Clim. Past, 20, 2701–2718, 2024
https://doi.org/10.5194/cp-20-2701-2024

Climate
of the Past
Open Access

Documents, reanalysis, and global circulation models: a new method for reconstructing historical climate focusing on present-day inland Tanzania, 1856–1890

Philip Gooding[1], **Melissa J. Lazenby**[2], **Michael R. Frogley**[2], **Cecile Dai**[1], **and Wenqi Su**[1]

[1]Indian Ocean World Centre, McGill University, Montreal, H3A 0E6, Canada
[2]Department of Geography, University of Sussex, Brighton, BN1 9RH, United Kingdom

Correspondence: Philip Gooding (philip.gooding@mcgill.ca) and Melissa J. Lazenby (m.lazenby@sussex.ac.uk)

Received: 12 May 2023 – Discussion started: 9 June 2023
Revised: 25 July 2024 – Accepted: 16 October 2024 – Published: 12 December 2024

Abstract. This article proposes a novel methodology for reconstructing past climatic conditions in regions and time periods for which there is limited evidence from documentary and natural proxy sources. Focusing on present-day inland Tanzania during the period 1856–1890, it integrates evidence from qualitative documentary sources with quantitative outputs from climate reanalysis and global circulation models (GCMs), which enables the creation of interdisciplinary seasonal time series of rainfall variability for three distinct locales. It does so by indexing each dataset to the same seven-point scale and weighting each output according to a predefined level of confidence in the documentary data. This process challenges the subjectivity of nineteenth-century Europeans in Africa, whose reports form the basis of the documentary material, and adds evidence from the region, which is currently lacking from the latest reanalysis products and GCMs. The result is an interpretation of documentary materials that is grounded in methods from both the humanities and natural sciences, as well as a more locally grounded estimation of rainfall that would otherwise be gained from referring to reanalysis or GCMs alone. The methodology is validated with reference to observed long-term trends gathered from (paleo)limnological studies and short-term trends gathered from documentary materials and instrumental records in nearby regions. It is shown to provide marked insights into four periods of environmental stress in the region's late nineteenth-century past. Future challenges may involve integrating evidence from oral traditions, which will require more in-region research and collaboration, and adapting the methodology for other regions and time periods.

1 Introduction

Building models that project the future effects of climate change is partly dependent on understanding climatic variability in the past. Since around the mid-twentieth century, this fact has acted as a mandate for historical climatologists to reconstruct past climatic conditions through the use of existing statistical records (e.g. rain gauges), natural proxies (e.g. tree rings), and climate forcings (e.g. well-mixed greenhouse gases), which has led to the creation of a number of global climate models, drought atlases, and reanalysis products. Additionally, in the last 20 years, climate historians have increasingly sought to make contributions, largely through indexing qualitative descriptions of weather and climate held in archives (Nash et al., 2021; Adamson et al., 2022). This article integrates these two methodologies to make interdisciplinary time series for seasonal rainfall in three locations in what is now inland Tanzania during the second half of the nineteenth century.

Integration of climatological and historical methods for this case study is a necessity borne out of the nature of the source material. While climate reanalysis and global circulation models (GCMs), including the Twentieth Century Reanalysis Project (20CRv3) and the Climate Modelling Intercomparison Project (CMIP5), estimate rainfall in the region for the period under review, they either incorporate very few proxies or no proxies at all (natural or archival) from Africa. For Africanists in the humanities and social sciences, Africa's absence from the underlying data makes deploying these projections uncomfortable, as it partly represents the continent's marginalization from global scientific discourse during and after colonialism. Nevertheless, the models are tantalizing, especially to equatorial eastern Africanists. Depending on the product used, they suggest daily, monthly, and annual estimations of rainfall, all of which represent a greater temporal resolution than that which is gatherable from the natural proxies in the region that have been analysed up to now, which are mostly limited to reconstructions of past lake levels (Nicholson and Yin, 2001; Verschuren et al., 2000; Bessems et al., 2008; Russell and Johnson, 2007; Alin and Cohen, 2003).

The historical documents for late nineteenth-century inland Tanzania are additionally problematic (cf. Brönnimann and Wintzer, 2019). They were written almost entirely by Europeans, including by so-called "explorers" and missionaries, who regularly understood the peoples, environments, and climates they encountered through frameworks underpinned by enviro-climatic determinism (Gooding, 2019; Gooding, 2022a; Rockel, 2022). In addition, they discussed climatic conditions irregularly. For example, although the first Europeans to document enviro-climatic conditions first-hand in inland Tanzania did so in 1856–1861, another did not do so again until 1869 (Burton, 1860; Speke, 1864a, b; Livingstone, 1875). Further, no individual European documented changing climate in a particular locale until the first missionaries settled in Mpwapwa in 1876, and even then their reporting was uneven. Thus, despite occasionally including reports on weather and weather-affected phenomena that can regularly be transformed into time series of climate variability (see Mutua and Runguma, 2020), any indexed time series made solely from European documents would necessarily rely on thin data, especially for the earlier decades under review, for which there are often no data at all.

Therefore, this article seeks to create time series of seasonal rainfall that incorporate data from reanalyses, GCMs, and documentary sources. It argues that evaluating the climatological materials against documents for seasons and years where the documents provide ample evidence allows them to be deployed with a certain degree of (un)certainty in years where documentary data are lacking. Where the documentary data are thin, the models improve the precision and/or revise conclusions that may otherwise have been made. Where the documentary data are non-existent, the models can be used in lieu, with a qualified amount of (un)certainty. In making these claims, the article also provides a rubric for historians and climatologists to use each other's sources to improve their reconstructions of past climatic conditions in different locales. This methodology provides climatologists with a more robust picture of past climates with added value from documentary datasets. Likewise, it enables historians to make interpretations of documentary materials that are rooted in the natural sciences as well as the humanities.

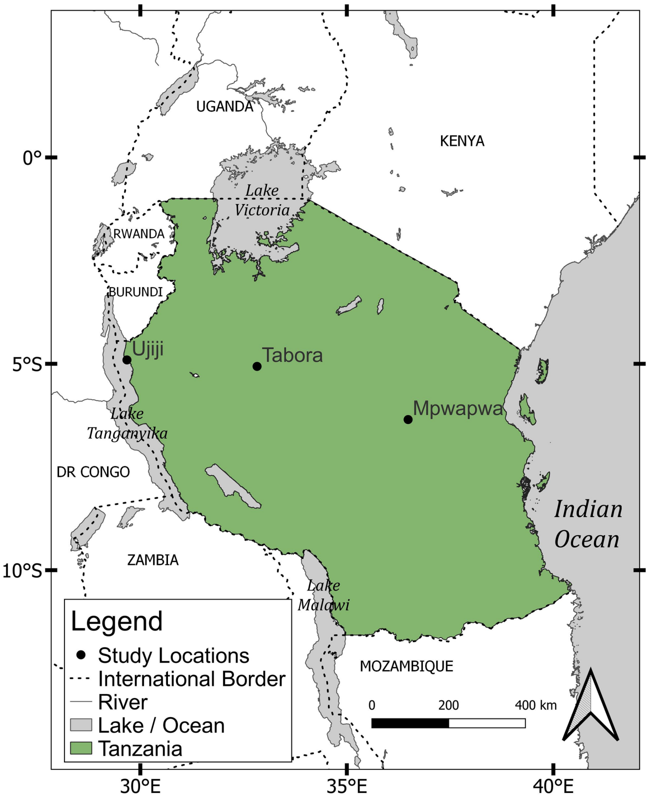

Figure 1. Map showing locations of three case study regions, Mpwapwa, Tabora, and Ujiji in inland Tanzania. The base map is taken from Wessel and Smith (1996). The shapefile for the green area marked as Tanzania is taken from Tanzania National Bureau of Statistics, UN OCHA ROSA (https://data.humdata.org/dataset/cod-ab-tza, last access: 2 December 2024).

The case study focuses on three towns in present-day inland Tanzania: Mpwapwa, Tabora, and Ujiji (Kigoma) (Fig. 1). These locales are chosen for several reasons. First, they were the three most important inland towns on a long-distance caravan route between the equatorial eastern African coast and Lake Tanganyika during the nineteenth century, on which ivory was the primary article of commerce. They thus have historical significance (Rockel, 2006; Pallaver, 2020; Gooding, 2022b; Castryck, 2022). Second, and partly because of their significance, nineteenth-century Europeans passed through and settled in their locales with more regularity than in other parts of present-day inland Tanzania, meaning that the documentary source base that refers to them is relatively abundant. Third, they are all on roughly the same latitude (between 4.5 and 6.5° S) and experience rainy seasons at roughly the same time: Mpwapwa receives most of its rainfall between December and April, Tabora and Ujiji receive most of theirs between November and April. Thus, it is expected that they would receive abundant, normal, and deficient levels of rainfall at roughly the same time – a phenomenon which is supported by existing climatological studies (Nicholson, 2017a).

To be clear, this is not the first interdisciplinary project to attempt to reconcile historical and climatological sources for equatorial eastern Africa. Sharon E. Nicholson was at the forefront of such efforts in the 1990s and 2000s, culminating in her masterful annual (January–December) reconstruction of Africa's rainfall variability in the nineteenth century, co-authored with Amin K. Dezfuli and Douglas Klotter (Nicholson et al., 2012, 2018). This dataset was developed from a mixture of rain gauge records, documentary sources, oral traditions, hydrological sources, and spatial reconstructions, although rain gauges are generally lacking for inland Tanzania. Further, Nicholson (2017b) has since made calls for historians to improve the documentary source base of such reconstructions, and she has noted the difficulty of placing oral traditions in time. Additionally, the annual (January–December) timescale of the Nicholson et al. (2012) reconstruction obscures seasonal variation in inland Tanzania's rainfall, as the region's rainy season transcends the beginning and end of a Gregorian year. Nevertheless, the hydrological sources, which are largely limited to limnological studies, point to broad trends that must be borne in mind when creating any time series of rainfall in the region, notably that they suggest a generally wet period from ca. 1840 until the mid-late 1870s and regular droughts from then until the early twentieth century (Hastenrath, 2001; Nicholson and Yin, 2001; Nicholson, 1999). Further, reconstructions based on documentary materials focused on nearby regions, including Kenya (Mutua and Runguma, 2020) and Malawi (Nash et al., 2018), as well as occasional data points deriving from rain gauges located in Zanzibar, Mombasa, and Kampala (Nicholson et al., 2012) provide additional validating material.

This article, therefore, adds new documentary and climatological sources to the latest reconstruction of nineteenth-century African climate, focusing on a particular region's seasonality rather than being constrained by the Gregorian calendar, while also bearing in mind observed long- and short-term trends in the wider equatorial eastern African region. It is hoped that the methodology developed in this article, which provides a rubric for integrating historical and modelled data and suggests ways that global climate reconstructions may be used as a representation for rainfall when there is little or no in-region archival or natural proxy evidence, may be adapted for other regions and time periods, including pre-1850 equatorial eastern Africa, for which oral traditions are essential to historical writing focused on the region. Research that incorporates oral traditions in this way, however, is contingent on more in-region research and collaboration.

The remainder of the article is divided into four sections. The first analyses the documentary data and the time series developed from it, incorporating degrees of (un)certainty for different data points. The second analyses the GCMs, reanalysis, and the trends for inland Tanzania's rainfall that can be observed from them. The third develops a methodology for integrating the historical and climatological data, and the final section describes the resultant time series and its implications for understanding rainfall patterns in inland Tanzania during the second half of the nineteenth century.

2 Documentary sources: "explorers" and missionaries

The documentary data referring to inland Tanzania in the years 1856–1890 comes in two forms. For the first ca. 20 years, it is comprised of "explorer" sources, such as those written by Burton (1860), Speke (1864a, b), Livingstone (1875), Stanley (1872, 1878), and Cameron (1877). These Europeans visited the region at different times, often observing climatic and environmental phenomena as they travelled and gathering information about previous seasons and years from informants. The second type of document consists of the letters and diaries of Europeans that resided in the region from ca. 1876, who were mostly missionaries. They were representatives the Church Missionary Society (CMS), the White Fathers (Père Blancs), the London Missionary Society (LMS), and the International African Association (Association Internationale Africaine, AIA). These sources provide a longer and more detailed time series of data about climatic and environmental conditions. Thus, generally speaking, the precision and accuracy of the documentary data is greater for the final ca. 15 years of the period under review than for the first 20, notwithstanding some exceptions.

Although each document type provides somewhat distinct opportunities and challenges for creating an indexed time series of rainfall, there are some prevailing themes. In general, "explorers" and missionaries were highly interested in documenting climatic conditions and variations, although their interest varied over time and space and between each author. Descriptions of rainy days, flood events, pasture conditions, and harvests, which are all to varying degrees related to climatic conditions, are abundant and can be used to make time series of rainfall variability (Nash et al., 2018; Mutua and Runguma, 2020). However, this feature of the documentary material is also highly problematic. Nineteenth-century meteorology, like cartography (Wisnicki, 2008), was part of a wider practice that sought to impose European science, and thus Europeans' ideas of "civilization", on equatorial eastern Africa(ns), erasing indigenous patterns of human–environment interaction and their understandings of climate and weather. In addition, missionaries' regular reports of drought and associated hardships acted partly as justification for European intervention in African affairs, which they (wrongly) assumed would increase drought resiliency (Gooding, 2023; Kjekshus, 1996; Doyle, 2006). As has been argued elsewhere, these reports may have been exaggerated to provoke emotional responses from readerships at home, who funded their missions (Endfield and Nash, 2002). At other times, missionaries may have minimized the degree of hardship to emphasize their missions' feasibility (Gooding, 2022a). In short, although highly valuable, the documents are highly subjective, and they both affected and were influenced by imperial knowledge-making, contributing to the "Scramble for Africa" from the mid-1880s.

Given this historical background (and in line with other documentary sources for other regions and time periods), it is probably unsurprising that Europeans commented on climatic conditions more when they were extreme, such as in instances of severe drought or floods, than during months, seasons, and years of regular rainfall (see Pfister, 1995; Brázdil, 2000; Brázdil et al., 2005). Droughts and floods had adverse impacts on Europeans' and surrounding societies' everyday lives and were thus deemed worthy of reporting. Such reports also appealed to their readership's understanding of African climates and environments. However, the reports still often lacked specificity. Europeans might instead refer to the health of crops and their ability to travel. For example, crops "threatening to dry out before they were mature" is a strong indicator of drought in the months leading up to the statement, while a missionary report of having to divert his direction of travel because of a "terribly flooded country" is probably indicative of excessive rainfall (A.G.M.Afr. Diaire de Bukumbi, 24 May 1884; CMS C/A6/O/16 Mackay to Smith-MacKenzie & Co, 16 May 1878). Thus, inferences must often be made from climate-affected phenomena, such as harvests, to suggest rainfall conditions. It also means that more certainty can be gathered from the documentary archive for extreme weather events than for years of average or close-to-average rainfall. Absence of discussion about climatic conditions may be indicative of regular rainfall, especially if there are no reports of disruptions to phenomena that are regularly affected by rainfall extremes, such as harvests and travel (Mutua and Runguma, 2020). Nevertheless, such an assumption necessarily comes with a degree of uncertainty (Pfister, 1995; Pfister et al., 2018).

Data from "explorer" sources additionally provides distinct challenges beyond the fact that there are several temporal gaps between reports. Lack of knowledge about the region's climate may have led to errors in reporting. For example, Richard Burton, who in 1857–1858 was a member of the first European party to travel to Lake Tanganyika, wrote that Ujiji's rainy season lasted from September to May, contrary to current scientific knowledge, which places the rainy season between November and April (Burton, 1860). There are at least two possible reasons for this discrepancy. The first is that the rainy season was particularly long in 1857–1858 and that he made assumptions based on his own experience. The alternative is that he mistakenly integrated secondary information about the "lake regions" of eastern Africa into his assessment of Ujiji's climate: a September–May rainy season broadly aligns with conditions on the northern shores of Lake Victoria, even if December–February is usually drier than September–November and March–May in the latter region. Nevertheless, a tantalizing reference to a flooded river in a normally arid zone about 100 km west of Mpwapwa in September 1857 suggests that inland Tanzania's rainy season may have begun significantly early in 1857–1858 (Burton, 1860). At the same time, Burton (1860) wrote that the rainy season began around Tabora in November 1857, lasting until mid-May 1858. Unfortunately, given the time gaps between different "explorer's" travels, there are no other documentary sources with which to verify or challenge Burton's reports. Thus, references such as these often provoke as many questions as answers, even though there might be a suggestion (in this instance) of an especially protracted rainy season in certain locales.

Other challenges arise from the missionary sources. The peak of their reports on climatic conditions occurred as they entered the region in the mid-to-late 1870s. This was likely informed by an enthusiasm for their "civilizing" project, of which imposition of European scientific methods and measurements was an important component. However, references to climatic conditions and their effects often became more fleeting over time: other factors, such as relations with indigenous rulers, the successes and failures of gaining converts, and internal disputes, started to dominate missionary reporting from the early 1880s. Additionally, adversity with populations in Ujiji led members of the LMS to abandon their station there in 1883, meaning that their reporting on climate over the town becomes less certain thereafter. Often, reports from nearby stations, such as at Kibanga and Kavala Island, are necessary to supplement the data. Meanwhile, in the same year, CMS missionaries temporarily moved the core of their Mpwapwa station 8 km out of town to Kisokwe, on the edge of a perennial river, enabling them to irrigate their garden. Thus, some subsequent reports of productive garden work and abundant harvests are probably more indicative of successful use of infrastructure than of rainfall (CMS G/3/A/5/O Cole to Lang, 17 January 1883; CMS G/3/A/5/O Cole to Lang, 15 February 1883; CMS G/3/A/5/O Cole to Lang, 1 July 1883).

Notwithstanding these challenges, this article uses a seven-point index system to quantify the qualitative descriptions of rainfall variability and its effects. This makes its outputs broadly comparable to those from the Nicholson et al. (2012) dataset for Africa's nineteenth-century rainfall, which also uses a seven-point system, even if the different methods and sources used mean that the datasets are not entirely interoperable. The decision to use a seven-point system instead of a five-point or three-point system, which are also commonly used in climate indices, reflects the high level of granularity in many of the documentary reports, especially from missionaries (cf. Pfister et al., 2018). The definitions of each index value are displayed in Table 1, along with descriptions about how the documentary index classes were derived from qualitative descriptions. Narrative evidence was collaboratively read and then graded for the time period to which the document(s) referred according to these definitions (see Adamson et al., 2022). Additionally, each line of data was graded on a two-point scale indicating how "certain" it is. A grade of 1 indicates a high degree of uncertainty, caused by ambiguity in the description, lack of verifying documentary material, the use of data from nearby locations as a proxy, and/or use of proxies that are imperfect indicators of rainfall conditions (such as abundant harvests from irrigated fields). Thus, almost all data points provided by "explorers" are given an uncertainty grade of 1. A grade of 2 indicates a higher degree of certainty, caused by the climate conditions being described in detail, by more than one source, and/or from within the locale to which the time series applies (Mpwapwa, Tabora, or Ujiji). A visualization of the data is shown in Fig. 2. Occasionally the data are abundant enough that changes within a season are observable. More frequently, an indexed value is attributed to the season as a whole.

The three time series reflect a total of 151 lines of data: 55 for Mpwapwa, 52 for Tabora, and 44 for Ujiji. The datasets underpinning Fig. 2, including transcriptions and comments on individual references, are available by link in the "Data availability" section. Each line of data refers to climatic conditions during a given period, ranging from 1 month to an entire rainy season. The number of documentary references for each line is between 1 (several) and 12 (line 31 of the Ujiji dataset). The latter example refers to November–December 1886 and includes data from a letter written by an LMS missionary based at Kavala Island and 11 separate diary entries by a White Fathers' missionary based at Kibanga. At Kavala Island, the LMS representative reported in early January that farmers had recently gone to the mainland to cultivate, which is later than usual and could suggest a slightly delayed beginning to the rainy season (CWM/LMS/06/02/012 Lea to Thompson, 6 January 1887). However, the evidence from Kibanga has much more granular data, with reports of "clouds . . . gathering" and abundant rain from the end of October (A.G.M.Afr. Diaire de Kibanga, 19 October 1886, 22 October 1886, 25 October 1886, 27 October 1886, 10 November 1886, 22 November 1886, 26 November 1886, 30 November 1886). That these were not just episodes of rainfall but part of a broader trend is confirmed by reports written in December, during which heavy rainfall caused a nearby stream to overflow on 1 December, following which the missionaries were able to plant wheat on 6 December, and on 16 December there were "big rains. . . these days" (A.G.M.Afr. Diaire de Kibanga, 1 December 1886, 6 December 1886, 16 December 1886). Read collectively, it was determined that these reports suggested slightly above-average rainfall in Ujiji (index value = 1) for November–December 1886 (see Nash et al., 2021). However, as the reports were made outside rather than within Ujiji, this data point only received a confidence value of 1. In addition to published data by "explorers", which provide references for all locales, data for Mpwapwa is informed principally by documents held in the CMS archive, with documents from the White Fathers' archive providing additional information for 1880–1882; the Tabora dataset is equally informed by documents in the CMS and White Fathers' archives, with occasional references to the LMS archive; and the Ujiji dataset is informed equally by references in the LMS and White Fathers' archives and by one reference from the AIA archive.

In their totality, the documentary datasets indicate certain region-wide trends. As expected, there is a limited quantity of data, especially data for which we attribute high levels of confidence, for the first 20 years under review, but there is a marked improvement on both counts from the second half of the 1870s. In line with expectations from the Nicholson et al. (2012) dataset, drought seasons and years were regular from this point onwards, apart from during a possible flood event in 1877–1878. These trends are largely supported by (paleo)limnological research that was conducted in the 1990s–2000s, which indicates declining lake levels across all the region's lakes from the late 1870s, a phenomenon that has regularly been attributed to frequent droughts (Nicholson and Yin, 2001). Additionally, the documents suggest severe drought across the region in the 1876–1877, 1879–1880, and 1883–1884 seasons (although the sources are uncertain for Ujiji in 1883–1884). Such records are broadly in line with rain gauge data from Kampala and Mombasa and with evidence from documentary materials referring to southern Kenya (Nicholson et al., 2012; Mutua and Runguma, 2020). As some historians have recently suggested, these climatic conditions may have been triggered by extreme El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) anomalies and atmospheric disturbances following the eruption of the Krakatau volcano in 1883 (Gooding, 2019; Rockel, 2022; Gooding, 2022b, c). Further climatological research would help to verify or challenge these summations.

Additionally, there are some regional differences within the data. Although the sources are uncertain, the documents suggest regular levels of rainfall in Mpwapwa during the second half of the 1882–1883 season, despite evidence for below-average rainfall around Tabora and Ujiji. This scenario at Mpwapwa is made more uncertain because the subsequent season coincided with widespread famine. This may be indicative of previous harvests being insufficient, triggered by deficient levels of rainfall, decreasing societal resilience to region-wide drought in 1883–1884 and thus putting into question the validity of observations gathered from missionary correspondence in 1882–1883 (Rockel, 2022). In any case, missionary reports are unequivocal that the underlying cause of famine in 1883–1884 was drought, even if structural factors may additionally have exacerbated shortages (CMS G/3/A/6/O Price to Lang, 2 May 1884; CMS G/3/A/6/O Price to Lang, 2 May 1884; CMS G/3/A/6/O Price to Lang 5 August 1884).

However, other differences between datasets are more immediately acceptable. The sources are explicit that rainfall was somewhat regular around Tabora and Mpwapwa in 1885–1886 and that the region around Ujiji was comparatively dry in the second half of the rainy season (although rainfall may have been excessive earlier on). For example, a member of the White Fathers that travelled between Tabora

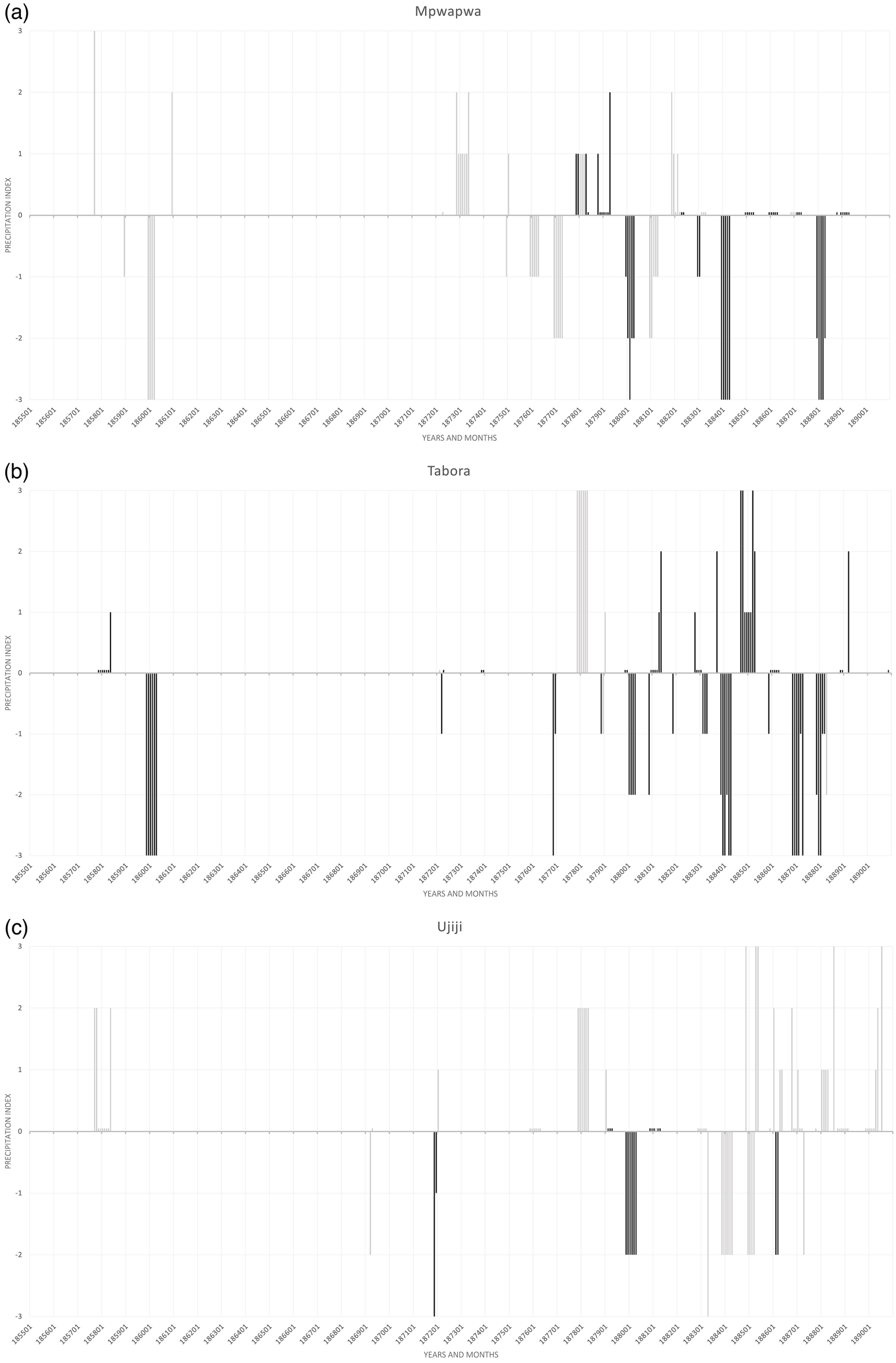

Figure 2. Time series plot of indexed rainfall for **(a)** Mpwapwa, **(b)** Tabora, and **(c)** Ujiji in 1856–1890. Solid black bars indicate the highest level of certainty from archival data (CL = 2), and grey bars indicate a reduced certainty level (CL = 1). Values of +0.05 are equal to 0 on the index. They are indicated on the plots as +0.05 to distinguish them from the seasons with no documentary data.

Table 1. Definitions of index values used to interpret qualitative descriptions of rainfall variability and its effects contained within documentary materials.

Index value	Description
−3	Drought-driven famine: source(s) indicate that a famine was tied specifically to drought conditions (see Rockel, 2022).
−2	Deficient rainfall: source(s) indicate adverse effects, such as reduced harvests or increased prices (but without references to "famine"), stemming from drought.
−1	Below-average rainfall: source(s) indicate that seasonal rain has fallen in the given period but that there were shorter periods where it did not fall when ordinarily it would have done.
0	Average rainfall: source(s) indicate no abnormalities, with supporting material indicating that planting, harvesting, and/or trading occurred according to normal seasonal cycles.
1	Above-average rainfall: source(s) indicate early start or late end to the rainy season and/or has references to "strong" or "abundant" rains.
2	Excessive rainfall: source(s) indicate adverse effects from overly abundant rainfall, such as localized infrastructure damage but without references to widespread flooding.
3	Rainfall-driven floods: source(s) indicate widespread floods in terrestrial zones (i.e. away from rivers that might seasonally burst their banks) that were tied to overly excessive rainfall.

and Ujiji in early 1886, wrote that, having had abundant rainfall around Tabora up to February, "almost everywhere we encountered nothing but perfectly dry roads, and more than once we saw ourselves on the point of suffering from thirst in places where usually, at such a season, one travels in water" (A.G.M.Afr. Unknown to White Fathers, 14 March 1886). According to other missionary sources, this drought affecting Ujiji may have extended northwards to the southern shores of Lake Victoria (A.G.M.Afr. Diaire de Bukumbi, 30 December 1885, 2 January 1886, 5 January 1886, 15 February 1886, 17 February 1886, 23 February 1886, 26 February 1886, 4 March 1886, 11 March 1886, 1 May 1886, 2 May 1886) and southwards over present-day Malawi and towards the southern Kalahari Desert (Nash et al., 2018).

Similarly, the sources indicate that the drought that affected Ujiji and Tabora in 1886–1887 did not extend to Mpwapwa and that the drought of 1887–1888 affected Mpwapwa and Tabora but not Ujiji. A diary entry in the White Fathers' archive, for example, directly contrasts an abundance of water around Mpwapwa with dryness in the vicinity of Tabora following the 1886–1887 rainy season (A.G.M.Afr. Diaire de Kipalapala, 30 May 1887). Meanwhile, a rain gauge temporarily stationed on Kavala Island, Lake Tanganyika, suggests regular rainfall in the first half of 1888 in Ujiji, contrary to several reports of drought in Tabora and Mpwapwa. The rain gauge further suggests that rain was more abundant in 1887–1888 than in 1885–1886 and 1886–1887, 2 years for which the documents suggest there was drought (Hore, 1892). Meanwhile, in both 1886–1887 and 1887–1888, documentary sources suggest that drought also affected regions around Lake Victoria, including around present-day Kampala, Uganda (A.G.M.Afr. Diaire de Bukumbi, 7 November 1886, 14 November 1886, 14 December 1886, 17 December 1886, 1 January 1887, 13–15 January 1887, 5 February 1887, 6–7 February 1887, 21 February 1887, 23–25 February 1887, 16 December 1887, 11 January 1888; A.G.M.Afr. Diaire de Rubaga, 21 September 1886, 9 February 1887; A.G.M.Afr. Livinhac to Lavigerie, 15 February 1887; A.G.M.Afr. C.14–535 Benoit to White Fathers, 28 June 1888; CMS G/3/A/5/O Mackay to Lang, 27 December 1886). Drought also affected parts of present-day southern Kenya in 1888 and 1889 (Mutua and Runguma, 2020). The documentary sources suggest that these were widespread droughts, perhaps associated with the aftereffects of Krakatau's eruption, although the geographical spread was uneven.

3 Global climate reconstructions (reanalysis and GCMs)

The climatic reconstructions employed in this article come in two forms: climate reanalysis and global circulation models (GCMs). Climate reanalysis products use observational data from regions and time periods where these data are abundant to model climatic conditions in regions and time periods where these data are lacking, such as in inland Tanzania during the nineteenth century. Specifically, we used the NOAA–CIRES–DOE Twentieth Century Reanalysis version 3 (20CRv3), which assimilates surface pressure observations to estimate climatic conditions, including precipitation rate (Prate), over 1° × 1° grid squares at a monthly scale from 1836–2015 (Slivinski et al., 2019). We also considered incorporating data from version 2 of the Last Millennium Reanalysis (LMR) and the Paleo Hydrodynamics Data Assimilation

(PHYDA) product (Tardif et al., 2019; Steiger et al., 2018). However, both these reanalysis products operate at an annual timescale (LMR: January–December; PHYDA: April–March), and the PHYDA reanalysis only provides outputs that are suggestive of precipitation rate (for example, Palmer Drought Severity Index (PDSI) and Standardized Precipitation Evapotranspiration Index (SPEI)). Thus, lack of interoperability of these data with the seasonal data being collected hindered their incorporation into the interdisciplinary datasets being constructed here.

Unlike climate reanalysis, GCMs do not rely on observational or paleoclimatic data. Rather, they simulate the climate system based on natural (orbital, solar, volcanic) and anthropogenic (well-mixed greenhouse gases, ozone, tropospheric aerosols, land use) climate forcings. Here, we employed historical twentieth-century model simulations from a total of 25 models from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset, in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Meehl et al., 2007; Taylor et al., 2012). All model data were re-gridded to 1.5° × 1.5° to ensure uniformity. Model simulations from the Paleomodel Intercomparison Project (PMIP) were also explored, but unavailability of significant quantities of data from after 1850 limited their utility (Otto-Bliesner et al., 2009; Schmidt et al., 2012). By contrast, several time series from the CMIP5 model runs begin in 1850. These data were obtained from the Program for Climate Model Diagnosis and Inter-comparison (PCMDI). The first ensemble members (r1i1p1) of CMIP5 historical runs were extracted but only for models that had data beginning from 1850 (see Table 2). The reanalysis and GCM datasets are visualized in Fig. 3 and Fig. 4 in terms of anomalies in millimetres per day for *p* rate and precipitation, respectively.

There are marked discrepancies between the outputs for each locale, some of which are immediately explainable. For example, the scale of rainfall anomalies varies widely between the reanalysis and GCM datasets. This is at least partly attributable to the fact that the outputs from the CMIP5 datasets are multi-model ensemble means, indicating that output anomalies are typically small due to some offsetting between different models. Thus, large anomalies, which are occasionally apparent in the 20CRv3 and indexed documentary datasets, have been obscured, as is further evident from the much more amplified anomalies indicated in individual runs (see Supplement Fig. S1 for individual CMIP5 runs for Mpwapwa, as an example).

For the first 20 years of the period under review, the 20CRv3 outputs suggest generally average or above-average rainfall across almost all seasons. This is in line with most hydrological sources from the region (Nicholson and Yin, 2001). The CMIP5 datasets on the other hand, intersperse positive and negative anomalies with a predominance of the former, suggesting several years of abundant rainfall around the late 1860s and early 1870s, as well as deficient rainfall

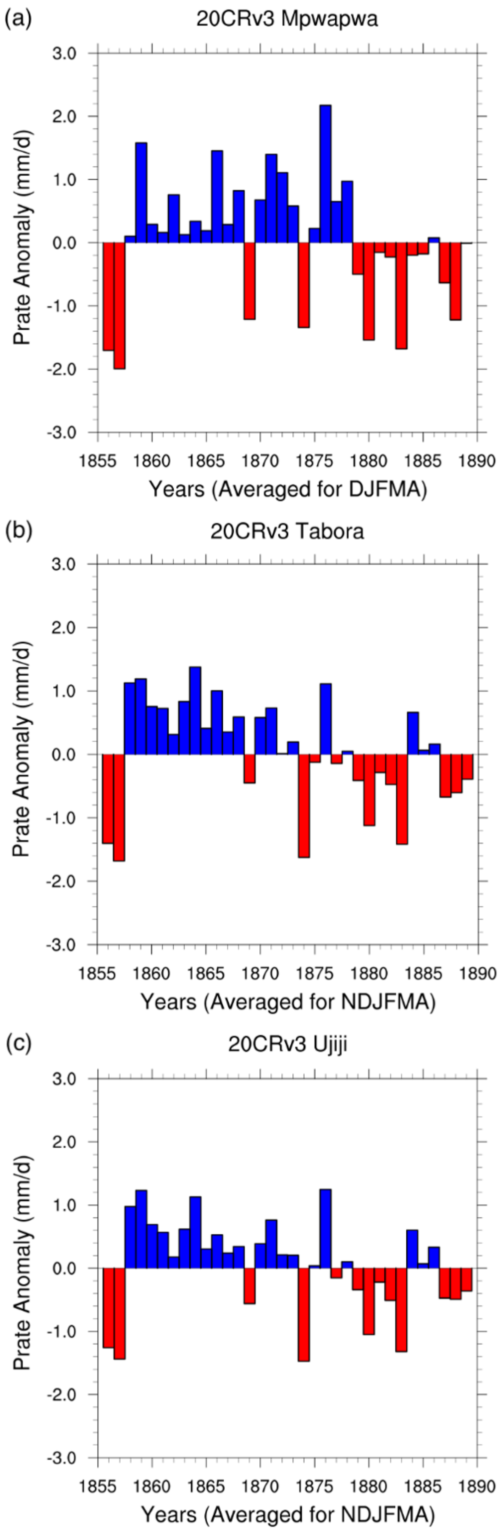

Figure 3. Time series showing the 20CRv3 precipitation rate anomalies for **(a)** Mpwapwa for the season DJFMA, **(b)** Tabora for the season NDJFMA, and **(c)** Ujiji for the season NDJFMA. Blue bars indicate positive precipitation rate anomalies, and red bars indicate negative precipitation rate anomalies.

Table 2. List of the 25 CMIP5 models used.

Model name	Modelling centre (or group)	Institute ID	Atmospheric resolution
ACCESS1.0 ACCESS1.3	Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	1.25° × 1.9°
BCC-CSM1.1	Beijing Climate Centre, China Meteorological Administration, China	BCC	2.8° × 2.8°
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China	GCESS	2.8° × 2.8°
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	CCCMA	2.8° × 2.8°
CCSM4	National Center for Atmospheric Research, United States	NCAR	0.94° × 1.25°
CESM1(BGC) CESM1(CAM5)	Community Earth System Model Contributors, United States	NSF-DOE-NCAR	0.94° × 1.25°
CMCC-CM CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	CMCC	0.75° × 0.75°, 1.9° × 1.9°
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique, France	CNRM-CERFACS	1.4° × 1.4°
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence, Australia	CSIRO-QCCCE	1.9° × 1.9°
EC-EARTH	EC-EARTH consortium, European Union	EC-EARTH	1.1° × 1.1°
FIO-ESM	The First Institute of Oceanography, SOA, China	FIO	2.8° × 2.8°
INM-CM4	Institute for Numerical Mathematics, Russia	INM	1.5° × 2°
IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	Institut Pierre-Simon Laplace, France	IPSL	1.9° × 3.75°, 1.25° × 2.5°, 1.9° × 3.75°
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, the Atmosphere and Ocean Research Institute (The University of Tokyo), and the National Institute for Environmental Studies, Japan	MIROC	2.8° × 2.8°
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), the National Institute for Environmental Studies, and the Japan Agency for Marine-Earth Science and Technology, Japan	MIROC	1.4° × 1.4°
MPI-ESM-LR MPI-ESM-MR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology), Germany	MPI-M	1.9° × 1.9°
MRI-CGCM3	Meteorological Research Institute, Japan	MRI	1.1° × 1.1°
NorESM1-M NorESM1-ME	Norwegian Climate Centre, Norway	NCC	1.9° × 2.5°

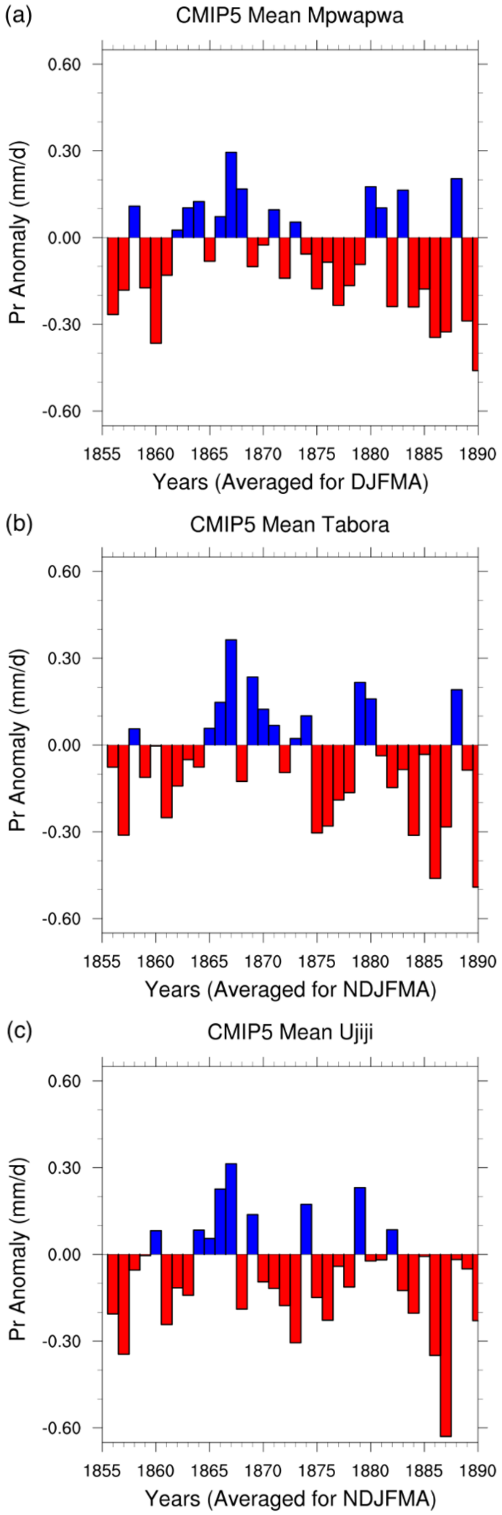

Figure 4. Time series showing the 25 multimodel-mean CMIP5 precipitation anomalies for **(a)** Mpwapwa for the season DJFMA, **(b)** Tabora for the season NDJFMA, and **(c)** Ujiji for the season NDJFMA. Blue bars indicate positive precipitation anomalies, and red bars indicate negative precipitation anomalies.

during the mid-1870s. This is broadly in line with some evidence from the indexed dataset, as well as from reports of a slight decline in the level of Lake Tanganyika around this time, before increasing again around 1877–1878 (Nicholson, 1999). Indeed, the negative precipitation anomalies are stronger and more frequent for Ujiji than for Mpwapwa and Tabora, suggesting that there may have been lower levels of rainfall in Lake Tanganyika's catchment than in other parts of present-day inland Tanzania.

Despite these discrepancies, there are certain areas of agreement between most of the climatological datasets. First, there appears to have been a significant region-wide drought towards the end of the 1850s, although its exact timing and duration is unclear. Incorporating data from the documentary dataset, which relies on data contained in John Hanning Speke's account, will add temporal precision in this context. Even so, the fact the climatological sources suggest that the drought affected Ujiji indicates that it extended to regions far beyond where Speke travelled. Second, agreement between five out of six datasets of below-average rainfall in 1869–1870 corresponds with documentary evidence from southern Kenya that suggests region-wide drought in the late 1860s (Mutua and Runguma, 2020), even if there is no direct evidence from Tanzania. Third, drought is universally indicated in the mid-late 1880s, especially in the 1883–1884 season. This is notwithstanding the occasional year of relatively regular rainfall, as suggested by the 20CRv3 reanalysis. Finally, in line with hydrological sources from the region and relevant parts of the documentary datasets, the reanalysis and GCMs indicate that the period ca. 1860–1875 was wetter than the period ca. 1875–1890.

4 Integrating documentary and climatological data

Integration of documentary, reanalysis, and GCM datasets to make an interdisciplinary seasonal time series for each locale necessitated beginning with a two-step process for making each dataset interoperable. First, we modified the temporal resolution of the indexed documentary datasets so that each season could be expressed using a single numerical value. It is acknowledged that this process could potentially obscure in-season rainfall variability that is apparent in some documentary accounts from the 1870s–1880s. For example, the highly variable rainfall suggested in the missionary archive for Ujiji in 1885–1886 ranged between "excessive" (January), "deficient" (February–March), and "above average" (April) but probably amounted to regular levels of rainfall in the totality for the season (see Fig. 2c) (see Nash et al., 2021; Pfister et al., 2018). Nevertheless, our approach gave a strong indication of overall rainfall levels across entire seasons and brought the temporal resolution of the indexed documentary dataset into line with those of the reanalysis and GCM datasets, facilitating intercomparison at the same temporal scales. Figure 5 indicates seasonal rainfall according to the indexed documentary dataset, which were established by averaging out seasonal variations and the levels of confidence in each.

The second step required interpreting the reanalysis and GCM data points in terms of indexed anomalies, rather than in terms of millimetres of precipitation per day ($\text{mm}\,\text{d}^{-1}$). The outputs for each dataset were converted into a seven-point precipitation scale, in line with the indexed documentary datasets. This required multiplying each reanalysis and GCM dataset by a factor that would make the most extreme anomaly equal to ± 3.5. For the reanalysis, this was a factor of 1.6 (the most extreme value was +2.2 for 1876–1877 in Mpwapwa); for the GCM, this was a factor of 5.5 (most extreme value was −0.63 for 1886–1887 in Ujiji). The assumption was made that all indexed reanalysis and GCM values between −3.5 and −2.5 were broadly representative of the definitions applied for values of −3 in the indexed documentary dataset, that reanalysis and GCM values between −2.5 and −1.5 were indicative of indexed documentary values of −2, and so on. This approach therefore allowed conversion of the reanalysis and GCM data to the same scale as the documentary data, enabling direct comparisons and integration, while also maintaining the temporal resolution of both reanalysis and GCM datasets. The three indexed datasets for each locale are combined and visualized in Fig. 6.

Figure 6a (Mpwapwa) and 6b (Tabora) suggest similar patterns of rainfall variability up to 1860 and then an overall wetting trend (across all three datasets) up to ca. 1873. The subsequent interval is then characterized by a broad dominance of drying anomalies until the end of the period of interest. Ujiji displays the most dataset variability of all three localities (Fig. 6c) but also has the least documentary data available. General trends nevertheless suggest that wetter conditions in the first half of the period were followed by drier conditions, which is broadly in agreement with the other two localities. It is also clear from all datasets that the 1883–1884 season was anomalously dry at every locality.

The correlations between the datasets are low, which is expected due to the relative shortness of the time series and the missing values in the indexed documentary datasets. It is worth noting, however, that higher correlations are evident between the reanalysis dataset and CMIP5 model dataset for Tabora and Ujiji. This provides higher confidence that the overall trends in these localities are likely to be more robust, as the two climatological datasets show some coherence. None of the above correlations are statistically significant at the 95th percentile except for the weighted 20CR versus the CMIP5 dataset. Table 4 is similar to Table 3, with the main difference being that missing values were excluded when calculating the correlations. None of the correlations were significant, most likely due to the reduced number of data points overall.

Additional correlations were carried out that separately incorporated data at confidence level values of either 2 (highest) or 1. One significant correlation emerged between the

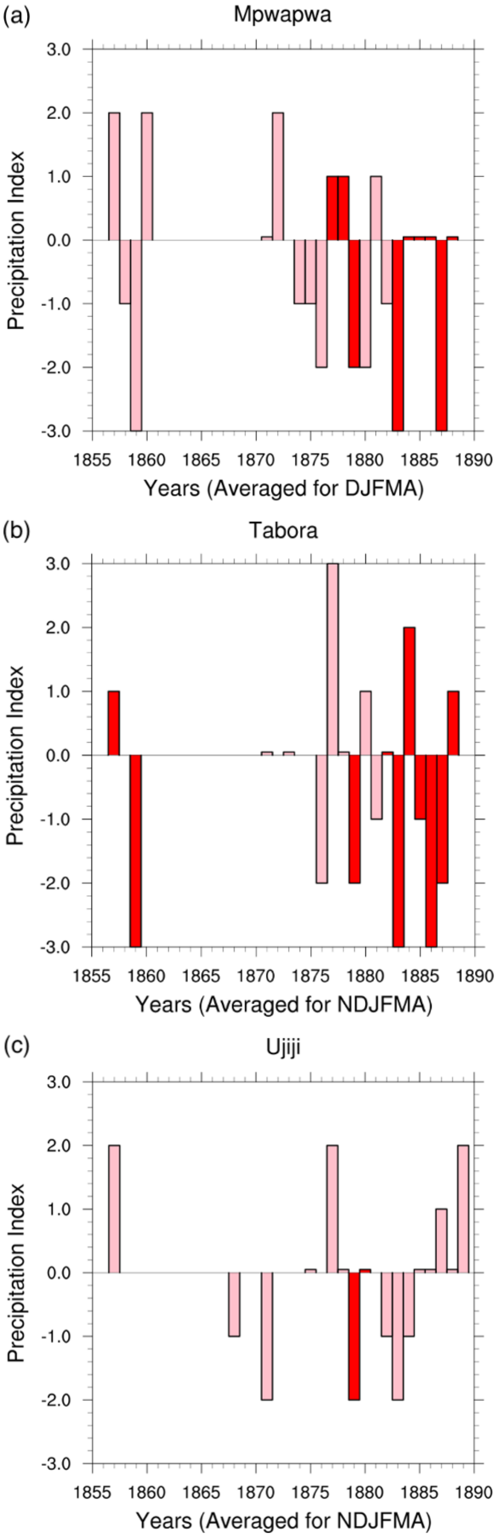

Figure 5. Seasonal documentary precipitation index values for **(a)** Mpwapwa, **(b)** Tabora, and **(c)** Ujiji. Red bars indicate when confidence level (CL) is 2, while pink indicates a CL of 1. The smallest colour bars and markings on the x axis indicate an index value of 0. An absence of any markings indicates that there was no documentary data for that period.

Table 3. Time series correlations between datasets for all three localities for the period 1856–1857 to 1889–1890 using Pearson's correlation, including missing values. All significant correlations at the 95th percentile level are indicated in bold.

Correlations (1856–1857 to 1889–1890)	Mpwapwa	Mpwapwa weighted	Tabora	Tabora weighted	Ujiji	Ujiji weighted
Index data vs. 20CRv3	0.09	0.10	−0.05	0.01	−0.13	−0.08
Index data vs. CMIP5	0.03	0.00	0.10	0.05	−0.03	−0.03
20CR vs. CMIP5	−0.01	0.12	0.24	**0.36**	0.22	0.28

Table 4. Time series correlations between datasets for all three localities for the period 1856–1857 to 1889–1890 using Pearson's correlation, excluding missing values. There are no significant correlations at the 95th percentile level.

Correlations (1856–1857 to 1889–1890)	Mpwapwa	Mpwapwa weighted	Tabora	Tabora weighted	Ujiji	Ujiji weighted
Index data vs. 20CRv3	0.08	0.10	−0.15	−0.13	−0.27	−0.26
Index data vs. CMIP5	−0.04	−0.07	0.16	0.15	−0.06	−0.08
20CR vs. CMIP5	−0.29	−0.38	−0.08	−0.10	−0.10	−0.09

Index Data and 20CRv3 dataset for Mpwapwa of $r = 0.73$ at the confidence level value of 2. This is promising, as it suggests that higher confidence in the indexed documentary data improves correlation with the reanalysis dataset, which is as close to observations as possible given the time period and location. All other correlations were insignificant at the 95th percentile level but are included in Table 5 for reference.

In integrating the datasets, divergent rules were used depending on the availability and confidence level in each data point from the documentary sources. When the confidence level value in the documentary data point was 1, equal weight was given to the documentary, reanalysis, and GCM datasets (33.3 %, 33.3 %, and 33.3 %, respectively). This was justified on the basis that the documentary data points often lacked specificity and/or verifying contextual material and occasionally relied on information from outside the locality under review. In this sense, it suffered from some of the same constraints as the reanalysis and GCM data points, which also rely on data collected over a broader geographical region. By contrast, given that documentary data points with a confidence level of 2 are the only ones to regularly incorporate cross-verified data from within each of the three localities, more weight was applied to these when integrating them with the reanalysis and GCM datasets (50 %, 25 %, and 25 %). When documentary data were absent, equal weight was given to the reanalysis and GCM values (50 % and 50 %). Correlations were calculated using both unweighted and weighted values (see Tables 3 and 4). The outputs in the resultant time series were then multiplied by a factor of 1.4 to minimize offsetting of extremes during the integration process (Fig. 7).

Figure 7 suggests that there are several outputs in common across each of the three localities with large positive or negative precipitation anomalies. The most notable of these are 1856–1857, 1866–1867, 1874–1875, 1879–1880, and 1883–1884. Of the 34 years analysed in total, the integrated dataset shows that 20 (or 59 %) of those years agree in the sign of the precipitation anomaly (i.e. conditions becoming wetter or drier). In quantifying the degree of statistical correlation between the three localities (again using Pearson's correlation coefficients), the relationship is strongest between Mpwapwa and Tabora ($r = 0.75$), followed by Tabora and Ujiji ($r = 0.68$), and lastly Mpwapwa and Ujiji ($r = 0.54$). All three correlations are significant at the 95th percentile level using Student's t test. This implies that the trends suggested by the newly integrated dataset were experienced similarly across all three localities. Overall, this outcome is broadly what might be expected due to their geographical proximity and similar seasonal climatology (Nicholson, 2017a).

5 Implications of the resultant time series

The time series represented in Fig. 7 have several implications for how historians and climatologists can interpret rainfall patterns in inland Tanzania during the second half of the nineteenth century. From a long-term perspective, they reinforce observed trends from (paleo)limnological studies that were incorporated into the Nicholson et al. (2012) dataset. They suggest a generally wet period during the third quarter of the nineteenth century, followed by a period of regular and severe droughts. The one exception to this is the record for Ujiji, which suggests slightly below-average rainfall for most of the 1870s. This may reflect depressed levels of rainfall in the catchment of Lake Tanganyika during the first part of the decade, as a limnological study suggests its level decreased slightly during this period before peaking again during a region-wide season of excessive rainfall in ca. 1877–1878 (Nicholson, 1999).

It is also notable that several extreme anomalies correlate with analysis of documentary evidence from southern Kenya

Table 5. Time series correlations between datasets for all three localities for the period 1856–1857 to 1889–1890 using Pearson's correlation, excluding missing values for different index data confidence levels (CLs). All significant correlations at the 95th percentile level are in bold.

Correlations (1856/1857–1889/1890)	Mpwapwa CL 1	Mpwapwa CL 2	Tabora CL 1	Tabora CL 2	Ujiji CL 1	Ujiji CL 2
Index data vs. 20CRv3	−0.22	**0.73**	−0.52	−0.12	−0.32	NA*
Index data vs. CMIP5	0.35	−0.53	0.04	0.17	−0.02	NA
20CR vs. CMIP5	−0.55	0.02	−0.18	−0.08	−0.05	NA

* Here, not available (NA) indicates there were only two data points at confidence level 2 for Ujiji, which makes this dataset insufficient for obtaining a correlation coefficient value.

and Malawi and with instrumental measurements taken from rain gauges located in Kampala, Mombasa, and Zanzibar. This suggests certain region-wide trends. For example, deficient rainfall in the late 1850s correlates with similar patterns recorded in southern Malawi (Nash et al., 2018); below-average rainfall for a season during the late 1860s correlates with drought recorded in southern Kenya (Mutua and Runguma, 2020); mid-1870s drought correlates with documentary evidence from southern Kenya and rain gauge measurements taken at Mombasa and Zanzibar (Mutua and Runguma, 2020; Nicholson et al., 2012; Gooding, 2022a); below-average rainfall and severe drought in 1879–1880 and 1883–1884 correlates with drought records across equatorial eastern Africa (Mutua and Runguma, 2020; Gooding, 2022c), with the latter example also extending to parts of northern Malawi (Nash et al., 2018); and late 1880s droughts correlate with evidence in southern Kenya (documents; Mutua and Runguma 2020), southern Uganda (documents and rain gauge; Nicholson et al., 2012; Gooding, 2022c), and Malawi (documents; Nash et al., 2018), although the timing and severity of the drought varied from place to place. Referring solely to inland Tanzania, the time series improve on the precision of existing climatological studies and standard interpretations of archival materials referring to rainfall. Four examples are discussed in turn below.

5.1 Drought in 1856–1860

Existing climatological studies do not point to drought in inland Tanzania during this period. Nicholson et al. (2012) suggest consecutive seasons of regular and/or slightly above-average rainfall. In addition, while historian Koponen (1988) used evidence derived from oral traditions to suggest a period of widespread drought during the 1860s, our time series suggest that an earlier date for such a phenomenon may be more appropriate. This may be in line with some interpretations of oral traditions from Ugogo (the region directly west of Mpwapwa) that date a famine called *Chonya-Magulu* (literally: "hobble") to the 1850s or ca. 1860 (Rockel, 1997). Similarly, drought appears to have pervaded southern Malawi around this time, suggesting certain trends in the wider region (Nash et al., 2018). Even so, standard readings of Speke's account of his second visit to the region would place the drought, which contributed to famine around Tabora and towards Mpwapwa, only in the 1859–1860 season (Speke, 1864a). However, the time series suggest that the famine probably instead resulted from a longer-term period of environmental adversity that reached its apex as Speke visited. Drought may have been putting pressure on agricultural production for several years leading up to 1859–1860, decreasing reserves that may otherwise have mitigated against crop failure. Moreover, warfare (which Speke, 1864a, reported on) and migration may have further hindered the 1859–1860 harvest, while also increasing demand for food, especially around Tabora (see McDow, 2018; Sheriff, 1987). Below-average or deficient levels of rainfall in 1859–1860 probably contributed to a longer-term environmental crisis affecting parts of inland central Tanzania in the late 1850s.

Nevertheless, there is still some uncertainty about the geographical extent of this drought. Although both the reanalysis and GCM datasets indicate severe drought across the region in 1857–1858, this contrasts with the inference from Burton's account that the rainy season started early in Ujiji during that year. The climatological data suggest that Burton and the natural inference from his account is probably incorrect. However, both the reanalysis and GCM datasets also suggest abundant rainfall in 1859–1860, but this is not supported by the much more certain account provided by Speke in these years. In this instance, Speke's reports unequivocally indicate drought around Mpwapwa and Tabora, and thus the interdisciplinary time series revise down the estimations of rainfall made by the reanalysis and GCM datasets for these years. The challenge, however, is that Speke's account of this season does not provide any data for Ujiji, and thus the estimation for rainfall in that locale may be erroneously high, relying as it does only on the reanalysis and GCM time series. Here, only the incorporation of data from higher-resolution natural proxies from the region could provide more certainty about the depth, duration, and spatial extent of the drought.

5.2 Drought and floods in 1876–1878

Climatic conditions in equatorial eastern Africa in 1876–1878 have recently garnered historical attention in the context of wider anomalies affecting the Indian Ocean monsoon zone, which were triggered by extreme positive El Niño and Indian Ocean Dipole events (Gooding, 2019, 2022a; Singh et al., 2018). This research, which relied on missionary sources,

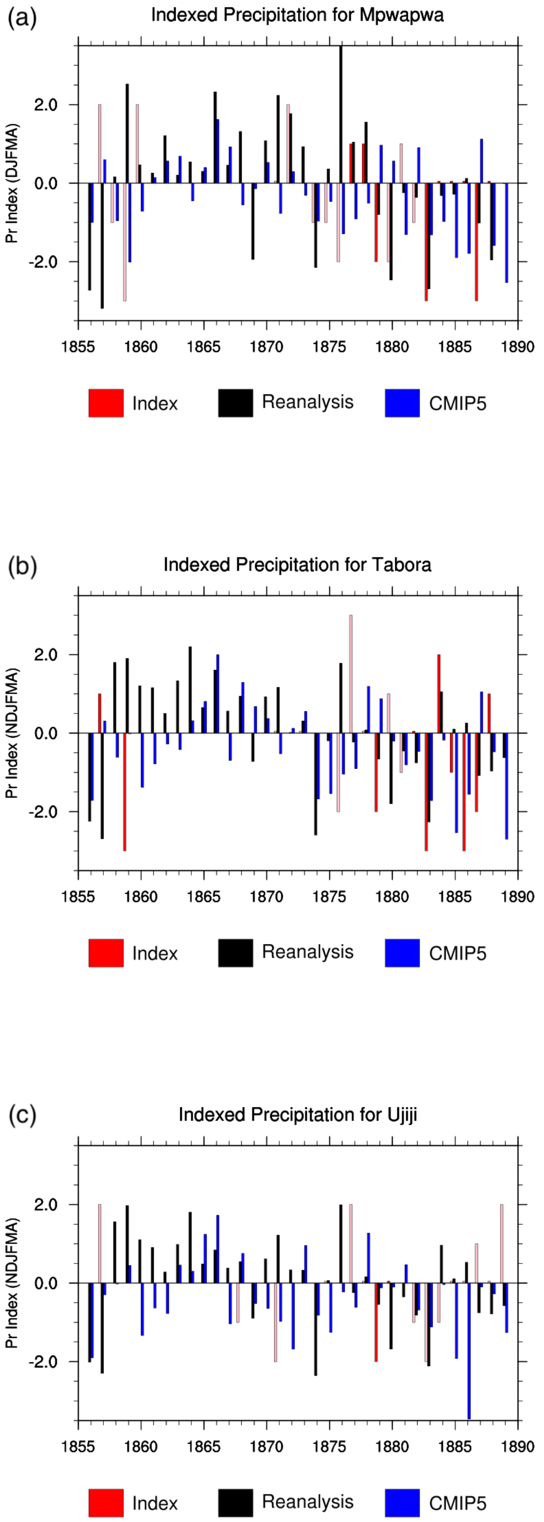

Figure 6. Time series for **(a)** Mpwapwa, **(b)** Tabora, and **(c)** Ujiji including all three datasets, which have been extrapolated to create a uniform precipitation index (Pr index) ranging from −3.5 to +3.5. A confidence level (CL) of 1 in the documentary datasets is shown in pink, while a CL of 2 is shown in red.

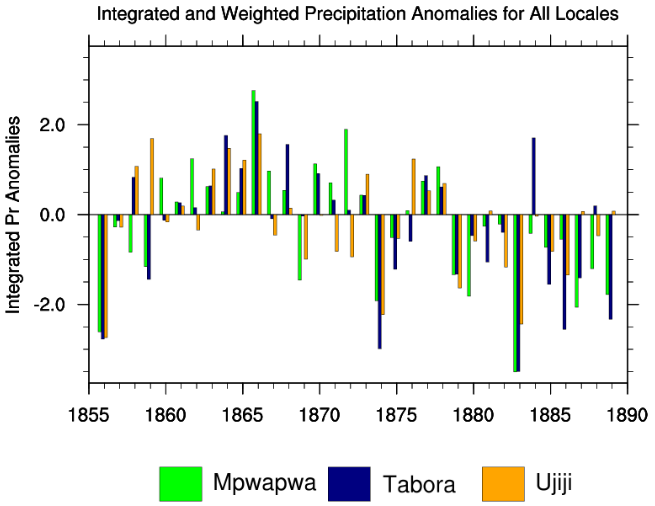

Figure 7. Time series representing integrated and weighted precipitation anomalies for all locales.

suggested widespread drought in the 1876–1877 season and abundant rainfall in 1877–1878 season. This reflected region-wide trends towards highly anomalous rainfall, including in present-day Kenya and Malawi, which has been established from documentary sources and a temporary rain gauge at Mombasa (Nash et al., 2018; Mutua and Runguma, 2020; Nicholson et al., 2012). The time series support this hypothesis and the wider regional patterns to a point. Although they support the general pattern (at least in Tabora), the level of anomaly may not have been as extreme as previously suggested. In this instance, the fact that missionaries were only just entering the region in 1876 may have influenced them to overstate the unusual nature of the climatic conditions they witnessed, partly because they were yet to understand what was and was not normal. However, these years are also among those with the greatest divergence between datasets that underpin the time series. In 1876–1877, the reanalysis dataset suggests excessive levels of rainfall across the region, while in 1877–1878 the GCMs suggest below-average levels of rainfall. Such results are inconsistent with the usual teleconnections between equatorial eastern African climate and positive ENSO and IOD events, although these relationships are still not fully understood (Nicholson, 2015). Thus, inconsistency in the GCMs and reanalysis may have offset extreme anomalies that are suggested in the documentary data and are reflected in the wider region affected by the Indian Ocean monsoon.

5.3 Drought in 1883–1884

The time series suggest that the 1883–1884 season experienced the deepest drought during the period under review. This is in line with recent historical work that emphasizes the importance of rainfall deficiency in this season to a range of historical processes in the region, including food security, epidemics, trade, migration, and political stability, which in turn may have undermined resistance to the imposition of colonial rule in the 1890s (Rockel, 2022; Gooding, 2022c, 2023). Further, similar conditions are reported in documents relating to southern Kenya and in a rain-gauge temporarily placed in Kampala (Mutua and Runguma, 2020; Nicholson et al., 2012). It also challenges the Nicholson et al. (2012) characterization of the season, which suggests that conditions in 1883–1884 were much like they were throughout most the 1880s. The reason that this season stands out in the time series is that all three datasets – the documents, reanalysis, and GCM – agree that rainfall was at least "below average" in this year, with most points suggesting either "deficient" or "famine" levels. In this sense, the climatological materials support standard interpretations of the archive, giving support for recent historical research.

5.4 Drought in 1885–1888

The time series point to below-average or deficient levels of rainfall across most of the region in three consecutive rainy seasons between the end of 1885 and April 1888. This is broadly in line with the Nicholson et al. (2012) dataset, in that they suggest below-average or deficient levels of rainfall across the years 1886–1888, with 1887 being the year of the deepest and most widespread drought. Additionally, qualitative reports of drought pervade the missionary archive referring to present-day Malawi (1885–1888) and southern Kenya (1888–89). Incorporating this evidence does, however, contravene standard interpretations of the documentary material, which suggest that drought conditions did not become established until the 1886–1887 season in Tabora, the 1887–1888 season in Mpwapwa, or at all in Ujiji. Thus, absence of discussion about drought in missionary correspondence in 1885–1886 may reflect the fact that a dearth of rainfall had yet to severely impact the societies in which they lived or that rainfall levels were high relative to recent seasons, such as in 1883–1884. Missionaries then only began to report on it when drought-related shortages began to affect them in subsequent years of deficient rainfall, especially in Mpwapwa and Tabora, for which the documentary record is relatively abundant. Meanwhile, incorporation of climatological materials for Ujiji suggests that the deficient levels of rainfall witnessed in February–March 1887 began earlier in the season and that the "uncertain" reports of excessive rainfall in January (see Fig. 2c) may be inaccurate.

5.5 Inter-disciplinary implications

From a historian's perspective, incorporation of climatological data allows for a method of analysing references to climate and its effects in documentary materials that is rooted in both the humanities and natural sciences. This is especially important for the case studies highlighted in this article, for which the documentary material is thin in both quantity and verifying material for much of the period of 1856–1890. Thus, reports of drought, which are regular in the archive, can be contextualized within longer-term climatic trends. A recurring theme is that such reports may often be more indicative of when droughts began to adversely affect the societies within which the Europeans lived or visited and not when the drought actually set in. Thus, historical interpretations of, for example, past famines in the region, may be better understood as the result of an unfolding of longer-term climatic, environmental, and societal factors, rather than the onset of a sudden disaster, as permeates some of the historiography (cf. Rockel, 2022; Mutua and Runguma, 2020; Gooding, 2023). It is expected that this approach could be used in other regions, especially in the Global South, where European-authored texts dominate the documentary record, even though those same European authors were still in the process of learning about and experiencing the climatic and environmental contexts they reported on.

Meanwhile, from a climatologist's standpoint, integration of documentary sources with reanalysis and GCM data adds much-needed precision to existing knowledge about past climatic conditions in inland Tanzania. Such a methodology is particularly necessary because high-resolution natural proxies have yet to be investigated in the region. Moreover, the ways in which global climatic teleconnections affect levels of rainfall in this region are still relatively poorly understood (Nicholson, 2017a). Thus, direct evidence from the region in the form of historical documents, hitherto not incorporated into global climate reconstructions, allows the models to be deployed with greater certainty and with an interpretation that is at least somewhat locally grounded, notwithstanding some discrepancies between historical and climatological data. Confidence in the reanalysis and GCMs is supported by a general correlation between the levels of their estimations of rainfall and what might be expected from analysis of (paleo)limnological research in the region. This allows them to be deployed with a qualified degree of (un)certainty in the seasons for which documentary data are absent.

6 Conclusions

The methods that underpin this article, which incorporate and integrate qualitative documentary data and quantitative data from climate reanalysis and GCMs, are replicable for other regions and time periods. They will be especially valuable for case studies for which the documentary and/or natural proxy data lack resolution, quantity, and/or verifying material. The results of using such methods, however, can also be refined as knowledge about the drivers of global and regional climate variability improves. A challenge moving forwards will be to establish how incorporation of documentary materials into reanalysis models can be achieved at wider temporal and spatial scales. Achieving this will add precision to current reanalysis models, which will further improve the precision of interdisciplinary time series, such as those provided with this dataset.

For inland Tanzania and surrounding regions, the next challenge will be to suggest rainfall variability for periods before the beginning of the documentary era. The 20CRv3 dataset may assist in this context at least as far back as 1836, before which data are still under construction. Other reanalysis datasets, such as the LMR and PHYDA products, may be deployed for earlier periods, although the outputs would have a lower temporal resolution. Using a more estimative approach may also be compatible with historians' usage of oral traditions, which, up to now, they have had difficulty placing in time. In-region research and collaboration will be necessary for such research to be undertaken. Only with the analysis of high-resolution natural proxies in the region, however, could seasonal rainfall variation be reliably estimated for periods before and including the early nineteenth century.

Appendix A: Archival sources

- Archivio Generale dei Missionari d'Africa (A.G.M.Afr): White Fathers' Archive, Rome, Italy
- Church Missionary Society Archive (CMS): Birmingham, UK
- Council for World Missions/London Missionary Society (CWM/LMS): London, UK
- Royal Museum for Central Africa Emile Storms Archive (RMCA ESA): Tervuren, Belgium

Data availability. The datasets that underpin the indexed time series made solely from documentary data (Fig. 2) and the integrated indexed time series (Fig. 7) are archived in the McGill University Dataverse and are freely available under a CC-BY license at https://doi.org/10.5683/SP3/LDODGI (Gooding et al., 2023).

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/cp-20-2701-2024-supplement.

Author contributions. PG proposed the initial ideas, analysed the documentary data, co-developed the project methods, and co-wrote the manuscript. MJL analysed reanalysis and GCM data, produced the figures, co-developed the project methods, and co-wrote the manuscript. MRF co-developed the project methods and edited the manuscript. CD and WS performed the initial experiments and analyses to ensure the feasibility of the project.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Acknowledgements. The research for this article was funded by the Social Sciences and Humanities Research Council of Canada. The authors wish to thank Daniele Battistelli and Riccardo Mercatali for their collection of documentary materials from the White Fathers' Archive. Part of this research was first presented as part of the Australian National University's "Environmental Exchanges" seminar series on 19 April 2023, and the authors would like to thank all those in attendance for their feedback and questions. The authors also acknowledge the World Climate Research Programme's Working Group on Coupled Modelling responsible for the CMIP5 model data, which were provided by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). More information on these model data can be found at the PCMDI website (https://esgf-node.llnl.gov/projects/esgf-llnl/, last access: 2 December 2024). Additionally, the authors acknowledge the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER); the National Oceanic and Atmospheric Administration Climate Program Office; and the NOAA Physical Sciences Laboratory, which support the Twentieth Century Reanalysis Project version 3 dataset. More information can be found at the Physical Sciences Laboratory Website (https://psl.noaa.gov/data/20thC_Rean/, last access: 2 December 2024). Finally, the authors would like to thank David Nash and an anonymous reviewer, whose constructive comments during the review process improved the manuscript significantly.

Financial support. This research has been supported by the Social Sciences and Humanities Research Council of Canada (grant nos. 430-2021-00363 and 895-2018-1011).

Review statement. This paper was edited by Keely Mills and reviewed by David Nash and one anonymous referee.

References

Adamson, G. C. D., Nash, D. J., and Grab, S. W.: Quantifying and reducing researcher subjectivity in the generation of climate indices from documentary sources, Clim. Past, 18, 1071–1081, https://doi.org/10.5194/cp-18-1071-2022, 2022.

Alin, S. and Cohen, A.: Lake-level history of Lake Tanganyika, east Africa, for the past 2500 years based on ostracode-inferred water-depth reconstruction, Paleogeogr. Paleocl., 199, 31–49, https://doi.org/10.1016/S0031-0182(03)00484-X, 2003

Bessems, I., Verschuren, D., Russel, J. M., Hus, J., Mees, F., and Cumming, B. F.: Paleolimnological evidence for widespread late 18th century drought across equatorial east Africa, Paleogeogr. Paleocl., 259 107–120, https://doi.org/10.1016/j.palaeo.2007.10.002, 2008.

Brázdil, R.: Historical climatology: definition, data, methods, results, Geogr. Cas., 52, 99–121, 2000.

Brázdil, R., Pfister, C., Wanner, H., von Storch, H., and Luterbacher, J.: Historical climatology in Europe – the state of the art, Climatic Change, 70, 363–430, https://doi.org/10.1007/s10584-005-5924-1, 2005.

Brönnimann, S. and Wintzer, J.: Climate data empathy, WIREs Clim. Change, 10, 1–8, https://doi.org/10.1002/wcc.559, 2019.

Burton, R. F.: The Lake Regions of Central Africa: a picture of exploration, Harper & Brothers, New York, NY, 572 pp., 1860.

Cameron, V. L.: Across Africa, Harper & Brothers, New York, NY, 508 pp., 1877.

Castryck, G. Kigoma-Ujiji: a global history of a liminal town, Habilitationsschrift, Universität Leipzig, Germany, 305 pp., 2022.

Doyle, S.: Crisis and Decline in Bunyoro: population and environment in western Uganda 1860–1955, James Currey, Oxford, United Kingdom, 276 pp., ISBN 9780821416334, 2006.

Endfield, G. H. and Nash, D. J.: Missionaries and morals: climatic discourse in nineteenth-century central southern Africa, Ann. Assoc. Am. Geogr., 94, 272–242, https://doi.org/10.1111/1467-8306.00313, 2002.

Gooding, P.: Tsetse flies ENSO and murder: the Church Missionary Society's failed ox-cart experiment of 1876–1878, Africa: rivista semestrale di studi e ricerche, 1, 21–36, https://doi.org/10.23744/2274, 2019.

Gooding, P.: ENSO, IOD, drought, and floods in equatorial eastern Africa, 1876–1878, in: Droughts, Floods, and Global Climatic Anomalies in the Indian Ocean World, edited by: Gooding, P., Palgrave-MacMillan, Cham, Switzerland, 259–287, https://doi.org/10.1007/978-3-030-98198-3_9, 2022a.

Gooding, P.: On the Frontiers of the Indian Ocean World: a history of Lake Tanganyika, c. 1830–1890, Cambridge University Press, Cambridge, United Kingdom, 251 pp., ISBN 9781009122023, 2022b.

Gooding, P.: Climate change and political instability in equatorial eastern Africa, 1876–1884, Int. J. Afr. Hist. Stud., 55, 207–29, 2022c

Gooding, P.: Resilience and vulnerability to drought in Unyanyembe (west-central Tanzania) in the 1830s and 1870s–1890s, Int. Rev. Environ. Hist., 9, 57–73, https://doi.org/10.22459/IREH.09.01.2023, 2023.

Gooding, P., Lazenby, M. J., Frogley, M. R., Dai, C., and Su, W.: Data for: Documents, Reanalysis, and Global Circulation Models: A New Method for Reconstructing Historical Climate Focusing on Present-day Inland Tanzania, 1856–1890, Borealis [data set], https://doi.org/10.5683/SP3/LDODGI, 2023.

Hastenrath, S.: Variation of east African climate during the past two centuries, Climatic Change 50, 209–217, https://doi.org/10.1023/A:1010678111442, 2001.

Hore, E. C.: Tanganyika: eleven years in central Africa, Edward Stanford, London, United Kingdom, 306 pp., 1892.

Kjekshus, H.: Ecology Control and Economic Development in East African History: the case of Tanganyika 1850-1950, 2nd Edn, James Currey, London, United Kingdom, 253 pp., ISBN 9780821411322, 1996.

Koponen, J.: People and Production in Late Precolonial Tanzania: History and structures, Finnish Society of Development Studies, Helsinki, 434 pp., ISBN 9519015601, 1988.

Livingstone, D.: The Last Journals of David Livingstone in Central Africa. From eighteen hundred and sixty-five to his death. Continues by a narrative of his last moments and sufferings, obtained from his faithful servants Chuma and Susi, Harper & Sons, New York, NY, 541 pp., 1875

McDow, T. F.: Buying Time: Debt and mobility in the western Indian Ocean, Ohio University Press, Athens OH, 378 pp., ISBN 9780821422823, 2018.

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAveney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: The WCRP CMIP3 multi-model dataset: a new era in climate change research, Bull. Am. Meteorol. Soc., 88, 1383–1394, https://doi.org/10.1175/BAMS-88-9-1383, 2007.

Mutua, T. M. and Runguma, S. N.: Documentary driven chronologies of rainfall variability for Kenya, 1845–1976, J. Clim. Weather Forecast., 8, 1–12, 2020.

Nash, D. J., Pribyl, K., Endfield, G. H., Klein, J., and Adamson, G. C. D.: Rainfall variability over Malawi during the late 19th century, Int. J. Climatol., 38, e629–e642, https://doi.org/10.1002/joc.5396, 2018.

Nash, D. J., Adamson C, D., Ashcroft, L., Bauch, M., Camenisch, C., Degroot, D., Gergis, J., Jusopović, A., Labbé, T., Lin, K-H. E., Nicholson, S. D., Pei, Q., Prieto, M. d. R., Rack, U., Rojas, F.. and White, S.: Climate indices in historical climate reconstructions: a global state of the art, Clim. Past, 17, 1273–1314, https://doi.org/10.5194/cp-17-1273-2021, 2021.

Nicholson, S. E.: Historical and modern fluctuations of Lakes Tanganyika and Rukwa and their relationship to rainfall variability, Climatic Change, 41, 53–71, https://doi.org/10.1023/A:1005424619718, 1999.

Nicholson, S. E.: Long-term variability of the east African "short rains" and its links to large-scale factors, Int. J. Climatol., 35, 3979–3990, https://doi.org/10.1002/joc.4259, 2015

Nicholson, S. E.: Climate and climatic variability of rainfall over eastern Africa, Rev. Geophys., 55, 590–635, 2017a.

Nicholson, S. E.: Climatology: methods, Oxford Research Encyclopedia of African History, 41 pp., https://doi.org/10.1093/acrefore/9780190277734.013.27, 2017b.

Nicholson, S. E. and Yin, X.: Rainfall conditions in equatorial east Africa during the nineteenth century as inferred from the record of Lake Victoria, Climatic Change, 48, 387–398, https://doi.org/10.1023/A:1010736008362, 2001.

Nicholson, S. E., Dezfuli, A., and Klotter D.: A two-century precipitation dataset for the continent of Africa, Bull. Am. Meteorol. Soc., 93, 1219–1231, https://doi.org/10.1175/BAMS-D-11-00212.1, 2012.

Nicholson, S. E., Funk, C., and Fink, A. H.: Rainfall over the African continent from the 19th through the 21st century, Glob. Planet. Change, 165, 114–127, https://doi.org/10.1016/j.gloplacha.2017.12.014, 2018.

Otto-Bliesner, B. L., Joussaume, S., Braconnot, P., Harrison, S. P., and Abe-Ouchi, A.: Modeling and data syntheses of past climates: paleoclimate modelling intercomparison project phase II workshop; Estes Park, Colorado, 15–19 September 2008, Eos, 90, p. 93, https://doi.org/10.1029/2009EO110013, 2009.

Pallaver, K.: A triangle: spatial processes of urbanization and political power in 19th-century Tabora, Tanzania, Afriques: débats, méthodes et terrains d'histoire, 11, 1–32, https://doi.org/10.4000/afriques.2871, 2020.

Pfister, C.: Monthly temperature and precipitation in central Europe 1525–1979: quantifying documentary evidence on weather and its effects, in Climate Since AD 1500, edited by: Bradley, R. S. and Jones, P. D., London, 118–142, https://doi.org/10.4324/9780203430996, 1995.

Pfister, C., Camenisch, C., and Dobrokvolný, P.: Analysis and interpretation: temperature and precipitation indices, in: The Palgrave Handbook of Climate History, edited by: White, S., Pfister, C., and Mauelshagen, F., Palgrave-Macmillan, London, 115–29, https://doi.org/10.1057/978-1-137-43020-5_11, 2018.

Rockel, S. J.: Caravan porters of the *Nyika*: labour, culture, and society in nineteenth century Tanzania, University of Toronto PhD Thesis, 1997.

Rockel, S. J.: Forgotten caravan towns in 19th century Tanzania: Mbwamaji and Mpwapwa, Azania: archaeological research in Africa, 41, 1–25, https://doi.org/10.1080/00672700609480432, 2006.

Rockel, S. J.: A forgotten drought and famine in east Africa, 1883–1885, in Droughts, Floods, and Global Climatic Anomalies in the Indian Ocean World, edited by Gooding, P., Palgrave-MacMillan, Cham, Switzerland, 289–343, https://doi.org/10.1007/978-3-030-98198-3_10, 2022.

Russell, J. M. and Johnson, T. C.: Little ice age drought in equatorial Africa: intertropical convergence zone migrations and El Niño-southern oscillation variability, Geology, 35, 21–24, https://doi.org/10.1130/G23125A.1, 2007.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), Geosci. Model Dev., 5, 185–191, https://doi.org/10.5194/gmd-5-185-2012, 2012.

Sheriff, A.: Slaves, Spices & Ivory in Zanzibar: integration of an east African commercial empire into the world economy, 1770–1873, James Currey, Woodbridge, United Kingdom, 317 pp., ISBN 9780821408728, 1987.

Singh, D., Seager, R., Cook, B. I., Cane, M., Ting, M., Cook, E., and Davis, M.: Climate and the global famine of 1876–1878, J. Clim., 31, 9445–9467, https://doi.org/10.1175/JCLI-D-18-0159.1, 2018.

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domíngues-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Le Blancq, F., Lee, T.-C., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moor, G. W. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C. A., Tinz, B., Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K., and Wyszyński, P.: Towards a more reliable historical reanalysis: improvements for version 3 of the twentieth century reanalysis system, Q. J. R. Meteorol Soc., 145, 2876–2908, https://doi.org/10.1002/qj.3598, 2019.

Speke, J. H.: Journal of the Discovery of the Source of the Nile, Harper & Brothers, New York, NY, 658 pp., 1864a.

Speke, J. H.: What Led to the Discovery of the Source of the Nile. William Blackwood & Sons, Edinburgh, United Kingdom, 372 pp., 1864b.

Stanley, H. M.: How I Found Livingstone: travels, adventures, and discoveries in central Africa including four months' residence with Dr. Livingstone, Sampson Low, Marston & Company, London, United Kingdom, 552 pp., 1872.

Stanley, H. M.: Through the Dark Continent or the Sources of the Nile Around the Great Lakes of Equatorial Africa and Down the Livingstone River to the Atlantic Ocean, 2 Vols, Sampson Low, Marston & Company, London, United Kingdom, 400–566, 1878.

Steiger, N. J., Smeardon, J. E., Cook, E. R., and Cook, B. I.: A reconstruction of global hydroclimate and dynamical variables over the common era, Sci. Data, 5, 1–15, https://doi.org/10.1038/sdata.2018.86, 2018

Tardif, R., Hakim, G. J., Perkins, W. A., Horlick, K. A., Erb, M. P., Emile-Geay, J., Anderson, D. M., Steig, E. J., and Noone, D.: Last Millennium Reanalysis with an expanded proxy database and seasonal proxy modeling, Clim. Past, 15, 1251–1273, https://doi.org/10.5194/cp-15-1251-2019, 2019.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bull. Am. Meteorol. Soc., 93, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

Verschuren, D., Laird, K. R., and Cumming, B. F.: Rainfall and drought in equatorial east Africa during the past 1,100 years, Nature, 403, 410–414, https://doi.org/10.1038/35000179, 2000.

Wessel, P. and Smith, W. H. F.: A Global Self-Consistent, Hierarchical, High-Resolution Shoreline Database, J. Geophys. Res.-Atmos., 101, 8741–8743, https://doi.org/10.1029/96JB00104, 1996.

Wisnicki, A. S.: Charting the frontier: indigenous geography, Arab-Nyamwezi caravans, and the East African Expedition of 1856–1859, Victorian Stud., 51, 103–137, 2008.