data figures 1 and 2). Our initial focus is on the Turkana Channel, which is the largest of the fault-bounded valleys. The Turkana Jet - which forms in this valley - is responsible for a large portion of the easterly water vapour transport across the rift system[17]. Phases when the Turkana Jet is strong are associated with drought across the bimodal (two rainy season) region of East Africa[15–17] and increased rainfall in downstream regions including the Ethiopian Highlands and parts of Central Africa[16,22]. We progressively alter the Turkana Channel from A) a blocked Turkana Channel, B) an incipient channel, C) the Control (observed topography) and D) a deeper-than-observed channel (Figure 1).

The role of the Turkana Channel

Progressive drying occurs in East Africa with the deepening of the Turkana Channel corresponding to experiments A to D (Figure 2). Annual mean rainfall is highest in East Africa in the Turkana Block experiment (Figure 2a). In this experiment, the model simulates 1,000 $mm.yr^{-1}$ (+500%) more rainfall in parts of dry northern Kenya and South Sudan compared to the control. Rainfall is lower across rainforest regions of central and western central Africa, with a reduction of 300 $mm.yr^{-1}$ near the Atlantic Coast. As the channel deepens from experiments B to D, including the Control, the upstream region of East Africa becomes progressively drier, while the Congo Basin becomes wetter. In the deeper-than-observed experiment (Figure 2c), rainfall is reduced in parts of East Africa and South Sudan by 200-400 $mm.yr^{-1}$ (-30-50%). This demonstrates the contribution of the Turkana Channel to the east-west rainfall gradient: the presence of the channel reduces rainfall in East Africa and contributes to the high rainfall totals in Central Africa. The decrease in rainfall over East Africa induced by the Turkana Channel is consistent across all months.

Changes to the integrated water vapour transport (IWVT) help to diagnose the rainfall alterations (Figure 3). In the Turkana Block experiment (Figure 3a) there is little easterly water vapour flux from east to central Africa north of the equator, as the Turkana low-level jet is no longer present. IWVT anomalies in the Turkana Block experiment are over 100 $kg.m^{-1}.s^{-1}$. The weakened easterlies are still present in the incipient valley experiment (Figure 3b). In the deeper-valley experiment (Figure 3c) there is enhanced easterly water vapour export, associated with the reduced rainfall in East Africa compared to the control. Downstream of the valley in South Sudan, rainfall decreases in the deeper-valley experiment as there is increased moisture divergence with a stronger jet. In the blocked experiment, rainfall increases in the South Sudan region.

Pan-African effect of Valleys

The Turkana Jet is one of five major easterly LLJs which form across the East African Rift System, the others forming in the Limpopo and Zambezi river valleys, and across topographic lows in the Tanzanian and Malawi highlands[17,24,25]. These LLJs, and associated valleys, are important for water vapour export, and we posit that they have a similar effect on the east-west rainfall gradient.

To test this hypothesis, we carry out an additional experiment (E - No Valleys), which blocks all the major topographic lows across the East African Rift System, from the Turkana Channel in the north to the Limpopo River Valley in the south (Figure 4). One can think of this experiment as imposing Andean-like topography across the eastern part of Africa. We find a pan-African effect on the annual mean rainfall (Figure 4). Rainfall increases across the entire eastern coastal sector of Africa and in the equatorial Indian Ocean, while there is large scale drying in the continental interior, and particularly along the western coast and in South Africa.

In the 'No Valley' experiment, the large-scale wetting is associated with a reduction in water vapour flux through the major valleys (Fig. 4c and 4d). In the control experiment, meanwhile, the valleys in the Rift System export water vapour from East Africa. The total, integrated water vapour transport (IWVT) across the rift system (see Methods) in the 'No Valley' experiment ($2.14\text{x}10^8$ kg.s^{-1}) is 25% less than in the control ($2.82\text{x}10^8$ kg.s^{-1}). This leaves more water vapor available for rainfall across Eastern Africa in the 'No Valley' experiment ($3.66\text{x}10^7$ kg.s^{-1}) compared to the control simulation ($2.73\text{x}10^7$ kg.s^{-1}) (see Methods for moisture budget calculation).

Discussion

The presence of valleys within the East African Rift System leads to a drier East Africa, and wetter Congo Basin. Previous modelling studies have implicated the rift system in East African dryness[12,26–28], but the shared assumption in these studies is that the uplift alone - which mainly occurred prior to 10 Ma - causes the aridity. In the 'No Valley' experiment, we show mechanistically that uplift alone does the opposite: the removal of valleys reduces the water vapour export from East Africa, while the regions of high topography act as an elevated heat source. This favors convection in East Africa, while necessarily reducing convection in the Congo rainforest, as diagnosed by the reduction in water vapour transport across the Rift System. Another important factor in East African aridity, The Somali Jet, strengthens in response to an uninterrupted barrier in the blocked valley experiments (Figure 3). This is consistent with other modelling studies, which show a weakening of the Somali Jet when the Rift System is lowered[26,28].

The expansion of grassland and mixed habitats, at the expense of dense forest, across East Africa in the last 8 million years is linked with broad faunal turnover[1], and is a cornerstone for a number of hypotheses relating to hominid evolution[2,4,29–32]. The lower rainfall in East Africa due to the formation of valleys is capable of explaining the large-scale vegetation shift. While estimates for the timing of valley formation vary between studies and across EARS, processes occurring in the last 10 Ma have shaped the present-day morphology[11,18]. Other global climate events could have contributed to the expansion of grasslands, including the late Miocene Cooling (5-7 Ma)[33] and onset of Northern Hemisphere glaciation (~2.75Ma)[34], but the development of valleys is an obvious proximate driver for rainfall change. Today, the presence of valleys is a key explanation for why East Africa is curiously dry for its latitude and prone to drought.

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Figure Legends

Figure 1 Overview of model experiments. *Surface altitude [m] for the four Turkana experiments: a) Turkana Block; b) Turkana Incipient; c) Control; d) deeper-than-observed channel. The 'T' marks the location of the Turkana Channel.*

Figure 2: The Turkana Channel influences the east-west rainfall gradient in tropical Africa. *Annual rainfall anomalies in the experiments compared to control ($mm.yr^{-1}$) for a) Turkana Block, b) Turkana Incipient and c) deeper-than-observed channel. Gray contours indicate regions with statistically significant differences between the Control and the experiments based on the two-tailed Mann-Whitney U test, after controlling for the False Discovery Rate (FDR), following Wilks (2016)*[23] *(See Methods). The p_{FDR} (n=20) values are 0.024, 0.002, 0.0008 for a-c), respectively*

Figure 3 Water vapour export from East Africa increases as the Turkana Channel deepens. *IWVT anomalies ($kg.m^{-1}.s^{-1}$; shading) and vectors compared to control (annual mean) for the three Turkana experiments compared to control: a) Turkana Block, b) Turkana Incipient c) deeper-than-observed channel. Gray contours indicate regions with statistically significant differences (evaluated on IWVT field) calculated via the two-tailed Mann-Whitney U test, after controlling for the False Discovery Rate (FDR), following Wilks (2016)*[23] *(See Methods). p_{FDR} values (n=20) are 0.032, 0.001, 0.001 for a-c), respectively*

Figure 4 Valleys lead to lower rainfall in East Africa with increased water vapour export across the rift system. a) *Surface altitude (m) for the control simulation b) The rainfall anomaly (No Valley - Control; $mm.yr^{-1}$). Vertical cross sections of the water vapour flux ($kg.kg^{-1}.m^{-1}s^{-1}$) perpendicular to the black line shown in a) (positive easterly, negative westerly) for c) the Control and d) 'No Valleys' experiments. The black filled area indicates the surface height in each experiment. The gray contours in b) indicate statistically significant differences in* *rainfall, calculated via the two-tailed Mann-Whitney U test, after controlling for the False Discovery Rate (FDR), following Wilks (2016)[23] (See Methods). The p_{FDR} values (n=20) is 0.022.*

Methods

The Model

The model used is the UK Met Office Unified Model set up in the GA7.05 configuration[35]. The model run is from 1990-2009 at a 25 km horizontal resolution over a pan-African domain (34.5°S-25°N, 13°W-73°E). The model has a non-hydrostatic semi-implicit and semi-Lagrangian dynamical core[36] and uses a mass-flux convection scheme based on Gregory and Rowntree (1990)[37]. Lateral atmospheric boundary conditions are provided by six-hourly fields of temperature, humidity, winds and surface pressure[38] from ERA-Interim reanalysis[39] and daily sea-surface temperatures are prescribed based on the NOAA Daily OISST v2.1 daily reanalysis[40].

To establish the adequacy of the control run, we compare the model data with observed and reanalysis datasets. For precipitation, we compare climatological rainfall with Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) precipitation[20] and Global Precipitation Climatology Project (GPCP) version2.2[21] (Extended Data Figure 1). The control run captures the observed distribution of rainfall over Africa, with rainfall hotspots over Madagascar; the Ethiopian Highlands; the Kenyan Highlands; the Rwenzori Mountains and the Cameroonian Highlands. Compared to CHIRPS, the model overestimates rainfall in some of these regions, including in parts of Central Africa and the Ethiopian Highlands. The overestimation of rainfall in the Congo Basin is a common issue across climate models (e.g.[41,42]). The model performs excellently in East Africa, successfully simulating the low annual rainfall totals.

We compare the model circulation with the latest European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis product (ERA5)[19]. We focus our attention on the zonal and meridional vertically-integrated water vapour transport which is a key diagnostic in Figures 3. These are calculated on model levels using specific humidity (q) and zonal (u) and meridional (v) winds, as:

$$\boldsymbol{Qu} = \int_{surface}^{toa} q\boldsymbol{u}\frac{dP}{g}$$

$$\boldsymbol{Qv} = \int_{surface}^{toa} q\boldsymbol{v}\frac{dP}{g}$$

$$\boldsymbol{IWVT} = \sqrt{\boldsymbol{Qu}^2 + \boldsymbol{Qv}^2}$$

Where *P* is pressure and g is gravitational acceleration (9.81 m.s^{-2}), and IWVT is the integrated water vapour transport (kg.m^{-1}.s^{-1}). The model performs very well in simulating the integrated water vapour flux in comparison with the ERA5 reanalysis (Extended Data Figure 2). In particular, the model is able to capture the magnitude and distribution of easterly valley jets along the East African Rift System (including the Turkana Jet at ~3°N, 36°E), as well as the southeasterly and southwesterly components of the Somali Jet in the western Indian Ocean.

The Experiments

Figure 1 shows the topography in experiments A to D and Figure 4d shows the topography cross section in experiment E. For each experiment, we manually edited the valleys in the high-resolution topography file (1km-resolution; NOAA GLOBE digital elevation model[43]) using the open-source GIMP editing software. We altered the high-resolution topography file to address both resolved and sub-grid scale orographic influences (for example, orographic drag), which are parameterized in the model. The altered high-resolution orography field was used to create new ancillary files (boundary conditions) for each experiment.

The experiments differ from other approaches to understanding orographic effects, which apply a scaling factor to the overall orographic field, for example, by progressively reducing the height of the topography by a given percentage. The approach employed here allows us to isolate the effect of the specific geomorphology of interest: the valleys. Since the aim of the experiments is to isolate the effect of valleys on African climate, we do not purport to reproduce specific time spans of Earth’s history. The latter is made difficult by a paucity of data of conditions at the time, and a lack of agreement between studies on the actual evolution of African topography over the Miocene-Pliocene period[11]. The sensitivity of African climate to valleys, revealed in our experiments, suggests that to clarify temporally linked orographic and climate dynamics, data needs to be collected at a sufficient resolution to allow timescales of valley development to be distinguished from broader scale uplift rates.

Moisture Budget calculation

We calculate the moisture budget for the East African region upstream of the Rift System shown in Extended Data Figure 1. Based on the Qu and Qv component of the integrated moisture flux, we first use the Metpy cross section components function (https://unidata.github.io/MetPy/latest/api/generated/metpy.calc.cross_section_com ponents.html) to find the component of the IWVT normal (inflow) to each segment of the regional boundary (Qn). We then integrate across each segment separately to find the total segment contribution:

$$\boldsymbol{Q_{seg}} = \int_{\boldsymbol{l_0}}^{\boldsymbol{l_n}} \boldsymbol{Q_n dl}$$

Where l is the length of the segment (m), and $\boldsymbol{dl}$ is ~26,000 m (corresponding to the average grid length for the model). We define positive contributions as moisture entering the region, and negative contributions as moisture leaving the region. Finally, we sum the contributions from all segments to calculate the moisture budget.

Statistical Testing

The 2-tailed Mann-Whitney U test is used to evaluate a null hypothesis of no difference between the experiments and the control (n=20 years). We follow Wilks (2016)[23] in applying a constraint on the False Discovery Rate (FDR) based on the distribution of p-values from each grid point in the composite map. The false discovery control level (α_{FDR}) is set conservatively following Wilks (2016) as $2\alpha_{global}$, where $\alpha_{global}=0.05$, such that $\alpha_{FDR}=0.10$. We report the threshold p_{FDR} for each test in the relevant Figure captions.

Data Availability

Model data arising from this paper used in plotting, and the edited high-resolution GLOBE dataset orography files for each experiment are available on publication at 10.5281/zenodo.6956995. ERA5 data is downloaded from (https://cds.climate.copernicus.eu/cdsapp#!/home). CHIRPS data is available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/. GPCP data is from https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00979. Data used in base maps for figures is publicly available from https://www.naturalearthdata.com/ and plotted with Cartopy (https://github.com/SciTools/cartopy/archive/v0.11.2.tar.gz)

The Met Office Unified Model is available for use under license. For further information on how to apply for a license, see http://www.metoffice.gov.uk/research/modelling-systems/unified-model

Code availability

Code for producing figures is available on publication at 10.5281/zenodo.6956995

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Author Contributions

C.M designed and ran the model experiments and wrote the manuscript. N.S helped setup and run the model experiments, and wrote part of the Methods section. R.W contributed to the design of the experiments and edited the manuscript. R.J contributed to the experimental design and edited the manuscript.

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Extended Data Legends

Extended Data Figure 1 Water vapour transport in control and reanalysis data *The arrows show the direction and strength at which atmospheric-column integrated water vapour is being transport (kg.m^{-1}.s^{-1}) in a) Control Experiment and b) ERA5. Shading gives the integrated water vapour transport (IWVT) magnitude (kg.m^{-1}.s^{-1}) (see Methods). The eastern African region we use to evaluate the moisture budget is bounded by the red line in a). ERA5 data[19] is available at (https://cds.climate.copernicus.eu/cdsapp#!/home).*

Extended Data Figure 2 Evaluation of rainfall in the control simulation. *Annual rainfall (mm.yr^{-1}) in a) The Control, b) CHIRPS and c) GPCPv2.2. CHIRPS[20] data is available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/. GPCP data[21] is from: https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00979.*