INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2018)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.5397

The land and its climate knows no transition, no middle ground, everywhere too much or too little: a documentary-based climate chronology for central Namibia, 1845–1900

Stefan Grab[a]* and Tizian Zumthurm[b,c]

[a] *School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa*
[b] *Institute of the History of Medicine, University of Bern, Switzerland*
[c] *Centre for African Studies, University of Basel, Switzerland*

ABSTRACT: Recent and historical austral summer and winter rainfall characteristics have been widely investigated across southern Africa. However, a notable gap of knowledge remains for the Namibian region. This article presents the first extensive 19th century (1845–1900) hydro-climate history for central Namibia, derived from documentary evidence. Unpublished and published data sources were scrutinized in various archives and libraries in Germany, Switzerland, Namibia and South Africa. Missionary Carl Hahn's detailed diaries are the most valuable source of information for the earliest period until 1859. Other important sources of information include the Rhenish Missionary Society (RMS) annual reports and monthly 'Berichte' (news), station chronicles, official annual reports for the colonial period (1894 onwards) and letters/diaries by traders, travellers, etc.

Climate information was transcribed, translated and organized chronologically. Using a five-point categorization system ranging from very wet (+2) to very dry (−2), each year was classified according to overall rainfall conditions during the rain season. A portion of the chronology is compared with instrumental rainfall data for Okahandja, Windhoek and Rehoboth and confirms good agreement. Possible associations between El Niño-Southern Oscillation (ENSO) phases and subsequent austral summer rainfall conditions are explored for central Namibia. Wetter years (42%) are over-represented in comparison to dry years (38%) during the second half of the 19th century in central Namibia, with a high percentage (42%) constituting either extremely wet or extremely dry years. Inter-annual rainfall variability between 1845 and 1900 seems more pronounced than elsewhere in southern Africa during this period. Extreme to very strong and prolonged El Niño (e.g. 1876–1878) and La Nina (e.g. 1865–1866) phases account for rare hydro-climatic synchronicity between southern African sub-regions and between continents of the Southern Hemisphere.

KEY WORDS Namibia; 19th century; hydro-climatic chronology; ENSO phases

Received 7 September 2017; Revised 6 December 2017; Accepted 7 December 2017

1. Introduction

There is much ongoing scientific attention concerned with global- to local-scale climate change (notably temperature and precipitation) over the last couple of centuries, particularly in the context of natural and enhanced anthropogenically induced forcing mechanisms which may have become increasingly dominant over the last two centuries (e.g. CO_2 emissions). In this context, Brunet and Jones (2011, p. 37) emphasize the need for 'improved and more robust climate assessments' which 'are of paramount importance for today's and tomorrow's society, in order to better understand, predict and respond to global climate change'. However, many such climate assessments require long-term data to accurately establish long-term trends, changes or cyclic patterns in the variance (amplitude) of climate parameters, or frequency (return periods) of extreme events (e.g. severe droughts, floods, heat waves and frosts) – these directly or indirectly impact carbon balance, human health, vegetation changes, etc. (Beer *et al.*, 2014). In addition, an improved understanding of long-term climate dynamics is invaluable for establishing future predictability of hydro-climatic extremes (Gergis and Henley, 2017). To this end, efforts have expanded the instrumental record through establishing relative annual rainfall and temperature variability prior to the instrumental period using documentary-derived data (e.g. del Rosario Prieto and Herrera, 2009; Dobrovolný *et al.*, 2010; Berland *et al.*, 2013; Adamson and Nash, 2014).

Instrumental climate records are particularly limited (spatially, temporally and in quality) for much of the African continent and hence Nicholson *et al.* (2012a, 2012b) have established a documentary-derived matrix

* Correspondence to: S. Grab, School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, Johannesburg, 2050, South Africa. E-mail: stefan.grab@wits.ac.za

of 'wetness' indices for 90 African sub-regions covering the entire 19th century. Particular effort has been made to establishing annually resolved, documentary derived 19th century rainfall chronologies for several sub-regions of southern Africa including the southwestern and Eastern Cape (Vogel, 1989), Namaqualand (Kelso and Vogel, 2007), the southern Kalahari (Nash and Endfield, 2002; Nash and Endfield, 2008), Lesotho (Nash and Grab, 2010) and southeastern South Africa (Nash *et al.*, 2016). Such work has also contributed towards the first consolidated effort using multiple archives and ensemble reconstructions to produce statistical rainfall reconstructions for southern Africa, and ultimately the entire Southern Hemisphere, covering the last two centuries (Neukom *et al.*, 2014; Gergis and Henley, 2017).

A remaining knowledge gap is recent-historical climate variability and change over central Namibia. Notwithstanding the relatively good instrumental records available for the region during the 20th century, these have yet to be robustly scrutinized. Preliminary assessments suggest rapid warming but no significant rainfall trends during the 20th century (Haensler *et al.*, 2010; Rohde and Hoffman, 2012). Although Nicholson *et al.* (2012a, 2012b) include 'southwest Africa' in the Africa-wide documentary-based 19th century wetness index, there is as yet no detailed annually resolved 19th century hydro-climatic chronology for central Namibia. To address this research gap, our objectives are to use documentary sources to: (1) establish inter-annual rainfall variability in the region from 1845 to 1900 and (2) elaborate on the nature of particularly wet and dry periods.

2. Geographic and climatic setting

For this study, the area of central Namibia is based on a cluster of missionary stations broadly covering the region from ca. 21°15′S to the tropic of Capricorn (ca. 23°26′S), and from 15°57′E to 19°03′E (Figure 1). However, information from coastal stations further to the west (e.g. Rooibank, Swakopmund and Walfvis Bay) is also used as such stations are located along (or near) episodically flowing river mouths (i.e. Kuiseb and Swakop Rivers), thus providing evidence for heavy rainfall events over the central interior when, on rare occasions, such rivers reach the Atlantic coastline. Central Namibia is primarily a highland plateau (Khomas Hochland Plateau and Rehoboth Plateau) with rolling terrain and inselbergs dissected by river valleys (Goudie and Viles, 2015a). Much of this central plateau lies between 1500 and 2000 m asl but the western parts of the study area (central western plains) reach lower elevations of between 800 and 1500 m asl. Vegetation comprises mainly of Thornbush and Highland Savannah with variable grass and shrub cover depending on topography, soils and climate. Riparian vegetation (thornbush, trees) is found along major rivers (e.g. Omaruru, Swakop and Kuiseb).

Namibia has a varied climate, ranging from hyper arid/arid in the south and along the coast, to semi-arid towards the central interior and somewhat wetter towards the northeast of the country (Figure 2). Central Namibia's climate is influenced by distinct circulation patterns which account for strong rainfall and temperature gradients, both temporally and spatially. The region is located in the subtropical high-pressure zone at the polewards side of the tropical Hadley circulation, with consequent descending air causing dry conditions (Goudie and Viles, 2015b). The hyper arid coastal and adjacent interior climate is controlled by the strength of marine upwelling associated with the northerly moving Benguela current along the southwest African coast, which is driven by the intensity and strength of the South Atlantic anticyclone (SAA) (Nicholson, 2000). There is an influx of moisture during austral summer from north of Namibia, through the Congo air boundary (CAB). This includes a northeasterly moisture source from the Indian Ocean over Tanzania and Zambia, and an equatorial Atlantic source which is cyclonically recurved over Angola (Nicholson and Entekhabi, 1987; Jury, 2010; Sletten *et al.*, 2013) (Figure 1). The CAB primarily brings moisture to northernmost Namibia to ca. 15°–20°S, and its influence on rainfall further southwards is rapidly reduced (Leroux, 1998). However, tropical temperate troughs (TTTs) may develop over Namibia as a heavy NW-SE rain-bearing cloud band during mid to late austral summer. This is in response to a low pressure developing over southern Angola/northeastern Namibia (the so-called Angola/Botswana low) (Hart *et al.*, 2013; Macron *et al.*, 2014) and/or the summer heat low over the southern Kalahari (Rácz and Smith, 1999). Such conditions favour a more southerly transfer of moisture from the tropical SE Atlantic into central Namibia and southwestern Botswana (Macron *et al.*, 2014). Such TTT are an important source of moisture and in some years contribute a substantial proportion of precipitation over central Namibia; more commonly developing during La Niña than El Niño years (Ratna *et al.*, 2013).

Moisture is also advected into southern Africa from the southwestern Indian Ocean and tropical Africa, but this gradually dissipates westwards due to southwesterly airflow linked to the SAA (Todd and Washington, 1999; Todd *et al.*, 2004). Nevertheless, such moisture may be sufficient to permit advective thunderstorms over central Namibia. During austral winter, cyclonic fronts advect moist, cold conditions along the South African west coast, which on rare occasions bring some moisture as far north as central Namibia.

On exceptionally rare occasions, SW Indian Ocean tropical cyclones may track into the interior of southern Africa and even impact southern and central Namibia, as was the case with cyclone Leon-Eline in 2000 (Reason and Keibel, 2004). In this instance, it caused late summer flooding in parts of Namibia and the months of February and March were each two standard deviations above average rainfall (Reason and Keibel, 2004). Although the past frequency of tropical cyclones over Namibia is unknown, it is possible that some of the reported episodic catastrophic floods during the Holocene and historical times (Smith *et al.*, 1993; Heine and Völkel, 2011) may have been triggered through such cyclonic occurrences.

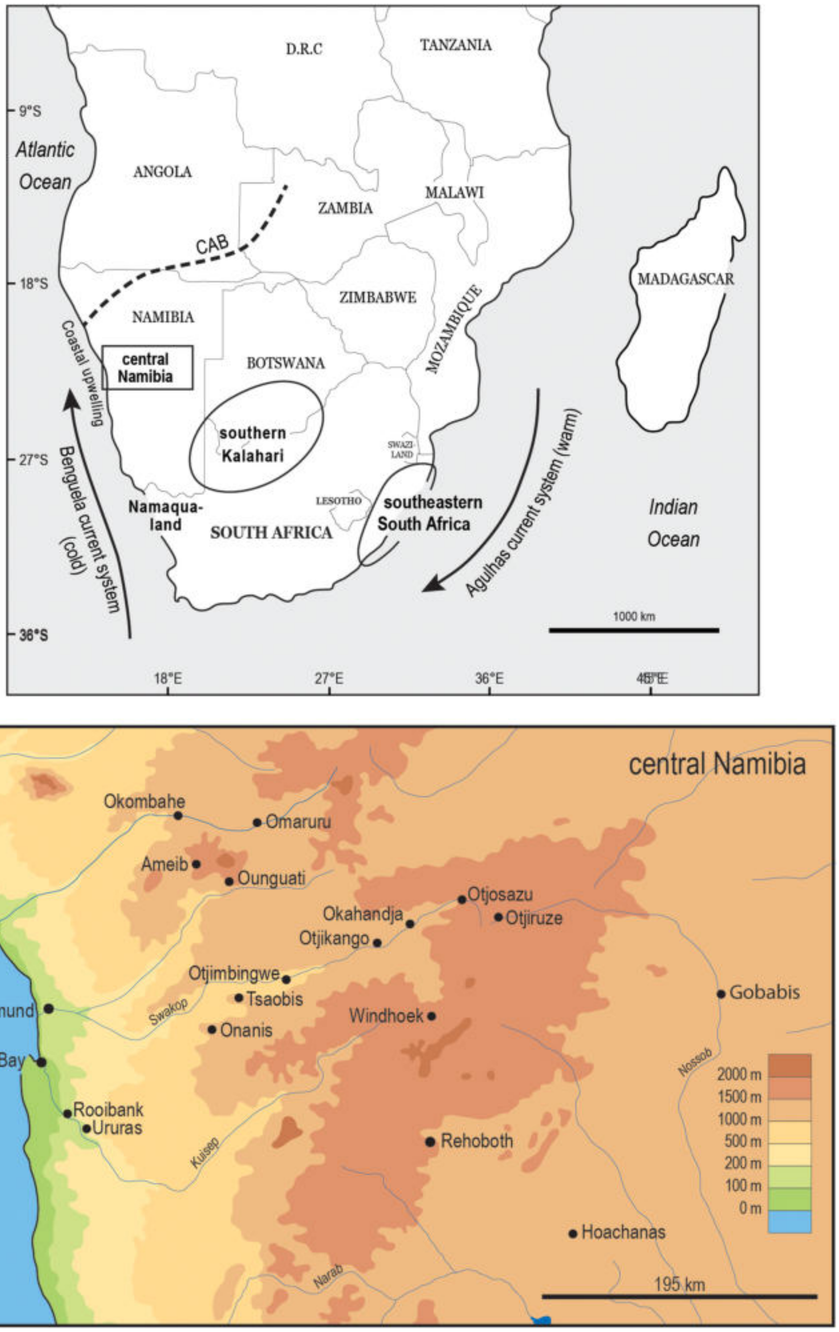

Figure 1. The southern African climate context (CAB = Congo Air Boundary). The study region of central Namibia and other key regions for 19th century climate comparisons are included. Circled regions are for a southeast to northwest climatic transect. The enlarged colour map of central Namibia includes station locations from which historical climate information was obtained. [Colour figure can be viewed at wileyonlinelibrary.com].

The El Niño-Southern Oscillation (ENSO) modulates rainfall over large parts of the eastern half of Africa, and in particular has a strong influence over southeastern Africa. However, the magnitude, seasonal timing and duration of rainfall response to ENSO phases is both spatially and episodically variable (Nicholson and Kim, 1997). For instance, central South Africa experiences maximum positive rainfall anomalies in OND and maximum negative anomalies in FMA. In contrast, central Namibia has its maximum positive rainfall anomaly in JFM and maximum negative anomaly in MAM (Nicholson and Kim, 1997).

There remains a dearth of scientific information on climate dynamics and the nature of climate variability and change in Namibia. Past work has focussed on human vulnerability to climate change (e.g. Angula and Kaundjua, 2016), peoples' perceptions to climate change (e.g. Kaundjua *et al.*, 2012), ecosystem responses to projected climate change (e.g. Thuiller *et al.*, 2006) and agro-ecological knowledge systems and its potential adaptive capacity to future climate change (Newsham and Thomas, 2011). Yet, these studies are unable to draw on any detailed and well-informed quantitative assessment of recent decadal-scale rainfall and temperature changes, this

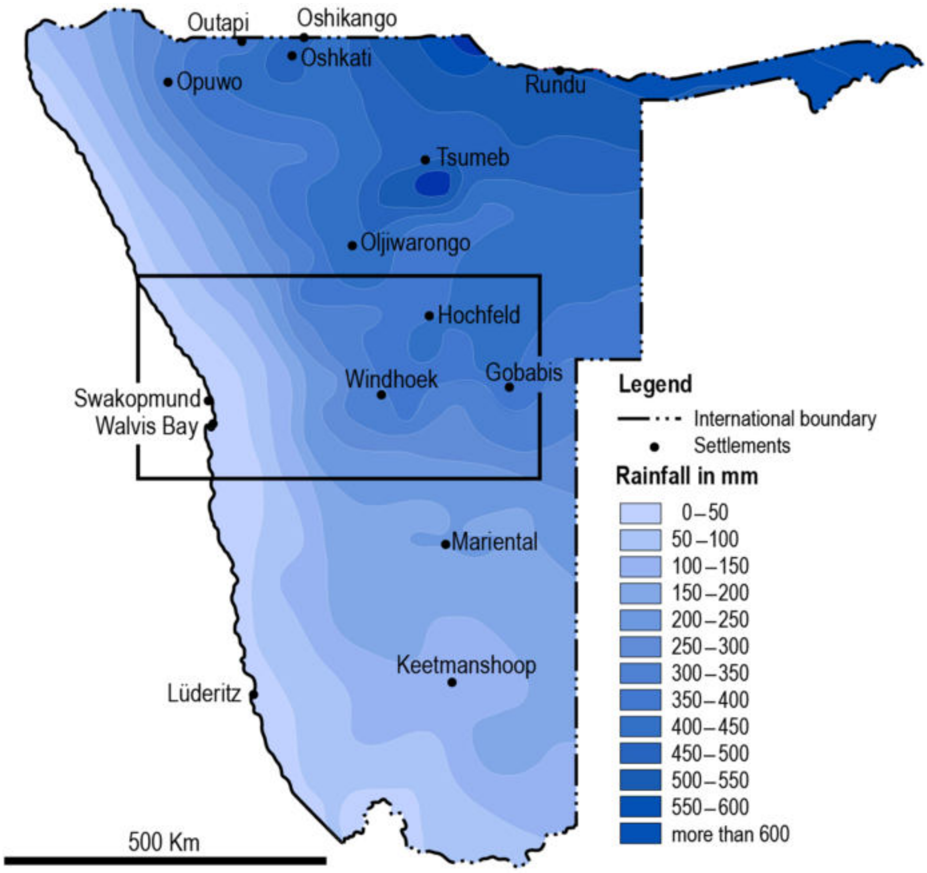

Figure 2. Rainfall map of Namibia with study region. Redrafted after: SFB 389 'ACACIA' subproject E1, University of Cologne. [Colour figure can be viewed at wileyonlinelibrary.com].

despite instrumental station data being relatively widely available.

The study area of central Namibia receives between ca. 100 and 150 mm pa in the extreme southwest to ca. 400 and 450 mm pa in the extreme northeast (Figure 2). Windhoek, which is relatively central to the study region, receives ca. 300–350 mm pa. Inter-annual variation in precipitation increases both southwards and westwards. Of total annual rainfall, ca. 98% falls from October to April, and ca. 70% falls during mid to late summer (i.e. January–March) (Hijmans *et al.*, 2005). Mean annual temperatures exceed 22 °C in the northwest and average 19–20 °C over the central plateau, with Windhoek recording extremes of 41 °C (in 2013) and −0.6 °C (in 2016) over the last 20 years (based on records available through the National Oceanic and Atmospheric Administration (NOAA)).

3. Data sources and methods

The most substantive and valuable documentary records for central Namibia before German Colonial rule, were kept by missionaries of the RMS (Rhenish = of the River Rhine) (Table 1). The RMS was established in Germany and initially sent out missionaries to the Cape Colony where the first station (Wupperthal) was established in 1829, and later spread to other regions, taking over some of the former London Missionary Society stations, including what is today Namibia. The RMS opened the first missionary station at Otjikango (then known as Neu-Barmen) in 1844 under the leadership of Carl Hugo Hahn. Hahn's detailed diaries and keen interest in recording weather and climate make these an invaluable source for the earliest period to ca. 1859. Over the years, several additional missionary stations were established in central Namibia, also providing detailed annual accounts on weather/climate and the environment (Figure 3). The RMS's annual reports (ARRMS), monthly *Berichte* (BRM), station chronicles and quarterly reports sent by the missionaries to Germany and published without major changes provide key sources of information from such stations. Some of the more important stations and start years from which information became available include Rehoboth (1845), Rooibank (originally known as Scheppmannsdorf 1847), Otjimbingue (1849), Hoachanas (1853), Gobabis (1857), Oinanis (1864), Omaruru (1868), Ameib (1869), Okahandja (1870), Omburo (1871), Otjosazu (1872) and Windhoek (1878). Published letters, diaries and memoirs of various missionaries complement the official RMS sources. Given that several missionaries (e.g. Carl Hugo Hahn, Franz Heinrich Kleinschmidt, Johannes Rath and Jakob Irle) resided or travelled in the region for many years, they became increasingly familiar with the climatic conditions and thus provide

Table 1. Details of primary documentary sources and referencing codes used in the text.

Code	Details of source	Location
ARRMS	Annual reports of the RMS: these reports were usually compiled by local missionaries between April and June and then forwarded to the mission central in Wuppertal, Germany	Archives of the Mission 21, Basel, Switzerland
BRM	Berichte der Rheinischen Mission (Reports of the Rhenish Mission): this is a monthly magazine of the RMS that contained diaries and reports written by the missionaries	Archives of the Evangelical Lutheran Church, Windhoek, Namibia
CAD	Cape Archives Depot: ZK16/2/72 (Microfilm) = the 'Official Journal of Resident Magistrate Walfish Bay'	Western Cape Provincial Archives, Cape Town
ELKIN	Evangelisch-Lutherische Kirche in Namibia (Evangelical Lutheran Church in Namibia): Elkin V.23.1 is the station chronicle for Omaruru, compiled by a missionary ca. 1915 using reports, diaries and letters from missionaries that had been stationed there	Archives of the Evangelical Lutheran Church, Windhoek, Namibia
NAN	National Archives of Namibia: NAN A.004 is the diary of colonial official Hugo von Goldammer. A.071 is the memoir of German trader and farmer Ludwig Conradt, compiled in 1904 after he had lived in the colony for 20 years. A.547 is a diary of A. Henker, a German soldier	Windhoek
RMG	Rheinische Missionsgesellschaft (RMS): RMG 2.588 C/I 8 is the station chronicle for Otjimbingue, compiled by missionary Schmitz in ca. 1920 using reports, diaries and letters from missionaries that had been stationed there. 2.589 C/i 9 is the chronicle for Rehoboth. 2.585 C/i 6 is collected material for various stations. 1.577 a B/c II 3 is letters from Hahn to the mission headquarters	Archives of the United Evangelical Mission (VEM), Wuppertal, Germany
Chapman	Memoirs of this English explorer, first published in 1868	Basler Afrika Bibliographien
Hahn	Diaries of this missionary, edited by Brigitte Lau	Basler Afrika Bibliographien
Irle	A book of ethnographic, historical and missionary writing of this missionary, first published in 1906	Basler Afrika Bibliographien
Moritz	Diaries and letters of missionary F.H. Vollmer, edited by Walter Moritz	Basler Afrika Bibliographien

insightful perspectives in later years. Various missionary documents were sourced from the archives of the *Vereinte Evangelische Mission* (VEM) in Wuppertal, Germany and *Archives of the Evangelical Lutheran Church in Namibia* (ELCIN), Windhoek. Annual reports, written by district officials, and journals of resident magistrates, become available during the German Colonial period, from 1894/1895 onwards, and provide additional information on climate, environment, agriculture (e.g. harvests) and health/diseases – these were accessed from the National Archives of Namibia (NAN) in Windhoek. Finally, relevant information was also extracted from diaries and letters written by other Europeans either staying or travelling through central Namibia during the mid to late 19th century; these include traders [C. J. Andersson (1850–1867); A. Eriksson (1879–1900+); L. Conradt (1887–1900+)], travellers [J. Chapman (1849–1863)], soldiers [A. Henker (1890–1900+)], and British Colonial Officers [W. C. Palgrave (1876–1880)]. Such texts were available through the William Cullen Library, University of the Witwatersrand (Johannesburg), and the Cape Archives Depot (CAD, or Western Cape Provincial Archives) in Cape Town.

All climatic information and climate-dependent phenomena (e.g. state of grass/grazing/crops, river flow), were recorded verbatim and organized chronologically according to 'rain years' (July of year 1 to June of year 2). Although data density (quotation entries per year) is low (12–13 pa) and total 679 for the period 1845–1900, relative to that available for other southern African regions during the 19th century, quotations provide considerable weather and climatic detail and are thus data rich. For most years, one or more detailed quotations provide much information about the seasonal climatic conditions, such as for example:

Otjimbingue: 'The year 1852 was a good rain-year. Towards the end of 1851 it had already rained a bit, to the east more so than in Otjimbingue, and so much that the river came down. In N-Barmen and Rehoboth it rained tremendously. On 29 January the Swakop had already flowed for over a month. At Otjimbingue itself, it had then not rained too strongly, but smaller showers came down and the pastures became very beautiful' (RMG 2.588 C/i 8, 34).

Initially (1845/1846), information was only available from one station (Otjikango) and thus spatial representation was low, but then grew over the course of time (Figure 3), hence impacting the confidence in our results (or ability to represent the region as a whole). Based on the collective annual commentaries, each year is classified according to overall rainfall conditions during the rain season, using a five-point system as previously used for other sub-regions of southern Africa (e.g. Nash *et al.*, 2016). The classification follows: very wet/floods (+2)/relatively wet

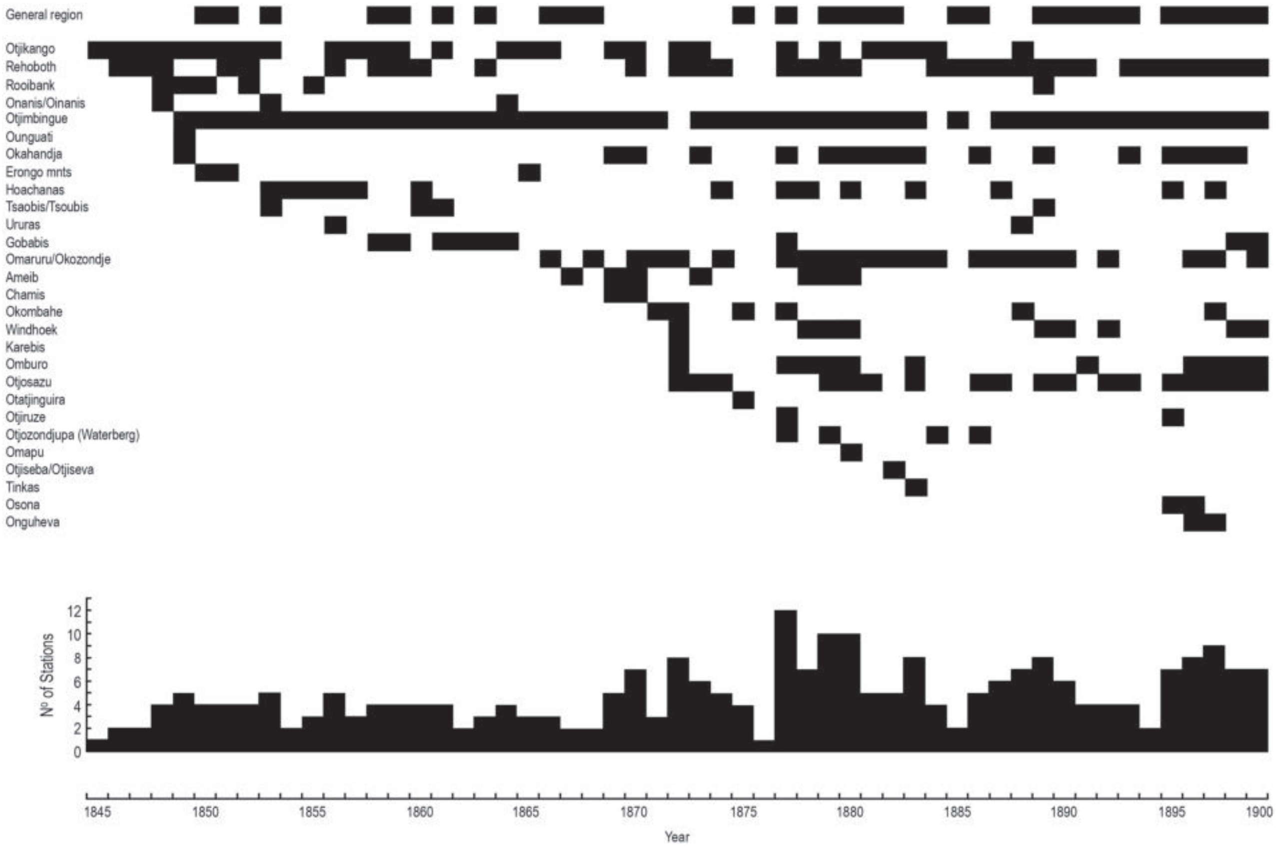

Figure 3. Locations (in annual order) for which 19th century climate data are available in central Namibia: 1845–1900.

(+1)/seasonal rains or 'normal' conditions (0)/relatively dry (−1)/very dry/drought (−2) (Table 2). Very wet years may have reports of heavy/prolonged rain and rivers such as the Kuiseb and Swakop in flood, flowing long distances towards the western coastline and/or even reaching their mouths (an 'atypical' annual occurrence). In contrast, a very dry/drought year generally has little or no rain over most of the region, with adverse implications on water and grazing resources. Where information was too limited, the rain season was indicated as 'unclassified'. Using a similar semi-quantitative annual rating system, it is also possible to compare rainfall trends for the second half of the 19th century with other southern African regions (Namaqualand, southern Kalahari and southeastern South Africa).

The semi-arid climate, often patchy rainfall distribution, and steep precipitation gradients across the region, offer particular challenges to such classification and thus differentiating between normal and slightly wet or dry conditions becomes more challenging. Differences in sub-regional seasonal rainfall (i.e. between stations even only 100 km apart) may be large and at times require different classifications; in such cases an overall average classification is considered, but details on such differences elaborated upon. To this end, each annual classification is given a confidence rating following Kelso and Vogel (2007)(1 = low confidence; 2 = moderate confidence; 3 = high confidence), and additionally specifies the nature of concerns where the confidence is low (Table 2). For instance, the rain years 1845–1847 are given a low confidence (1) because records are only available from Otjikango, and although information may be detailed enough for this station, it is spatially limited for classifying the region as a whole.

Earliest instrumental rainfall data for central Namibia were accessed and digitized from the '*Mitteilungen aus den Deutschen Schutzgebieten*', Band XXXII. During the 1880s and 1890s, rain gauges at older colonial stations had a diameter of 240 mm as used in the Kingdom of Sachsen and proposed by the 'Verein für Erdkunde' (Society for Earth Sciences) in Leipzig. The oldest and most complete record is for Rehoboth, starting in 1883, but with data gaps for the 1885/1886 and 1890/1891 rain seasons. Omaruru also has a record starting in 1883 but has a large data gap between the rain seasons of 1885/1886 and 1898/1899. Further rainfall records become available for Windhoek and Okhandja from 1891/1892 onwards. These station records are presented for the period 1883–1913, and compared against the annual documentary-derived rainfall classification to test its reliability. More recent 20th century quality checked rainfall records for Windhoek were obtained through the NOAA database, but these end in 2002 due to data gaps thereafter.

Finally, reconstructed austral summer rainfall conditions for central Namibia are compared against each immediately preceding El Niño, La Niña and neutral year (1845–1900) using the annual ENSO status based on Gergis and Fowler (2009, table 9) – as also previously tested for southeastern Africa by Nash *et al.* (2016). In

Table 2. Annual hydro-climatic summary for central Namibia for the rains years 1845/1846 to 1899/1900.

Year	Precipitation	Confidence rating	Details
1845–1846	Seasonal rains	1 – Good information for Otjikango; a lack of information for the wider region	Good late rains in Otjikango; grass green in Jan; Swakop river flowed in February; poor rains in Rehoboth
1846–1847	Unclassified	1 – good information for Otjikango; a lack of information for the wider region	Rains in Otjikango in October, November, December, February
1847–1848	Very wet	3 – informative statements	Otjikango: late but abundant rains; water stored until April in Rehoboth; Kuiseb River reached Rooibank on 5 March
1848–1849	Relatively wet	2 – records suggesting both very wet but also dry conditions (depending on place and time)	Swakop River flowed at Ounguati on 22 December; drought until February in Otjikango, then abundant rains until April
1849–1850	Very wet	3 – good agreement that widespread abundant rains through the season	Abundant rains in Otjikango from December until April; Swakop River flowed several times; abundant rains at Schmelen's Hope and Otjimbingue in January and February; sufficient water available to at least end of April in Erongo
1850–1851	Very dry	2 – given the semi-arid nature of the region, this season might be classified as 'relatively dry'	Poor rains in Rehoboth, Otjimbinge, Erongo, Windhoek; reports of sporadic rains in Oct, Nov, Jan; general lack of grass
1851–1852	Very wet	3 – overall good and agreeable information for the region as a whole	Early drought reports from Rehoboth, Otjikango; heavy rains after end of December in Otjikango, Otjimbingue; Swakop flowed all of January; Kuiseb, flowed February/March and destroyed Rooibank; Kuiseb and Swakop Rivers reached the ocean
1852–1853	Relatively dry	1 – limited information	Hahn reports rain around Onanis (Naukluft) in February, Andersson reports rain from northwest of Rehoboth in April, no river flow
1853–1854	Very dry	1 – limited information	Reports of drought in Otjimbingue; rains in Hoachanas for Christmas; no river flow in summer; rains in Hoachanas on 6, 7 June; river flowed in winter
1854–1855	Relatively wet	2 – limited but agreeable information	Good rainy season in Hoachanas; late rains in Otjimbingue; Swakop River flowed and Kuiseb River reached Rooibank end of February
1855–1856	Relatively wet	3 – overall good and agreeable information for the region as a whole	Heavy rains in November in Rehoboth; Kuiseb River flowed to Ururas in November; Swakop River reached Otjimbingue in November & again in February; exceptionally good pastures in March near Tinkas
1856–1857	Seasonal rains	3 – overall good and agreeable information for the region as a whole	Early drought in Hoachanas; heavy rains in December; some late rain in May; rains around Otjimbingue in January, some in March and April; good pastures
1857–1858	Very wet	3 – overall good and agreeable information for the region as a whole	Swakop River flowed at Otjikango in September; good rains in Otjimbingue in November and December when Swakop flowed; drier further east; heavy rains in March in Rehoboth, Otjikango, and Otjimbingue; devastating flood in Otjimbingue
1858–1859	Very dry	2 – difficult to classify given good rains early in the season but mid and late season rains failed across the region	Good rains in November and December in Otjikango and Otjimbingue when Swakop River flowed; thereafter reports of severe drought/hunger from Otjimbingue, Rehoboth, Otjikango
1859–1860	Very dry	2 – difficult to classify given a long severe summer drought, but which had sufficient late rains to permit river flow	Reports of severe drought from Otjimbingue and Rietfontein; late season rains when the Swakop River flowed from 29 April until mid-May
1860–1861	Relatively dry	3 – overall good and agreeable information for the region as a whole	Reports of drought from Otjimbingue, Windhoek, Gobabis, Swakop flowed at Otjikango in April
1861–1862	Relatively wet	2 – agreeable but limited information	Swakop flowed strongly and caused damage at Otjimbingue in December, January
1862–1863	Very wet	3 – overall good and agreeable information for the region as a whole	Good rains in Otjimbingue, Gobabis, Rehoboth, starting in November; Kuiseb flowed to the ocean in early 1863
1863–1864	Relatively wet	3 – overall good and agreeable information for the region as a whole	Good rains January to March and ground soaked; good pastures in Otjikango and Otjimbingue; Swakop River came down in January

Table 2. Continued

Year	Precipitation	Confidence rating	Details
1864–1865	Seasonal rains	1 – limited information	Good harvests in Otjimbingue and Salem; water still available during winter in Khan
1865–1866	Very dry	3 – overall good and agreeable information for the region as a whole	Reports of great drought conditions from Otjikango, Otjimbingue and elsewhere
1866–1867	Very dry	2 – limited information	Irle writes about a general regional drought, identifying 1867 as one of the driest and no river flows
1867–1868	Very dry	3 – limited but agreeable information to the great drought conditions	Numerous reports of severe drought from Otjimbingue and the region generally
1868–1869	Very dry	2 – sources suggest there may have been some sub-regional variability owing to 'patchy' nature of rainfall	Some early January rain in Otjimbingue when the Omusema when Swakop flowed; reports of continued severe drought from Otjikango, Otjimbingue, Chamis, Ameib
1869–1870	Seasonal rains	3 – overall good and agreeable information for the region as a whole	Reports of severe early drought from Ameib, Otjimbingue, Otjikango, Okahandja, Rehoboth. Later good rains in Okahandja, Otjikango, Omaruru, Chamis, Ameib. Swakop flowed in Otjimbingue in April
1870–1871	Relatively dry	2 – limited but agreeable information	Reports of drought form Omaruru and Otjimbingue; land looks sterile
1871–1872	Relatively dry	2 – limited but agreeable information	Report of drought from Otjikango; Brinker reports on the 'year by year increasing drought'
1872–1873	Relatively wet	3 – overall good and agreeable information for the region as a whole	Late rains in Otjimbingue; good rains in Otjosazu
1873–1874	Relatively wet	3 – overall good and agreeable information for the region as a whole	Good rains from January in Omaruru, Otjimbingue, Rehoboth, Otjosazu, Hoachanas; floods in Otjosazu, Otjimbingue, Otjikango
1874–1875	Relatively wet	2 – limited but agreeable information	Good rains from January onwards in Otjimbingue, reports of good grazing
1875–1876	Seasonal rains	1 – limited information (may have been relatively wet)	Report of good rains in Otjimbingue and abundant vegetation growth
1876–1877	Relatively dry	3 – overall good information for many sub-regions	Reports of drought from Okombahe, Rehoboth, Hoachanas, Omburo, Otjimbingue, Otjikango, Omaruru, Windhoek. Some rain in Nov at Okahandja, Otjikango. Some rain in February in Omburo and Omaruru, Otjikango and Otjimbingue, flood in Otjizeva on 25 February
1877–1878	Very dry	3 – overall good information for many sub-regions	Reports of drought from Hoachanas, Omaruru, Rehoboth, Otjimbingue, Ameib-Walfish Bay, Omburo; rain in Rehoboth in October
1878–1879	Very dry	3 – overall good information for many sub-regions	Reports of drought from Otjikango, Okozondje, Omburo, Otjosazu, Ameib, Omaruru, Otjimbingue. Some Nov rains in Otjikango. Some March rains in Okozondje, Otjikango, Otjizeva; Some April/May rains in Omaruru, Omburo, Otjimbingue, Rehoboth
1879–1880	Seasonal rains	2 – good but varied information; seemed like the rains were patchy	Spring at Ameib ran dry; reports of drought from Otjosazu, Otjimbingue (until January), Rehoboth (until February), Ameib (continuing); good rains in December/January in Omaruru and Omburo; good rains from January in Otjimbingue; Swakop River flowed for 3 weeks; sufficient rains in Hoachanas
1880–1881	Very wet	3 – overall good information for several sub-regions	Report of drought from Otjikango, Okahandja and Otjimbingue until mid-January; then exceptional rains everywhere, severe floods in Okahandja, Otjimbingue
1881–1882	Very dry	3 – overall good information for several sub-regions	River flowed at Osona on 22 November; good rains in December; severe drought in Otjimbingue; other reports of drought form Otjiseva, Otjikango, Rehoboth, Omaruru
1882–1883	Seasonal rains	3 – overall good information for several sub-regions	Flood at Okahandja in February; good rains at Omaruru in January and at Otjosazu since November; Swakop flowed strongly at Otjimbingue; poor rain in Otjikango until March; rains seemed patchy and variable

Table 2. Continued

Year	Precipitation	Confidence rating	Details
1883–1884	Relatively wet	2 – few sources but good agreement	Reports of good rains in Otjikango, Omaruru, Rehoboth
1884–1885	Very wet	3 – overall good information for several sub-regions	Very heavy rains for 3 months in Otjimbingue, like not experienced before by Bernsmann; Kuiseb River flowed to Walvis Bay
1885–1886	Unclassified	1 – limited weather-related information	Nothing notable mentioned and seemed like ‘normal year’
1886–1887	Relatively wet	2 – information geographically limited but agreeable	Good rains in Otjimbinuge, even some in May and July Omusema River flowed in January, Swakop River flowed in February
1887–1888	Very dry	3 – overall good information for several sub-regions	Rains in October and some in December in Otjosazu, Otjimbingue, but no further rains mentioned for the new year; reports of severe drought from Omaruru, Omburo, Otjosazu
1888–1889	Very dry	3 – overall good information for several sub-regions	Reports of summer drought from Rehoboth, Okombahe, Omburo, Otjimbingue, Omaruru; Good late April rains
1889–1890	Seasonal rains, spatially and temporally patchy	3 – overall good information for several sub-regions	Early October/November rains in Rehoboth, Otjimbingue; Swakop River flowed in Otjimbingue in October, November, March. Late rains in Rehoboth; reports of drought from Otjimbingue, Rehoboth, Otjosazu
1890–1891	Seasonal rains, spatially patchy	3 – overall good information for several sub-regions	Reports of drought from Otjimbingue, Otjosazu; good rains elsewhere, e.g. Omaruru; variable and patchy rain season
1891–1892	Relatively wet	3 – overall good information for several sub-regions	Kuiseb River flowed at Otjimbingue in October; good rains in December/January; Kuiseb River flowed to Rooibank; southern drought (Rehoboth)
1892–1893	Very wet	3 – overall good information for several sub-regions	Kuiseb River reached Walfish Bay in February, March, Swakop River also reached the ocean; Heavy January rains Otjimbingue, Windhoek and elsewhere
1893–1894	Seasonal rains	3 – overall good information for several sub-regions	Good December rains in Otjosazu; early drought in Otjimbingue then some good rains in February/March
1894–1895	Relatively dry	2 – information geographically limited but agreeable	Early and mid-season drought in Otjimbingue, then good late season rains
1895–1896	Very dry	3 – overall good information for several sub-regions	Reports of widespread drought but a good rainy season in Otjimbingue
1896–1897	Very wet	3 – overall good information for several sub-regions	‘Was an especially good rain year’; December floods in Omaruru and Otjimbingue
1897–1898	Relatively wet	3 – overall good information for several sub-regions	Reports of early drought from Hoachanas, Otjimbingue, Rehoboth; Swakop River flowed for 3 weeks in January; good rains in Otjihaena; gardens disturbed by river flows
1898–1899	Relatively wet	3 – overall good information for several sub-regions	Good rains at numerous places poor rains in Gobabis
1899–1900	Seasonal rains	2 – difficult to classify given highly variable reports	Reports of severe drought from numerous places; good rains for northern and central regions of Namibia; conflicting reports

The assigned rainfall classification is given a confidence rating following Kelso and Vogel (2007): 1, low confidence; 2, reasonable confidence; 3, high confidence.

addition, the austral summer rainfall classifications for central Namibia are compared against those of the southern Kalahari (Nash and Endfield, 2002) and southeastern Africa (Nash *et al.*, 2016), which represents a ca. 1800 km NW-SE transect through southern Africa (Figure 1).

4. Rainfall variability over central Namibia

The earliest instrumental rainfall record at Rehoboth (1883–1913) records an annual mean of 246.7 mm [varying from 76 mm (1912/1913) to 599 mm (1892/1893)] (Figure 4). For the period 1891–1913 (22 years), Rehoboth records an annual mean of 255.3 mm, Windhoek 383.9 mm and Okhandja 394.7 mm, reflecting typical sub-regional variability from the drier southern to wetter northern region. For this period, Rehoboth also has a higher percentage standard deviation from the mean (53.8%) than the wetter northerly stations (between 41 and 47%). A longer (102 year) 20th century record (1901–2002) available for Windhoek, registers a mean of 359 mm, while that for the period 1981–2002 is 325 mm (Figure 5). The 20th century records negligible change through the 102 years (+0.4 mm decade^{-1}), but inter-annual variability seems to have declined since the mid-1960s. The earlier (late 19th/early 20th century) record represents a wet period, relative to more recent times. For Okhandja, Windhoek and Rehoboth, there is strong correlation in inter-annual rainfall variability for the period 1891–1913 ($r = 0.80$ to 0.95; $p < 0.001$).

The documentary-based rainfall chronology for the period 1845–1900 (55 rain seasons – 2 of which are unclassified) indicates 26% of rain seasons as very dry, 12% as relatively dry, 21% as 'normal', 27% as relatively wet and 15% as very wet (Figure 6). Wetter years (42%) are over-represented in comparison to dry years (38%) for central Namibia, which contrast with trends in the drier southern Kalahari (Nash and Endfield, 2002) and Namaqualand (Kelso and Vogel, 2007). These Namibian trends also strongly contrast with the much wetter southeastern South Africa, where during a similar period, 44% were drier years and only 32% wetter years (Nash *et al.*, 2016). Using the five-point system (Figure 6) for each rain season between 1845 and 1900, central Namibia receives a mean score of −0.06, while other regions score −0.20 (southeastern South Africa, using data from Nash *et al.*, 2016), −0.35 (southern Kalahari, using data from Nash and Endfield (2002)) and −0.98 (Namaqualand, using data from Kelso and Vogel (2007)). The Namibian results do not imply wetter conditions than southeastern South Africa, but rather that it was a relatively 'neutral' period in the context of its semi-arid climate, while other regions may have been 'drier than normal' in the context of their sub-regional climates. The subjective nature of reporting should also be acknowledged at this point and there might have been a tendency at times to over-report wet conditions. For the western and central parts of southern Africa, relative rainfall trends through the period 1845–1900 indicate negligible change ($y = 6\text{E} - 0.5x$) over central Namibia, but slight ($y = 0.0076x$) to somewhat stronger ($y = 0.0134x$) wetting in the southern Kalahari and Namaqualand, respectively (Figure 6). In contrast, southeastern South Africa experienced a strong ($y = -0.0236x$) drying trend during this time, indicating somewhat different sub-regional trends over the latter half of the 19th century.

5. Occurrence of floods and wet periods

Given the semi-arid environment and general scarcity of water in central Namibia, mission stations were established in proximity to springs or seasonally/episodically flowing rivers where wells dug into river beds provided water through the dry season. The availability of water is thus a much written about topic. The indigenous population also relied on such water sources, and so the missionary stations became focal points of human habitation for a variety of reasons including water and food provision, agricultural production and employment, schooling and places of worship. Accounts of rivers flowing (or in flood), as also the extent and duration of flow, provide valuable information on the timing and nature (e.g. intensity, duration) of rainfall in the central Namibian catchments of in particular the Swakop and Kuiseb Rivers (Figure 1). Given that water in both these rivers seldom reaches the Atlantic coastline, accounts of flow at or near the river mouths provide additional evidence for exceptional rains in the hinterland, as acknowledged by early writers such as Kolbe (Rooibank, 5 March 1848):

…we saw the water flowing in the Cuisep [Kuiseb River]. O this is here a remarkable and rare event! The current is strong, there must have been a vast amount of rain in the interior, as it is only very seldom that the water reaches the mouth of the Cuisep (RMG 2.585 C/I 6, 11).

Based on the documentary evidence, central Namibia experienced regular and prolonged wet phases during the second half of the 19th century, typically lasting between one to three rain seasons (Table 2 and Figure 6). This is in strong contrast to the less frequent and shorter duration of wet phases recorded in other parts of southern Africa (e.g. Nash and Endfield, 2002; Kelso and Vogel, 2007; Nash and Grab, 2010; Nash *et al.*, 2016). The following rain seasons or periods are classified as wet for central Namibia: 1847–1850, 1851–1852, 1854–1856, 1857–1858, 1861–1864, 1872–1875, 1880–1881, 1883–1885, 1886–1887, 1891–1893 and 1896–1899.

The first wet phase lasted three seasons (1847–1850) and was exceptional as the Kuiseb River reached Rooibank (near its mouth) in March 1848, and according to Kolbe who was based at Rooibank, the river again reached the ocean in 1849 (ARRMS 1850, 21), which meant abundant summer rains over the interior. This is further supported by missionary Hahn, who wrote in his diary at Otjikango, 21 April 1848 (p. 385): 'this year is extraordinarily rich in rain, even though the rains began very late'. The rain season of 1848–1849 started off very dry but when the rains eventually came in February through to April, it is reported by Hahn (diary entry – 5 March 1849) that everything was green and the ponds full of water attracting ducks, with water almost as abundant as 6 years earlier, suggesting that 1843 was a particularly wet year.

After a very dry season (1850–1851), abundant and continuous rains started in late December 1851 so that by mid-January 1852 the land was green and covered with a yellow blanket of flowers (Hahn Diaries, 17 January 1852, Otjikango, 582). The first few months of 1852 were exceptionally wet over central Namibia and the rain season described as a good one, and even in the drier southern regions of Rehoboth the rains were heavy. By 28 February the Kuiseb flowed to Rooibank causing devastating floods, destroying buildings and 'uprooting strong trees' along its banks (RMG 2.588 C/i 8, 3).

Wet conditions commenced during the 1854–1855 rain season and continued through to 1857–1858, interrupted only by a 'normal' rain season in 1856–1857. Although the rains arrived late in mid-February 1855 at Otjimbingue, the rains were then strong and ongoing for some weeks. In the extreme southern and drier part of the study region, Vollmer writes from Hoachanas on 8 April 1855: 'the Lord has especially blessed our station fields with rain this year' (Moritz, 2000, p. 27). The following rain season started early, so much so that the Swakop River flowed at

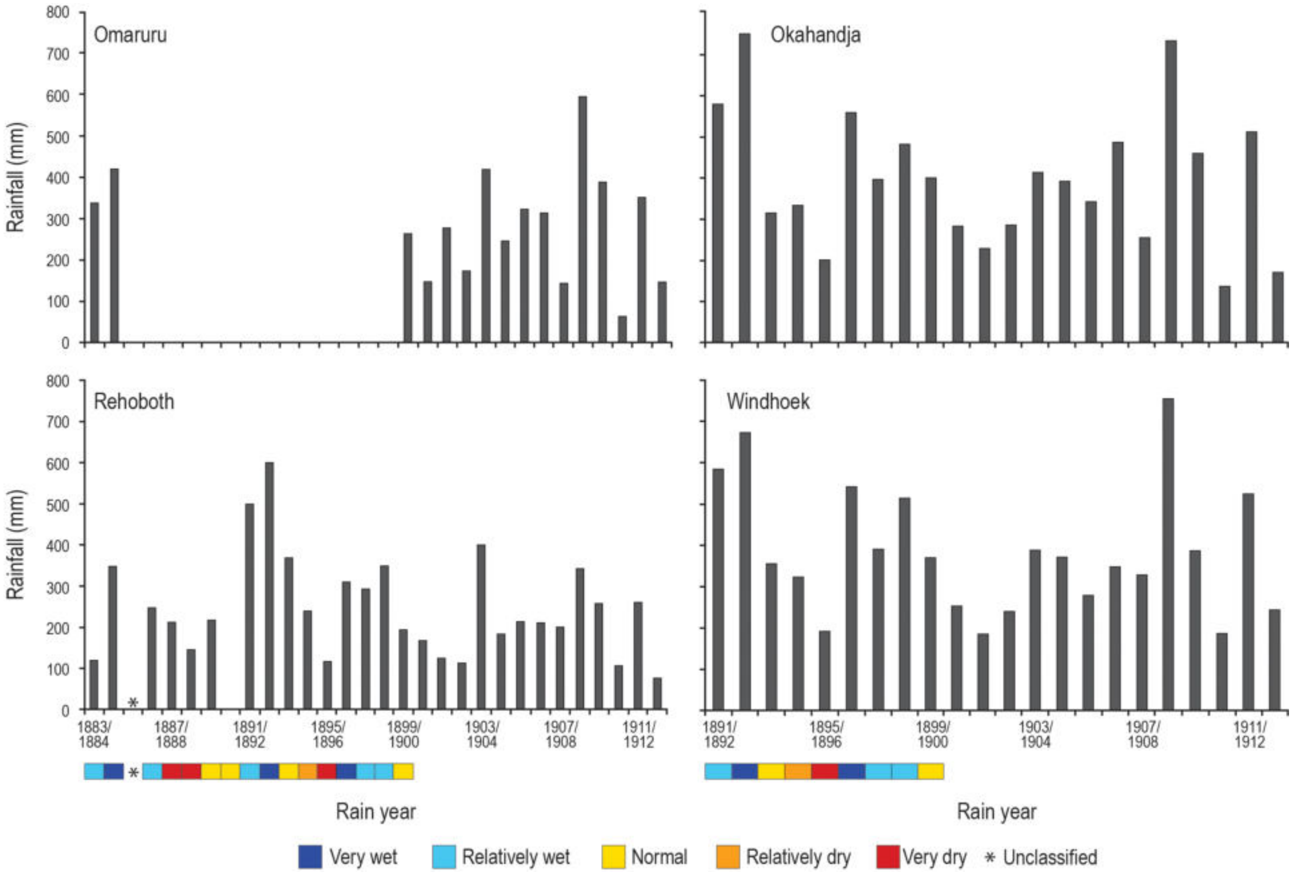

Figure 4. Total rainfall for Omaruru and Rehoboth (for the rain years 1883/1884 to 1912/1913) and for Okahandja and Windhoek (for the rain years 1891/1892 to 1912/1913). Below is the corresponding annual document-derived rainfall chronology for the central Namibian region. [Colour figure can be viewed at wileyonlinelibrary.com].

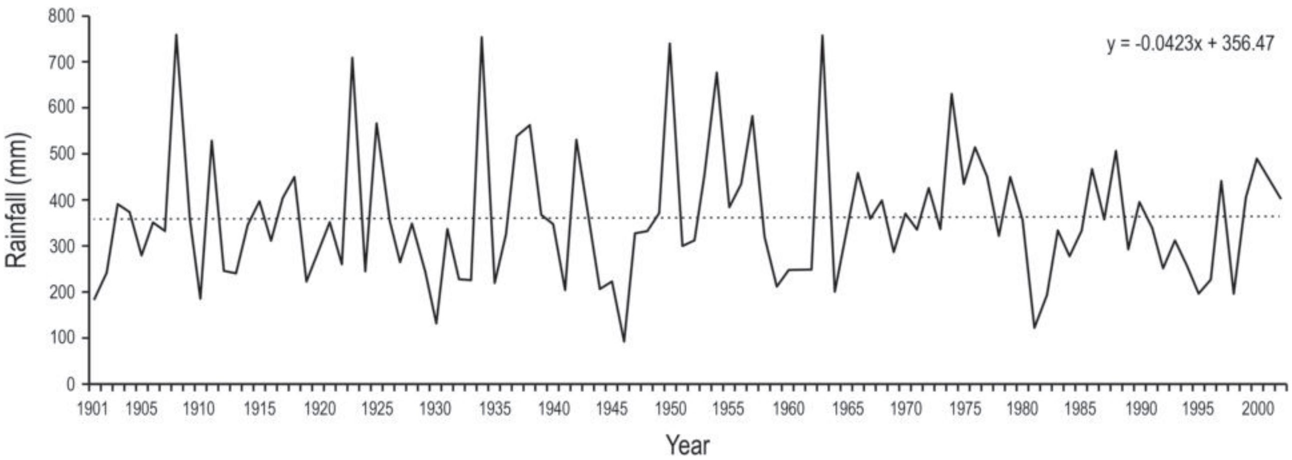

Figure 5. Annual rainfall totals (with linear trend line) for Windhoek: 1901–2002.

Otjimbingue by 19 November 1855, the earliest missionary Rath had seen it flow there (RMG 2.588 C/i 8, 60). The season is reported to have had good pastures and the Swakop eventually reached flood stage and caused damage to gardens at Otjimbingue in mid-February 1856. The rain season of 1857–1858 was very wet with rains starting exceptionally early in the season (at least by September) and heavy rains reported until March 1858 at several stations. Late that rain season (end March 1858) the Swakop reached flood stage and destroyed gardens and wheat fields in Otjimbingue (RMG 2.588 C/i 8, 84).

After a protracted dry period, central Namibia again experienced a three-season wet phase from 1861–1862 to 1863–1864. The period started off relatively wet, with flooded gardens at Otjimbingue in January 1862, while further south at Rehoboth it seemed considerably drier. The following rain season (1862–1863) was exceptionally wet throughout central Namibia. Although the vegetation

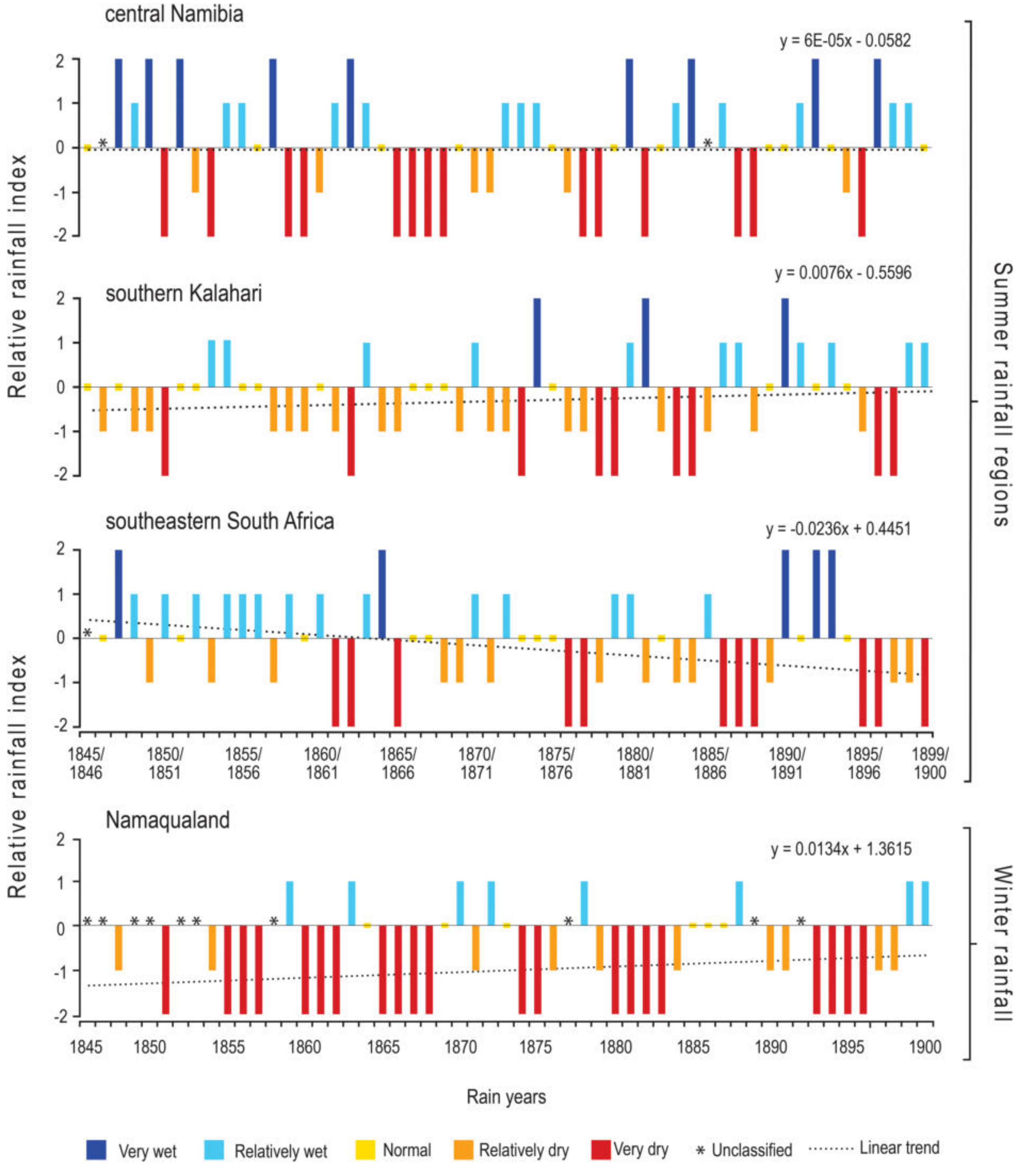

Figure 6. Document-derived annual rainfall chronology for central Namibia and other southern African regions between 1845 and 1900. Data for the southern Kalahari are after Nash and Endfield (2002), for southeastern South Africa are after Nash *et al.* (2016), and for Namaqualand are after Kelso and Vogel (2007). The relative linear rainfall trends are based on assigned values as follows: very wet (2), relatively wet (1), normal (0), relatively dry (−1), very dry (−2). [Colour figure can be viewed at wileyonlinelibrary.com].

was lush, the gardens suffered from too much moisture (fruit rot) and rivers overflowing their banks and caused damage. When Chapman travelled near the coast in August 1863, he learned from local inhabitants that they had never before seen such rains as experienced earlier that year. The Kuiseb River floods swept away dwellings and cattle and cleared the sandhills in its path (Chapman, 1971, p. 201). Good rains continued the following season, particularly from January to March of 1864 with reports of the ground soaked, the Swakop flowing at Otjimbingue, other small streams flowing, and the earth covered by high grass and flowers.

After the exceptionally long and devastating dry period lasting from 1865 to 1872, the drought was broken by three relatively wet rain seasons from 1872–1873 to 1874–1875. In all three of these seasons the rains arrived somewhat late (January) but continued through to March or April. Even the drier southern region of Rehoboth received abundant rains, which missionary Heidmann blamed as the cause for a deadly fever outbreak in January 1874 (RMG 2.589 C/i 9, 107f).

After a drier period from 1875 to 1880, the rain season of 1880–1881 began very dry with accounts of hunger and drought as late as December 1881 (ARRMS, 1880, 26). The rains only arrived in mid-January but from then it rained heavily for many days on end, such that the Swakop destroyed three dams that had been built along its course (RMG 2.588 C/i 8, 261f). Irle reports on 22 April 1881 from Otjosazu: 'The rains have fallen abundantly in the last months and have brought with them floods such as cannot be recalled in human memory … ' (BRM, 1881, 369). Missionary Eich provides a similar report in April from Okahandja: 'It took a long time for the rains to come, but then they were so prolonged, such as I have never experienced … ' (BRM, 1881, 372f).

The next wet phase commenced in the rain season of 1883–1884 and possibly lasted four rain seasons – to 1886–1887. Although the season of 1885–1886 is unclassified due to insufficient information, it was likely a 'normal' to 'wet' one, as a report written in early April by Ludwig Conradt, a farmer in Orumbo, mentions that the Kuiseb River flowed to Rooibank, an occurrence requiring abundant rains (NAN A,071, 77f). This wet period culminated with an extraordinarily wet rain season in 1884–1885 which in late March caused the Omusema River (tributary of the Kuiseb at Otjimbingue) to uproot trees along its banks (NAN, A.004, vol. 1). The Kuiseb River itself flowed to Walfvis Bay (Atlantic Ocean) on several occasions between 27 January and 30 March 1885, which was exceptional. In fact the entire settlement was 'surrounded by water' on 12–13 March (CAD, ZK16/2/72, Official Journal of the Resident Magistrate Walfish Bay). Heidmann at Rehoboth describes the year 1885 as one in which the rainfall was 'unusual' in quantity and consequently the land looked most beautiful (RMG 2.589 C/i 9, 312f). Further north at Otjimbingue, it is said that it rained 'gewaltig' (enormously) for three continuous months from the old (1884) into the new (1885) year, such as had never before been experienced by the missionary Bernsmann (RMG 2.588 C/i 8, 281).

A further two wet periods impacted central Namibia during the last decade of the 19th century, in 1891–1893 and again 1896–1899. The rains of early 1892 seem to have been abundant, particularly in the context of the previous years, with the Kuiseb reaching Rooibank in early February 1892 (RMG 2.588 C/i 8, 317). The period1892–1893 was very wet with widespread reports of heavy rains and its associated problems (e.g. schools closed, at times travel was near impossible in places). Missionary Henker reported from Windhoek that as of January 1893 one of the best rain seasons set in that he had ever experienced (NAN A.547, 50). The Swakop flowed into the Atlantic with great violence in January 1893, while the Kuiseb also reached the Ocean in February and March, when the entire Kuiseb valley was under water (RMG 2.588 C/i 8, 3). Missionary Meyer reported from Otjimbingue (1893):

It was as though all the sluice gates of heaven were opened. The high lying Otjimbingue was often like a lake. The river burst its banks and caused much damage (RMG 2.588 C/i 8, 320).

After a spell of three drier seasons, 1896–1897 was again very wet, as also supported in the instrumental rainfall records (Figure 4). Although described as an 'exceptionally good rain year', the rains again brought problems associated with flooding, and perceived to be the cause for a serious, widespread fever epidemic (ARRMS, 1897, 13).

6. Occurrence of droughts and relatively dry periods

Droughts in what is already a semi-arid and water-deprived environment caused much hardship to society during the second half of the 19th century, mainly through livestock deaths (e.g. lack of grazing, dehydration), crop failures and a lack of water for human consumption, in some cases leading to malnourishment and starvation. Based on documentary evidence, central Namibia had 19 dry rainfall seasons between 1845 and 1900, the most severe lasting four consecutive 'very dry' (drought) seasons (1865–1869). Irle (1906) remarks that significant drought events returned every 10 years and noted the years 1879, 1889 and 1896. Although such a perception is interesting in the context of potential cyclic hydro-climatic patterns, the current data rather support a 1–2 year, and more dominantly 4–5 year drought return period. The following rain seasons or periods are classified as dry for central Namibia: 1850–1851, 1852–1854, 1858–1861, 1865–1869, 1870–1872, 1876–1879, 1881–1882, 1887–1889 and 1894–1896.

Despite some sporadic rains in October, November and January of 1850–1851, respectively, there was hardly any thereafter. Mention is made of drought causing people to migrate in search of food and pastures from the southern (Rehoboth) to northern (Otjimbingue) parts of central Namibia. After a very wet rain season (1851–1852), the period 1852–1854 was dry to very dry. Despite abundant rains in December 1853 at Hoachanas (Moritz, 2000, p. 19), Rath reports on 10 October 1854 that it had rained very little across the entire land (and in some places almost nothing) over the last two rain seasons, during which time the Swakop River had not come down either (RMG 2.588 C/i 8, 52).

An even more severe dry phase occurred from early 1859 to late 1861. After a good start to the rain season in November/December 1858 when the Swakop River flowed at Otjimbingue, the rains discontinued in early 1859, but with apparently overwhelming heat at Otjikango (Hahn Diaries, 5 January 1859, Otjikango, 1126). The drought continued into the next rain season and by 30 January 1860, Chapman, based at Otjimbingue, comments:

We have had an uncommonly dry season and on our way up lost 20 of our cattle, chiefly from want of water … The *want of water has not been confined to one district, but in the whole country up to the Lake the fountains have failed…* (Chapman, 1971, p. 234).

Despite some very late rains at the end of April and in May 1860, this seemed too late to have had any positive consequence on the barren grasslands. The situation was similar the following rain season (1860–1861) when again the rains were limited to the late season, such that by September 1862, after three dry seasons, missionary Weber confirmed serious famine in the Gobabis region (BRM, 1863, 271).

The most prolonged and devastating dry phase during the second half of the 19th century in central Namibia, lasted from 1866 to 1869. Even in relatively dry years, the Swakop River reaches Otjimbingue on some occasions, but in the years 1866–1868 it never reached the station (Irle, 1906). The first of these years (1866) was already declared a 'great drought year' (by missionary Brincker) in which hunger had set in 'here and there' (RMG 2.585 C/i 6, 63–64). Irle (1906) mentions that general drought conditions occurred over central Namibia in the years 1771, 1792, 1833, 1844, 1867 and 1902/1903. It is not possible to confirm whether these may indeed be the greatest historical drought years in the region, but interestingly the year 1867 is mentioned as one of these. The rains again failed in early 1868 and people started leaving mission stations in search of better pastures and water. Although some rain fell in early January 1869 in the Otjimbingue region, when the Omusema and Swakop Rivers started flowing again, these rains were short lived and the year described as one of 'terrible drought' (RMG 2.588 C/i 8, 209). Widespread human hunger and starvation led to fragility, sickness and death across the region. Missionary Brincker describes the situation from Otjikango on 10 September 1869:

The drought and its consequences, the hunger, impacts us all very hard and many poor people are dying from exhaustion. Yes, some days back it was mentioned that amongst the Ovatjimba or poor Herero, the hunger is so large, that they have resorted to cannibalism, which might well be an exaggeration (RMG 2.585 C/i 6, 209).

By December 1869 the drought and hunger situation had worsened still, leading some Herero to perform rain making ceremonies (a common African practice during droughts, but one not otherwise mentioned by early settlers and travellers in central Namibia) (RMG 2.585 C/i 6, 88).

After a rain season that seemed 'normal' (1869–1870), another two relatively dry seasons (1870–1872) set in, during which no significant rains fell (BRM, 1872, 311). Water availability and land cover conditions during these 'normal' to 'relatively dry' years seem to have continued deteriorating as a consequence of compounded environmental stress over multiple years, in this instance triggered by four previous years of severe drought that had already depleted the water table, dried out springs and reduced grass cover. Missionary Brincker alludes to such an apparent cumulative drought impact over time at Otjikango (written end of August 1872): 'One thing worries me, even though it is a purely earthly issue, namely the year-by-year increasing drought' (BRM, 1873, 234f).

In his diary entry dated 20 September 1871, missionary Hahn recognizes that abundant rains would be required to improve the depleted grazing situation (RMG 1.577 a B/c II 3). Such year-on-year accumulative and worsening drought conditions is again evident over the period 1876–1879, which started off with a year classified as 'relatively dry' and was followed by two successive 'very dry' years. According to missionary Schröder, the dry conditions in the first year already damaged fruit trees, followed by a year (1878) of 'renowned' stock deaths and named the 'year of the great drought' (RMG 2.585 C/i 8, 3). Conditions deteriorated even further in 1879 with many human and stock deaths blamed on a drought like most missionaries could not recall, and again declared the 'year of the great drought' (ELKIN, V.23.1 Omaruru, 51).

Severe drought returned in 1881–1882, as reported from several stations (Table 2), but was further complicated by war and so the Herero people were forced to keep their livestock in close proximity to stations, consequently not only overgrazing these areas but destroying grass roots through trampling pressure (ELKIN, V.23.1 Omaruru, 101). Then some years later, another severe drought phase (1887–1889) caused many livestock deaths and a major exodus of people from stations (ARRMS 1888, 23). The final widespread drought phase of the 19th century (1894–1896) culminated in a very severe drought in 1896, as is also confirmed through the instrumental rain records (Figure 4). However, under exceptional climatic circumstances, the usually much drier western region of central Namibia (Otjimbingue), received good rains (NAN, ZBU, 146, A.VI.A.3, vol. 2, 12).

7. Rainfall and ENSO phases

For central Namibia, 60% of all dry years between 1845 and 1900, immediately follow El Niño events, and 30% of all dry years follow the La Niña phase (Table 3). Similarly, wet years coincide most strongly with La Niña (59%) and less so with El Niño phases (23%). Such teleconnections between rainfall and ENSO seem most positive before the mid-1880s, and thereafter become notably negative with four wet El Niño and two dry La Niña events between 1884 and 1900. To this end, the very dry 1887–1888 rain season immediately followed a very strong La Niña event. Very strong ENSO phases between 1846 and 1900 only coincide with one very wet season (1880–1881), yet four very strong El Niño phases corresponded with very dry years.

8. Discussion and conclusions

This work presents the first annually constrained 19th century hydro-climatic chronology for central Namibia, based on documentary sources. Both the value and limitations of documentary sources for climate reconstructions

Table 3. Rainfall conditions for austral summer rain seasons immediately following each El Niño, La Niña and neutral year: 1845–1900.

	El Niño	Neutral	La Niña
Dry rain seasons	1852–1853, **1853/1854**, **1858/1859**, 1860/1861, **1865/1866**, **1866/1867** 1868/1869, 1876/1877, **1877/1878**, 1878/1879, **1881/1882**, **1888/1889**	**1859/1860**, **1895/1896**	**1850/1851**, **1867/1868**, 1870/1871, 1871/1872, **1887/1888**, 1894/1895
Seasonal rains 'normal' year	1845/1846, 1856/1857, 1889/1890, 1899/1900	1869/1870, 1882/1883	1875/1876, 1879/1880, 1890/1891, 1893/1894
Wet rain seasons	**1857/1858**, **1884/1885**, 1891/1892, **1896/1897**, 1897/1898	1854/1855, 1855/1856, 1883/1884, 1898/1899	**1847/1848**, 1848–1849, **1849/1850**, 1851/1852, 1861/1862, **1862/1863**, 1863/1864, 1872/1873, 1873/1874, 1874/1875, **1880/1881**, 1886/1887, 1892/1893

Annual ENSO values are based on Gergis and Fowler (2009, table 9). Years in bold indicate extreme dry or wet rain seasons.

have been widely elaborated upon (e.g. Brázdil *et al.*, 2005; Nash and Grab, 2010; Berland *et al.*, 2013) and will thus not be repeated here, but ought to be read in consideration of such limitations. Notwithstanding the limitations, accounts of weather for the most part are very detailed, factual and written by well-educated individuals who took much interest in weather and climate. Although there are only 9 years (1891/1892–1899/1900) of overlap between the documentary based rainfall classification and the instrumental station records, these show good agreement (Figure 5). Agreement is strongest with the centrally located Windhoek ($r = 0.86$; $p = 0.00294$) and least so with Rehoboth ($r = 0.70$; $p = 0.03577$), thus the results in this article likely better represent the central and more northerly parts of central Namibia, than the drier southerly region.

Results show relatively high extreme inter-annual rainfall variability over central Namibia between 1845 and 1900, perhaps more so than in other regions of southern Africa. On five occasions consecutive rain seasons follow opposite extremes [i.e. from very wet (floods) to very dry (drought), or vice versa]. A high percentage (42%) of years are 'extreme' years, either experiencing severe drought or floods with abundant rains; of these, 39% were very wet years. In contrast, the southern Kalahari and southeastern South African regions only experienced 20 and 28% 'extreme' years, respectively, during the 19th century. In addition, the southern Kalahari and southeastern South African regions had few very wet years as opposed to very dry years (25 and 28%, respectively), hence accounting for a less extreme and frequent inter-annual variability. The high inter-annual and seasonal climatic variability over central Namibia was something that became recognized as a 'climatic norm' by the German missionaries. This is reflected in an *Evangelische-lutherische Kirche in Namibia* report (1876): 'The land and its climate knows no transition, no middle ground, everywhere too much or too little' (ELKIN, V.23.1 Omaruru, 27). A particular challenge to this study has been providing seasonal climatic classification to a region that at times also has high rainfall variability over relatively small spatial scales (particularly along west to east and north to south transects). This was the case in the rain season of 1867–1868 when the rains failed entirely in Otjimbingue in early 1868 and grazing conditions were in a terrible state, yet some rains fell and streams flowed three times in the usually drier Omaruru region further south, where grazing was apparently sufficient (BRM, 1868, 355).

Despite the large inter-annual variability, there are some broader temporal hydro-climatic patterns during the second half of the 19th century. It would seem that the late 1840s to 1850s was the wettest period. There were seven wet and four dry seasons between 1847 and 1859, providing a mean wetness index score of 0.38 for this period. Coincidently, this was also the wettest period for eastern South Africa between 1836 and 1900 (index score = 0.46) (Nash *et al.*, 2016), yet the southern Kalahari remained near normal to marginally dry (index score = −0.38) (Nash and Endfield, 2008). The 1860s and 1870s were the driest over central Namibia, as also over other parts of southern Africa during the second half of the 19th century (Nash and Endfield, 2008; Nash and Grab, 2010; Neukom *et al.*, 2014; Nash *et al.*, 2016). For the austral summer rainfall transect from central Namibia to southeastern South Africa, the longest and possibly most severe dry phase to affect all sub-regions, lasted from 1876 to 1879 (Figure 6). This widespread and temporally extended drought coincided with the infamous long and very strong El Niño phase from 1876 to 1878 (Aceituno *et al.*, 2009; Gergis and Fowler, 2009). This ENSO event had widespread global impact and accounts for one of only two synchronous drought events across all three major continents (excluding Antarctica) in the Southern Hemisphere during the latter half of the 19th century (southeastern Australia having drought from 1876 to 1877 and southern South America in 1876 and 1878). The only other synchronous Southern Hemisphere drought occurred in 1865–1866, which too was associated with an extended and very strong

El Niño phase (1865–1866) (Gergis and Fowler, 2009). Somewhat wetter conditions returned to central Namibia in the 1880s. Apart from the 1880–1881 rain season, there is no further synchronicity of wet years between sub-regions in southern Africa. The extreme (1879) to very strong (1880) La Niña that accounted for this outstanding southern African wet season (1880–1881), coincidently also corresponded with substantial wetness in southeastern Australia in 1879–1880 (Gergis and Fowler, 2009).

Irle (1906) mentions 'general-drought' conditions in Namibia during the years 1771, 1792, 1833, 1844, 1867 and 1902/1903 (assumed to be spatially widespread and particularly severe droughts). Notably, several of these major drought events follow immediately after very strong El Niño phases in 1770, 1791, 1866 and 1902 (based on data from Gergis and Henley, 2017). These findings tentatively suggest that extended and very strong to severe ENSO phases (for both El Niño and La Niña) produce extreme climatic conditions and rare hydro-climatic synchronicity across southern African summer rainfall sub-regions, and even across continents of the Southern Hemisphere.

Instrumental records for Windhoek indicate wet conditions during the 1890s (mean = 420 mm), relative to the 20th century mean (358 mm). The documentary-based rainfall chronology supports relatively wet conditions during the 1890s. The central Namibian trend through the 1890s is similar to that for the southern Kalahari (Nash and Endfield, 2002); namely starting wet, turning dry, then wet again. However, the trend differs considerably with that of southeastern South Africa which had five very wet or 'normal' years followed by five very dry or relatively dry years (Nash *et al.*, 2016). The instrumental rainfall record for Rehoboth suggests much drier conditions during the 1880s (mean = 215 mm) than 1890s (mean = 330 mm). Thus, tentative deductions on decadal-scale relative rainfall amounts during the latter half of the 19th century, compared to that during the 20th century, is that the 1850s were near average, the 1860s to 1880s below average, and the 1890s above average. The general rainfall trend from the late 1840s to 1900 is one of negligible change (Figure 6).

Finally, our study provides some important lessons when considering the potential climatic role in ecosystem changes. In most instances, work (e.g. Thuiller *et al.*, 2006; Reid *et al.*, 2008) has considered only the most recent climate change and potential future climate change scenarios as drivers impacting ecosystem sensitivity, natural resources and economics. What this and other palaeo-climate studies (e.g. Chase *et al.*, 2009) have demonstrated, is that extreme climate variability and change is not new to central Namibia; rather it has been a characteristic of the Namibian climate through much of the Holocene. Planning ahead to accommodate such ongoing climatic extremes and changes requires looking into the past and identifying particular patterns and causes for the most extreme events, as this may help improve short- to long-term forecasts.

Acknowledgements

We thank the two anonymous reviewers who provided valuable input, which helped improve the manuscript.

References

Aceituno P, Prieto MDR, Solari ME, Martínez A, Poveda G, Falvey M. 2009. The 1877–1878 El Niño episode: associated impacts in South America. *Clim. Change* **92**: 389–416.

Adamson GCD, Nash DJ. 2014. Documentary reconstruction of monsoon rainfall variability over western India, 1781–1860. *Clim. Dyn.* **42**: 749–769.

Angula MN, Kaundjua MB. 2016. The changing climate and human vulnerability in north-central Namibia. *Jàmbá J. Disaster Risk Stud.* **8**: 1–7.

Beer C, Weber U, Tomelleri E, Carvalhais N, Mahecha M, Reichstein M. 2014. Harmonized European long-term climate data for assessing the effect of changing temporal variability on land–atmosphere CO_2 fluxes. *J. Clim.* **27**: 4815–4834.

Berland AJ, Metcalfe SE, Endfield GH. 2013. Documentary-derived chronologies of rainfall variability in Antigua, Lesser Antilles, 1770–1890. *Clim. Past* **9**: 1331–1343.

Brázdil R, Pfister C, Wanner H, Von Storch H, Luterbacher J. 2005. Historical climatology in Europe – the state of the art. *Clim. Change* **70**: 363–430.

Brunet M, Jones P. 2011. Data rescue initiatives: bringing historical climate data into the 21st century. *Clim. Res.* **47**: 29–40.

Chapman J. 1971. *Travels in the Interior of South Africa 1849–1863*. South African Biographical and Historical Studies, Vol. **10**. A. A. Balkema: Cape Town, South Africa.

Chase BM, Meadows ME, Scott L, Thomas DSG, Marais E, Sealy J, Reimer PJ. 2009. A record of rapid Holocene climate change preserved in hyrax middens from southwestern Africa. *Geology* **37**: 703–706.

Dobrovolný P, Moberg A, Brázdil R, Pfister C, Glaser R, Wilson R, van Engelen A, Limanówka D, Kiss A, Halíčková M, Macková J. 2010. Monthly, seasonal and annual temperature reconstructions for central Europe derived from documentary evidence and instrumental records since AD 1500. *Clim. Change* **101**: 69–107.

Gergis JL, Fowler AM. 2009. A history of ENSO events since AD 1525: implications for future climate change. *Clim. Change* **92**: 343–387.

Gergis J, Henley BJ. 2017. Southern Hemisphere rainfall variability over the past 200 years. *Clim. Dyn.* **48**: 2087–2105.

Goudie A, Viles H. 2015a. Landscapes. In *Landscapes and Landforms of Namibia*, Goudie A, Viles H (eds). Springer: Cham, The Netherlands, 3–25.

Goudie A, Viles H. 2015b. Climate. In *Landscapes and Landforms of Namibia*, Goudie A, Viles H (eds). Springer: Cham, The Netherlands, 37–46.

Haensler A, Hagemann S, Jacob D. 2010. Climate history of Namibia and western South Africa. In *Biodiversity in Southern Africa: Patterns and Processes at Regional Scale*, Vol. **2**, Schmiedel U, Jürgens N (eds). Klaus Hess Publishers: Göttingen, Germany and Windhoek, Namibia, 2–5.

Hart NC, Reason CJ, Fauchereau N. 2013. Cloud bands over southern Africa: seasonality, contribution to rainfall variability and modulation by the MJO. *Clim. Dyn.* **41**: 1199–1212.

Heine K, Völkel J. 2011. Extreme floods around AD 1700 in the northern Namib Desert, Namibia, and in the Orange River catchment, South Africa – were they forced by a decrease of solar irradiance during the Little Ice Age? *Geogr. Pol.* **84**(special issue, part 1): 61–80.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25**: 1965–1978.

Irle J. 1906. *Die Herero. Ein Beitrag zur Landes-, Volks- & Missionskunde*. C. Bertelsmann, Gütersloh, 352 pp.

Jury M. 2010. Climate and weather factors modulating river flows in southern Angola. *Int. J. Climatol.* **30**: 901–908.

Kaundjua MB, Angula MN, Angombe ST. 2012. Community perceptions of climate change and variability impacts in Oshana and Ohangwena regions. *J. Stud. Humanit. Soc. Sci.* **1**: 21–32.

Kelso C, Vogel CH. 2007. The climate of Namaqualand in the nineteenth century. *Clim. Change* **83**: 357–380.

Leroux M. 1998. *Dynamic Analysis of Weather and Climate*. John Wiley: London 365 p.

Macron C, Pohl B, Richard Y, Bessafi M. 2014. How do tropical temperate troughs form and develop over southern Africa? *J. Clim.* **27**: 1633–1647.

Moritz W (ed). 2000. *Ein Bielefelder Missionar als Pionier in Namibia. Tagebuch und Briefe des F.H. Vollmer, Hoachanas 1853–1866 (Aus alten Tagen in Südwest, Heft 15)*. Nation Press: Werther, Germany.

Nash DJ, Endfield GH. 2002. A 19th century climate chronology for the Kalahari region of central southern Africa derived from missionary correspondence. *Int. J. Climatol.* **22**: 821–841.

Nash DJ, Endfield GH. 2008. Splendid rains have fallen: links between El Niño and rainfall variability in the Kalahari, 1840–1900. *Clim. Change* **86**: 257–290.

Nash DJ, Grab SW. 2010. A sky of brass and burning winds: documentary evidence of rainfall variability in the Kingdom of Lesotho, southern Africa, 1824–1900. *Clim. Change* **101**: 617–653.

Nash DJ, Pribyl K, Klein J, Neukom R, Endfield GH, Adamson GC, Kniveton DR. 2016. Seasonal rainfall variability in southeast Africa during the nineteenth century reconstructed from documentary sources. *Clim. Change* **134**: 605–619.

Neukom R, Nash DJ, Endfield GH, Grab SW, Grove CA, Kelso C, Vogel CH, Zinke J. 2014. Multi-proxy summer and winter precipitation reconstruction for southern Africa over the last 200 years. *Clim. Dyn.* **42**: 2713–2726.

Newsham AJ, Thomas DS. 2011. Knowing, farming and climate change adaptation in north-central Namibia. *Global Environ. Change* **21**: 761–770.

Nicholson SE. 2000. The nature of rainfall variability over Africa on time scales of decades to millenia. *Global Planet. Change* **26**: 137–158.

Nicholson SE, Entekhabi D. 1987. Rainfall variability in equatorial and southern Africa: relationships with sea surface temperatures along the southwestern coast of Africa. *J. Clim. Appl. Meteorol.* **26**: 561–578.

Nicholson SE, Kim J. 1997. The relationship of the El Niño–Southern Oscillation to African rainfall. *Int. J. Climatol.* **17**: 117–135.

Nicholson SE, Klotter D, Dezfuli AK. 2012a. Spatial reconstruction of semi-quantitative precipitation fields over Africa during the nineteenth century from documentary evidence and gauge data. *Quat. Res.* **78**: 13–23.

Nicholson SE, Dezfuli AK, Klotter D. 2012b. A two-century precipitation dataset for the continent of Africa. *Bull. Am. Meteorol. Soc.* **93**: 1219–1231.

Rácz Z, Smith RK. 1999. The dynamics of heat lows. *Q. J. R. Meteorol. Soc.* **125**: 225–252.

Ratna SB, Behera S, Ratnam JV, Takahashi K, Yamagata T. 2013. An index for tropical temperate troughs over southern Africa. *Clim. Dyn.* **41**: 421–441.

Reason CJC, Keibel A. 2004. Tropical cyclone Eline and its unusual penetration and impacts over the southern African mainland. *Weather Forecast.* **19**: 789–805.

Reid H, Sahlén L, Stage J, MacGregor J. 2008. Climate change impacts on Namibia's natural resources and economy. *Clim. Policy* **8**: 452–466.

Rohde RF, Hoffman MT. 2012. The historical ecology of Namibian rangelands: vegetation change since 1876 in response to local and global drivers. *Sci. Total Environ.* **416**: 276–288.

del Rosario Prieto M, Herrera RG. 2009. Documentary sources from South America: potential for climate reconstruction. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **281**: 196–209.

Sletten HR, Railsback LB, Liang F, Brook GA, Marais E, Hardt BF, Cheng H, Edwards RL. 2013. A petrographic and geochemical record of climate change over the last 4600 years from a northern Namibia stalagmite, with evidence of abruptly wetter climate at the beginning of southern Africa's Iron Age. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **376**: 149–162.

Smith RMH, Mason TR, Ward JD. 1993. Flash-flood sediments and ichnofacies of the late Pleistocene Homeb silts, Kuiseb River, Namibia. *Sediment. Geol.* **85**: 579–599.

Thuiller W, Midgley GF, Hughes GO, Bomhard B, Drew G, Rutherford MC, Woodward F. 2006. Endemic species and ecosystem sensitivity to climate change in Namibia. *Global Change Biol.* **12**: 759–776.

Todd MC, Washington R. 1999. Circulation anomalies associated with tropical temperate troughs in southern Africa and the south west Indian Ocean. *Clim. Dyn.* **15**: 937–951.

Todd MC, Washington R, Palmer PI. 2004. Water vapour transport associated with tropical-temperate trough systems over southern Africa and the southwest Indian Ocean. *Int. J. Climatol.* **24**: 555–568.

Vogel CH. 1989. A documentary-derived climatic chronology for South Africa, 1820–1900. *Clim. Change* **14**: 291–307.

