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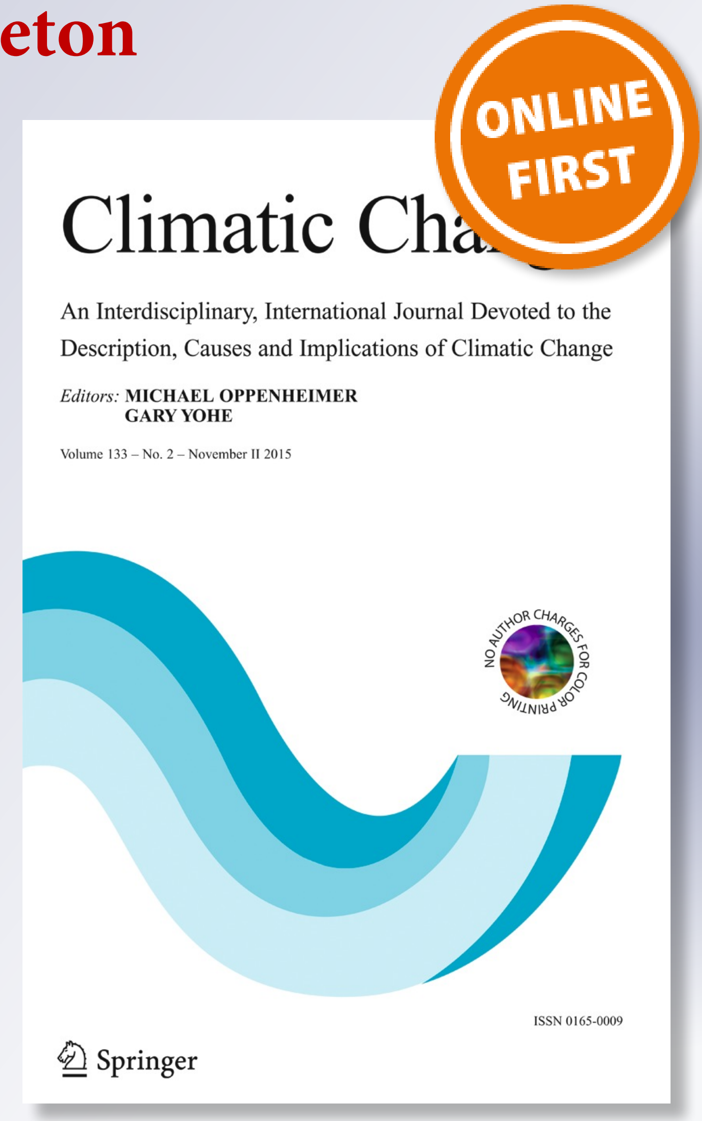

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Seasonal rainfall variability in southeast Africa during the nineteenth century reconstructed from documentary sources

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Abstract Analyses of historical patterns of rainfall variability are essential for understanding long-term changes in precipitation timing and distribution. Focussing on former Natal and Zululand (now KwaZulu-Natal, South Africa), this study presents the first combined annual and seasonal reconstruction of rainfall variability over southeast Africa for the 19th century. Analyses of documentary sources, including newspapers and colonial and missionary materials, indicate that the region was affected by severe or multi-year drought on eight occasions between 1836 and 1900 (the rainy seasons of 1836–38, 1861–63, 1865–66, 1868–70, 1876–79, 1883–85, 1886–90 and 1895–1900). Six severe or multi-year wet periods are also identified (1847–49, 1854–57, 1863–65, 1879–81, 1890–91 and 1892–94). The timing of these events agrees well with independent reconstructions of 19th century rainfall for other parts of the southern African summer rainfall zone (SRZ), suggesting subcontinental scale

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variability. Our results indicate that the relationship between El Niño and rainfall in southeast Africa was relatively stable, at least for the latter half of the 19th century. El Niño conditions appear to have had a more consistent modulating effect upon rainfall during the 19th century than La Niña. The rainfall chronology from this study is combined with other annually-resolved palaeoclimate records from mainland southern Africa and surrounding oceans as part of a multi-proxy rainfall reconstruction for the SRZ. This reconstruction confirms (i) the long-term importance of ENSO and Indian Ocean SSTs for modulating regional rainfall; and (ii) that summer precipitation has been declining progressively over the last 200 years.

1 Introduction

Detailed investigations into patterns of rainfall variability during previous centuries are essential for understanding the degree to which recent rainfall levels and distributions differ from long-term averages. Many areas of the northern hemisphere mid-latitudes have long instrumental datasets with which to undertake such analyses. However, for much of the world, the instrumental record begins only in the late 19th or early- to mid-20th centuries. In Africa, rainfall data become plentiful for Algeria in the 1860s and for South Africa in the 1880s, but are absent over much of the continent until the early 1900s (Nicholson et al. 2012). Rainfall analyses for the majority of areas and for earlier time periods are dependent instead upon proxy information derived from natural and anthropogenic archives.

Annually resolved moisture-sensitive terrestrial natural archives are rare in Africa. In their absence, historical documents have proven to be one of the most valuable sources of information about rainfall variability. Information extracted from historical sources has been used to reconstruct rainfall patterns at both continental (Nicholson 1981, 2000, 2001; Nicholson et al. 2012) and regional scales (Vogel 1989; Nash and Endfield 2002, 2008; Kelso and Vogel 2007; Nash and Grab 2010; Hannaford et al. 2015), and, recently, has been combined with natural proxy data to explore long-term trends in rainfall levels (Neukom et al. 2014). However, other than Nash and Endfield (2008), work has focussed upon reconstructing time-series of annual rather than seasonal rainfall levels.

This study aims to redress this imbalance and presents the first historical reconstruction of annual- *and* seasonal-level rainfall variability for southeast Africa. The reconstruction spans the period 1836–1900 and centres upon the former regions of Natal and Zululand, now part of KwaZulu-Natal (KZN), South Africa (Fig. 1a). Instrumental rainfall data for Pietermaritzburg and Durban are available from 1860 and 1871 respectively within the Global Historical Climatology Network (GHCN) dataset; however, the time series contain numerous gaps during the 19th century.

The study area falls within the southern African summer rainfall zone (SRZ) and has a strongly seasonal precipitation regime (Fig. 1b). KZN is the wettest province of South Africa, with rainfall along the northeast coast exceeding 1300 mm pa but declining to c.800 mm pa inland (Schulze 2001). The dominant rain-generating weather systems for the SRZ include ridging anticyclones, tropical-extratropical cloudbands, cut-off lows and mesoscale convective complexes (Tyson 1986). Levels of summer rainfall are closely associated with sea surface temperature (SST) anomalies in the southwest Indian Ocean (SWIO) (e.g. Mason 1995; Reason and Mulenga 1999), with warmer SSTs generally correlated with wetter summers. Summer rainfall is also modulated as a result of El Niño-Southern Oscillation (ENSO) teleconnections (e.g. Lindesay et al. 1986; Nicholson and Entekhabi 1986; Ropelewski and

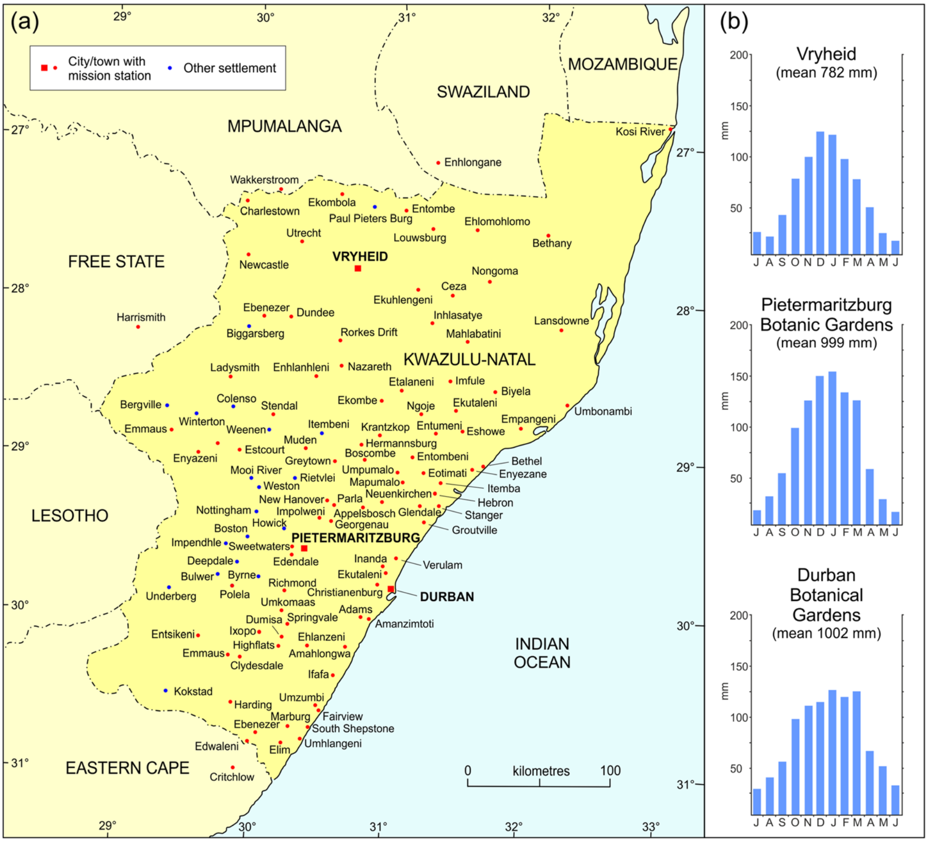

Fig. 1 (**a**) Locations within present-day KwaZulu-Natal and adjacent areas with 19th century documentary evidence used in this study; (**b**) Mean annual rainfall distribution (July-June) for Durban Botanical Garden (1871–1997), Pietermaritzburg Botanic Gardens (1907–1989) and Vryheid (1925–2015) derived from GHCN-D v2 data

Halpert 1987; Rocha and Simmonds 1997; Reason et al. 2000; Meque and Abiodun 2015). The link between El Niño and summer drought is strongest in southeast Africa (e.g. Richard et al. 2000), with reduced rainfall commonly occurring during the February-April following the El Niño event (Nicholson and Kim 1997). La Niña events, in contrast, are often associated with wetter summer conditions in the SRZ (Van Heerden et al. 1988; Nicholson and Selato 2000). Positive phases of the Southern Annular Mode (SAM) are usually associated with anomalously wet conditions over the SRZ, while mid-latitude westerlies may extend further north in negative phases (Gillett et al. 2006) bringing drier conditions.

Methodologies for reconstructing seasonal climate variations from documentary sources are well-established in Europe and Asia (e.g. Glaser et al. 1999; Adamson and Nash 2014). Adapting these approaches, we explore the influence of ENSO modulation upon seasonal rainfall variability in southeast Africa during the 19th century. In addition, we use our chronology, plus recent work by Hannaford et al. (2015) and Woodborne et al. (2015), to extend the multi-proxy reconstruction developed by Neukom et al. (2014), and consider rainfall variability within the southern African SRZ over the last 200 years.

2 Materials and methods

The historical sources used for this study are detailed in Table 1 and section S1 of the Electronic Supplemental Material (ESM). Documents describing the environment of Natal and Zululand first appear in the late 18th-early 19th centuries. Increased numbers of written accounts are available from the 1820s, after Europeans settled at Port Natal (now Durban). However, it was not until 1836, when the first mission stations of the American Board of Commissioners for Foreign Missions were established, that descriptions of the climate/environment of the region become plentiful. As a result, the rainy season of 1836–37 is the starting point for our chronology. Various British, German and Norwegian missionary societies established mission stations from the early 1840s. Pietermaritzburg, the administrative capital of the Natal Colony under British rule, also saw significant growth from the 1840s, and, along with this, the availability of colonial documents. A number of regional newspapers were also established in the mid-19th century. Of these, the *Natal Witness* – first printed in February 1846 – was the most important for this study.

Each of the collections in Table 1 was analysed using standard historical climatology methods (section S2; Nicholson 1979, 1981; Brázdil et al. 2005). All information on climate or climate-dependent phenomena was recorded verbatim and, if necessary, translated into English. Occasional instrumental rainfall data were included within issues of the *Natal Witness* from 1850 onwards (Nash and Adamson 2014) – these were used to supplement qualitative materials. A total of 7220 quotations or other observations were recorded.

Individual quotations were sorted chronologically by July-June 'rain-year' and by location, to facilitate the reconstruction of rainfall across the region as a whole. Relatively few

Table 1 Locations of historical archives and repositories visited for primary sources used in this study, together with abbreviation codes used in footnotes

Name of archive	Key collections	Code
Bodleian Library at Rhodes House, University of Oxford, UK	Society for the Propagation of the Gospel materials for Natal and Zululand	USPG
British Library, London, UK	Various books and monographs, British Newspapers 1600–1950 (online), 19th Century British Newspapers (online)	n/a
Council for World Mission archive, SOAS, London, UK	Wesleyan Methodist Missionary Society materials for Natal and Zululand	WMMS
Evangelisch-lutherisches Missionswerk Niedersachsen, Archiv, Hermannsburg, Germany	Hermannsburg Missionary Society materials for Natal and Zululand, including copies of the *Hermannsburger Missionsblatt* periodical	ELM
Houghton Library, Harvard University, USA	American Board of Commissioners for Foreign Missions papers for Natal and Zululand	ABCFM
Killie Campbell Africana Library, University of KwaZulu-Natal, Durban, South Africa	19th century diaries and other manuscripts, *Natal Witness* newspaper, Natal Blue Books plus other materials	KCAL
Msunduzi Municipal Library, Pietermaritzburg, South Africa	19th century materials, including *Natal Witness* newspaper, *Natal Almanac*, Natal Blue Books	n/a
National Archives, London, UK	Various books, British Colonial Office materials	n/a
Norwegian Mission Society archive, Stavanger, Norway	Norwegian Mission Society materials for Natal and Zululand	NMS

quotations were available for the rain-years 1836–37 to 1859–60 (Figure S1), so it was only possible to generate annual classifications for this period. On average, 155 quotations per year were available for 1860–61 onwards, providing sufficient data to permit seasonal (JAS, OND, JFM, AMJ) rainfall reconstruction.

Quotations for each rain-year or season were analysed collectively to generate a five-point classification of rainfall conditions from +2 (very wet/floods) to −2 (very dry/drought). Classifications of +2 or −2 were only awarded where observers described extreme wet or dry conditions, often with significant environmental and/or socio-economic impacts, during a major part of the rain-year or season. To generate annual rainfall classifications from seasonal data, the seasonal scores for individual rain-years were summed, averaged and rounded to the nearest whole number. Scores for OND and JFM were double-weighted to reflect the contribution of rainfall during these seasons to annual totals (see Fig. 1b).

A criticism often levelled at documentary-based climate reconstruction is that the analytical process is prone to investigator bias (cf. Nash and Adamson 2014). To counter this, the seasonal series for 1860–61 to 1899–1900 were constructed independently by authors DJN and KP and then compared. Of the 160 seasonal classifications during this period, 59 % of scores were identical, 34 % within one class and 7 % within two classes. There was greatest agreement during extreme years and least for seasons where conditions fluctuated around 'normal'; this is to be expected given that documentary sources capture extreme events most effectively (Brázdil et al. 2005). Only four of the seasonal scores generated opposing signs (+1 versus −1). These were all seasons with large spatial differences in rainfall intensity across the study area. The results presented in Section 3 are the agreed final classifications.

Following Kelso and Vogel (2007), each annual classification was allocated a confidence rating. A rating of 1 (low confidence) was awarded to rain-years – mostly in the 1830s and early 1840s – where there was either a limited number of sources or the quality of information was low. A rating of 3 (high confidence) was awarded to rain-years with multiple date- and place-specific references to rainfall conditions, and where detail within the majority of quotations was high. All rain-years from 1859–60 onwards fall within this category.

The methodology used to extend the SRZ multi-proxy rainfall reconstruction was identical to that of Neukom et al. (2014); see section S3. The reconstruction incorporated all published annually-resolved climate records from southern Africa and surrounding oceans that spanned all or part of the 19th and 20th centuries. These included four documentary series (from Vogel 1989; Nash and Endfield 2002, 2008; Nash and Grab 2010 and this study), three coral δ^{18}O and/or Sr/Ca series (Zinke et al. 2004; Zinke et al. 2009), one tree-ring width series (Therrell et al. 2006), a baobab tree-ring isotope series (Woodborne et al. 2015) and two rainfall series derived from ships' logs (Hannaford et al. 2015).

As the rainfall chronology in this study ends in 1900, it was necessary to extend the record to the present-day to allow calibration within the multi-proxy dataset. This was achieved using a "pseudo-documentary" approach (Neukom et al. 2009), whereby instrumental data for Durban Botanical Garden, Pietermaritzburg Botanic Gardens and Kokstad from the GHCN-D v2 dataset were combined to form a weighted composite series and degraded to match the statistical properties of the historical chronology (section S3.1). The same approach was used to degrade 20th century data within the Hannaford et al. (2015) reconstructions (section S3.2). The instrumental target for the reconstruction was calculated using ONDJFM rainfall totals from the CRU TS 3.0 grid, and represents a spatial average of mainland southern African SRZ rainfall (section S3.3). An ensemble-based nested principal component regression was used to reconstruct SRZ ONDJFM rainfall back to 1797 (cf. Luterbacher et al. 2002; Neukom et al. 2010).

3 Rainfall variability over southeast Africa during the 19th century

The results of the documentary-derived rainfall reconstruction for 1836–1900 are presented in Fig. 2 and compared with other annually-resolved terrestrial proxy records for southern Africa in Fig. 3. In total, 13 (22 %) of the 59 rain-years were classified as very dry/drought, 13 (22 %) as relatively dry, 14 (24 %) as 'normal', 14 (24 %) as relatively wet and 5 (8 %) as very wet/floods. Drier rain-years (44 % of the total) are over-represented in comparison to wetter (32 %) – a common outcome of documentary reconstructions in dryland areas – but this difference is not statistically significant ($\chi^2 = 4.983$, $p = 0.289$). The chronology shows very good agreement with the weighted composite rainfall data for Pietermaritzburg, Durban and Kokstad during the 35 years of overlap (Pearson's $r = 0.69$, $p \ll 0.01$), better than all the documentary series used in the Neukom et al. (2014) reconstruction. The chronology is also significantly correlated ($r = 0.257$, $p = 0.048$) with the only other documentary rainfall reconstruction for Natal and Zululand (Zone 79 in Nicholson et al. 2012); the weaker r-value is likely due to methodological and source material differences.

3.1 Regional drier and wetter periods

Southeast Africa was visited by severe or multi-year drought on eight occasions during the study period (1836–38, 1861–63, 1865–66, 1868–70, 1876–79, 1883–85, 1886–90, and 1895–1900). The most severe of these dry spells was the drought of 1861–63 and the most prolonged that of 1895–1900. Conditions during these two events are now considered.

The drought of 1861–63, which affected areas of the SRZ at least as far north as Zimbabwe and west as Namaqualand (Fig. 3), began with below average rainfall in AMJ 1861. Despite the onset of seasonal rains in October 1861, drought continued well into the early austral summer, with the *Natal Witness* reporting in late November:

> "The principal topic and cause of alarm has been the protracted drought, the fear of the continuance of which had driven produce and food of every description up to famine prices".[1]

By the close of 1861 and during much of 1862, drought affected large areas of former Natal,[2] with famine conditions and starvation documented in various districts of Zululand;[3] this period is referred to in Zulu oral traditions as the 'Mbete famine' (Webb and Wright 2014). Drought was particularly severe during JAS and OND 1862, in part owing to a delayed start to the 1862–63 rainy season. A report in the *Natal Witness* in late October 1862 noted:

> "Within the last few days some acceptable showers have fallen around the city [Pietermaritzburg], but it is feared they have not extended far inland, where they are so much-needed. No ordinary Natal rains have as yet come down this season. It is probably not within the recollection of any colonist that September and October have before passed over without frequent splendid storms."[4]

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[1] *Natal Witness*, 29 November 1861

[2] *Natal Witness*, 19 September 1862; ELM, ASA 4.1, 94, Müden, Natal, 1865–1905

[3] e.g. NMS Mission Archives, A1045-130-3, Ommund Oftebro, 31 December 1861; USPG D25a, Bishop McKenzie, Kwanaqua, Zululand, 26 January 1863

[4] *Natal Witness*, 21 October 1862

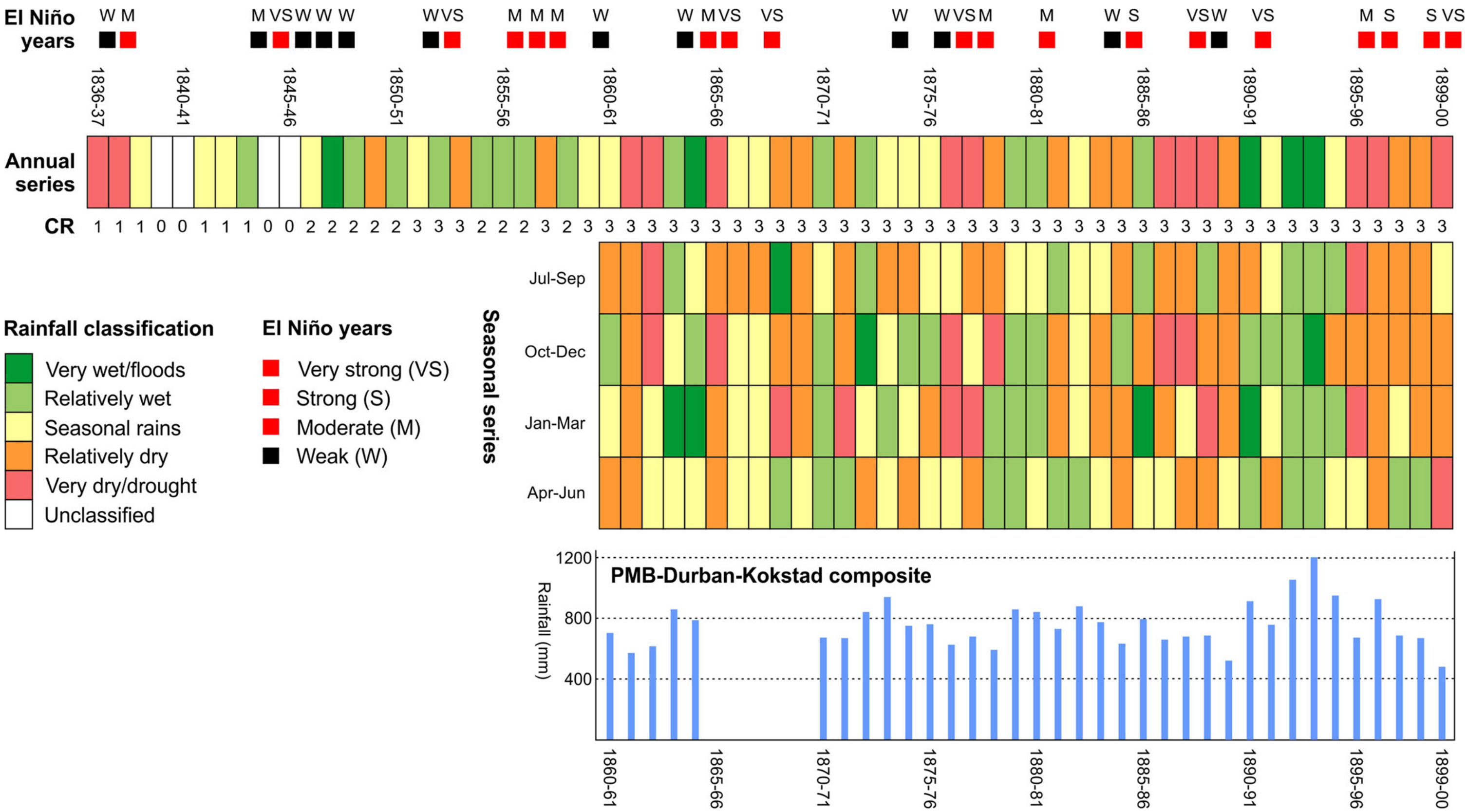

Fig. 2 Annual (1836–1900) and seasonal (1860–1900) rainfall variability in Natal and Zululand derived from documentary sources. Also indicated are confidence ratings [CR] for each rain-year and El Niño years (from Gergis and Fowler 2009). Composite rainfall totals (July-June) for Pietermaritzburg Botanic Gardens (PMB), Durban Botanical Garden and Kokstad for 1860–1900 (from GHCN-D v2 data) are included for comparison

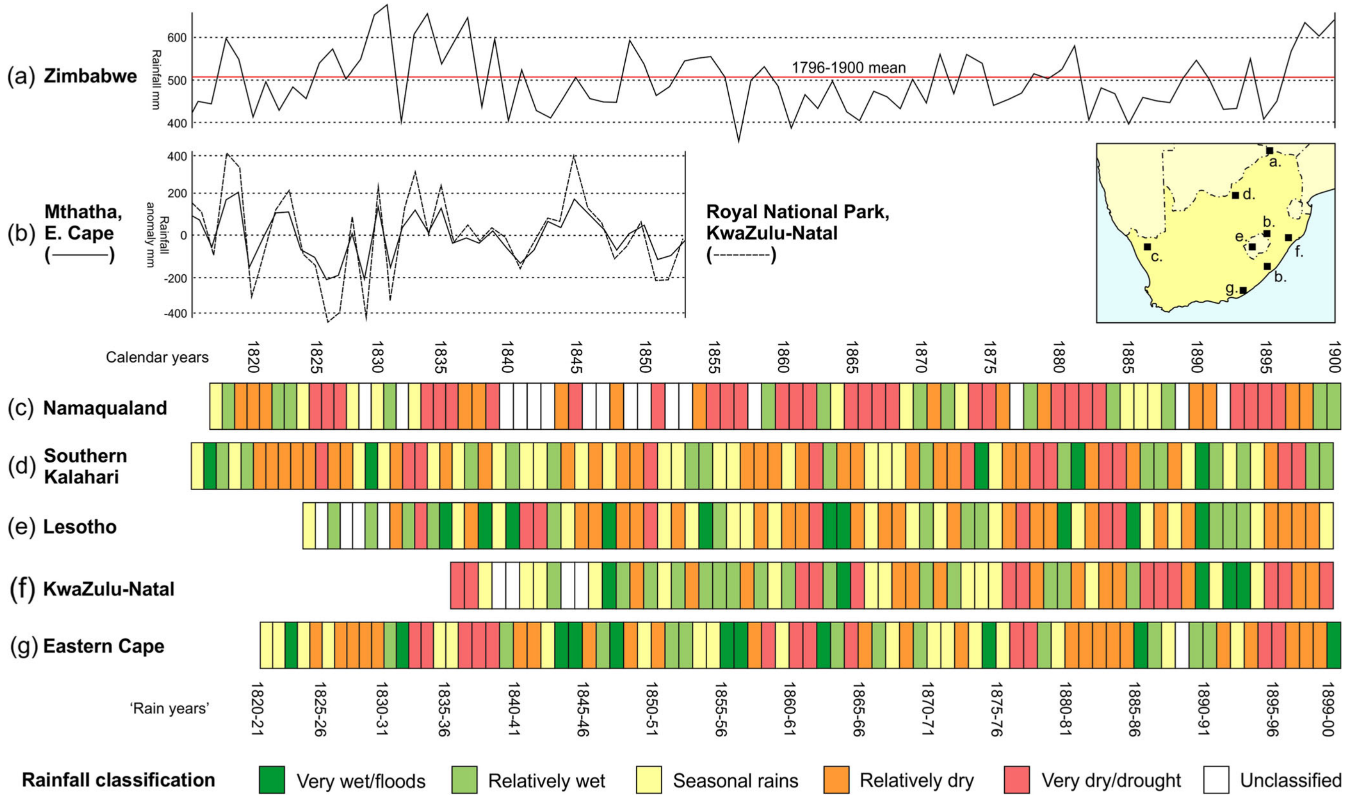

Fig. 3 Comparison of results for KwaZulu-Natal (f) with selected annually-resolved terrestrial series of 19th century rainfall variability for the southern African summer rainfall zone: (**a**) tree ring-width series for Zimbabwe (Therrell et al. 2006); (**b**) ships' logbook-derived series for Mthatha, Eastern Cape, and Royal National Park, KwaZulu-Natal (anomaly relative to 1979–2008 mean) (Hannaford et al. 2015); (**c**)–(**g**) documentary-derived series for Namaqualand (Kelso and Vogel 2007), the southern Kalahari (Nash and Endfield 2002, 2008), Lesotho (Nash and Grab 2010) and the Eastern Cape (Vogel 1989)

The drought had significant impacts on food supplies, livestock, and agricultural activities,[5] and triggered social conflict and unrest in parts of Zululand (Klein et al. in review). Seasonal rains occurred around Pietermaritzburg in early December 1862[6] and at Durban towards the end of the same month.[7] Dry conditions returned during January and February 1863, but were eventually broken by heavy rains and extensive flooding in March 1863.[8]

The development of the 1895–1900 drought (discussed in detail in Pribyl et al. in review) followed a similar pattern to the 1861–62 event. Despite light showers in September and isolated thunderstorms in October,[9] the 1895–96 rainy season (an ENSO-neutral year) did not begin until mid-November 1895.[10] Reports of hot, dry 'berg' winds blowing from the north and northwest,[11] in some cases accompanied by blowing dust,[12] in September and October 1895 suggest that this delay was linked to sustained high pressure over the subcontinental interior. Such conditions are common over KZN during SAM negative phases; Jones et al. (2009) reconstruct the SAM index in late-1895 at c.-1.5. The failure of the early rains led to a loss of pasture land, livestock deaths,[13] and a delay in ploughing and the sowing of crops,[14] with the impacts of drought further exacerbated by locust incursions in October/November 1895.[15] Relatively dry conditions continued throughout much of the 1896–97 rainy season[16] and, coupled with further locust incursions and the outbreak of the rinderpest epidemic,[17] led to crop damage, severe food shortages[18] and population dispersal.[19] Conditions were such that famine relief measures were instigated in Zululand in 1896.[20]

Relatively dry conditions continued into the early austral summer of 1897–98, but normal to above average precipitation fell across Natal and Zululand during JFM and AMJ 1898 (Fig. 2). The 1898–99 rainy season began with only slightly below average precipitation in October 1898,[21] but this was followed by drought in November/December 1898 and JFM 1899, with significant impacts upon agricultural activity.[22] The 19th century

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[5] NMS Mission Archives, A1045-130-13, Hans Schreuder, 12 January 1863; NMS Mission Archives, A1045-139-14, Tobias Udland, 15 January 1863; *Natal Witness*, 6 February 1863

[6] *Natal Witness*, 5 December 1862

[7] *Natal Witness*, 2 January 1863

[8] *Natal Witness*, 27 March 1863

[9] e.g. *Natal Witness*, 18 October and 25 October 1895

[10] NMS Mission Archives, NMT March 1896 Vol. 51., Ole Steenberg, 8 January 1896; *Hermannsburger Missionsblatt* 43/6, Hermannsburg 1896, 58–61

[11] e.g. *Natal Witness*, 4 October 1895

[12] KCAL KCM 98/75/7/1–3 Thomas Groom. File 7. Diaries 1895

[13] *Natal Witness*, 8 August 1895

[14] *Hermannsburger Missionsblatt* 43/6, Hermannsburg 1896, 58–61

[15] e.g. *Hermannsburger Missionsblatt* 44/3, Hermannsburg 1897, 48–9; USPG D114, S.M. Samuelson, St. Paul's, Zululand, 28 November 1895; ABCFM, Harvard, Houghton Library, 15.4, vol. 13, Henry Bridgeman, Umzumbe station report, June 1896

[16] e.g. *Hermannsburger Missionsblatt* 44/7, Hermannsburg 1897, 148–50; NMS Mission Archives, A1045-140b-7, Nils Braatvedt, 8 December 1896

[17] e.g. NMS Mission Archives, A1045-140b-7, Markus Dahle, 31 October 1896; ABCFM, Harvard, Houghton Library, 15.6.2, vol. 1., Zulu, East Africa, Woman's Board of Missions 1886–1899, Laura Mellen, Esidumbini, 13 October 1897

[18] NMS Mission Archives, A1045-140b-7, Nils Braatvedt, 8 December 1896; *Hermannsburger Missionsblatt* 44/7, Hermannsburg 1897, 148–50

[19] USPG E51b, S.M. Samuelson, Polela, 30 June 1896

[20] *Natal Witness*, 19 October 1897

[21] *Natal Witness*, 17 November 1898

[22] *Natal Witness*, 21 January 1899; *Natal Witness*, 21 February 1899

closed with a further year of severe drought. Below average rainfall was reported by observers across Natal and Zululand from October 1899[23] until late May 1900,[24] with impacts not only upon cereals such as maize and sorghum,[25] but also root crops and winter fodder.[26]

In addition to drought episodes, six severe or multi-year wet periods were also identified (1847–49, 1854–57, 1863–65, 1879–81, 1890–91, and 1892–94). The early 1890s included a run of extremely wet years and appear to have been the wettest period of the 19th century, with the 1850s the wettest decade as a whole. Heavy rains in January and February 1891, for example, led to extensive flooding across former Natal and Zululand, with a reporter for the *Natal Witness* at Polela noting:

> "We have been having a second deluge here; continuous rain for about six weeks, with occasionally one or two days on which we managed to catch a glimpse of old 'Sol'. The rivers are higher than they have been for years, and for two days during last week the punt on the upper Umkomanzi drift could not be worked."[27]

These heavy rains caused considerable damage to crops,[28] and appear to have been widespread across the SRZ (Fig. 3), from Natal and Zululand northwards into present-day Botswana and Zimbabwe (cf. Nash and Endfield 2008; Nash and Grab 2010). Heavy rains and flooding were also reported across the study area in JFM 1892, with 50 mm falling in 40 min at Pietermaritzburg on 28 March, washing away topsoil and turning the Umgeni River "...a good dark coffee colour".[29] Rather than being a product of short-duration storms, the very wet conditions in 1893–94 were caused by above-average precipitation throughout the rainy season. This included several weeks of steady rainfall in OND 1893[30] which damaged housing, caused flooding, and resulted in major landslides on the railway line close to Pietermaritzburg.[31]

The seasonal data within Fig. 2 illustrate the considerable variability in, for example, what constituted a historical drought year. Of the 11 very dry/drought years from 1860 to 1900, all but two (1861–62, 1896–97) included very dry conditions in at least one season, with the most severe droughts being associated with very dry conditions in OND or JFM. However, only three drought years (1861–62, 1865–66, 1896–97) exhibited below average precipitation across all four seasons. Three very dry rain-years started with normal (1876–77, 1899–1900) or above average (1888–89) precipitation during the early rainy season, with one (1887–88) exhibiting normal rains during the latter part of the summer. Very wet rain-years were equally varied, some (e.g. 1864–65) attributable to very heavy precipitation in OND and/or JFM only and others (e.g. 1892–93, 1893–94) characterised by year-round above average rainfall.

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[23] *Hermannsburger Missionsblatt* 48/2, Hermannsburg 1901, 17–18

[24] *Natal Witness*, 8 June 1900

[25] USPG E55b, C. Johnson, St. Augustine's, Zululand, 30 January 1900

[26] *Natal Witness*, 8 June 1900

[27] *Natal Witness*, 12 February 1891

[28] e.g. *Natal Witness*, 9 and 19 February 1891

[29] *Natal Witness*, 31 March 1892

[30] e.g. *Natal Witness*, 28 November 1893

[31] *Natal Witness*, 27 and 29 November 1893

3.2 ENSO-rainfall relationships

The richness of the archival materials available for KZN permits a detailed exploration of ENSO-rainfall relationships during the 19th century. Comparisons of 20th century precipitation and SST data indicate that, when present, ENSO-related modulation of rainfall in the SRZ is manifest in the rainy-season immediately following the onset of El Niño or La Niña conditions (e.g. Lindesay et al. 1986; Nicholson and Entekhabi 1986; Reason et al. 2000); this pattern occurred in southeast Africa during 18 of the 20 ENSO events from 1900 to 1990 (Nicholson and Kim 1997). Table 2 summarises reconstructed rainfall conditions in KZN during the austral summer immediately following each El Niño, La Niña and neutral year (derived from the Gergis and Fowler 2009 ENSO chronology). Of the 28 discrete El Niño years for which rainy season conditions have been reconstructed, 15 were associated with lower than average rainfall during the following austral summer (including nine very dry/drought years); of these rainy seasons, nine exhibited significantly reduced rainfall during JFM and/or AMJ. A further six El Niño years were followed by rainy seasons classified as normal. However, three of these exhibited reduced JFM and/or AMJ rainfall. Seven El Niño years were followed by wetter than normal rainy seasons. All but one of these years were prior to 1870, and fell during a period when coral $\delta^{18}O$ records from Madagascar indicate that the impact of ENSO on SWIO SSTs and atmospheric circulation was less strong (Zinke et al. 2004). Statistical relationships are considered in Section 4.

The long-term relationship between La Niña and rainfall over southeast Africa appears to be more complex. Rather than displaying evidence for anomalously wet conditions, as identified by many previous studies (e.g. Van Heerden et al. 1988; Nicholson and Selato 2000), Table 2 shows that 10 of the 33 discrete La Niña years for which rainy-season conditions have been reconstructed were followed by dry summers, and a further 10 by summers with normal rainfall.

Table 2 Reconstructed rainfall conditions in southeast Africa during the austral summer immediately following each El Niño, La Niña and neutral year (1836 to 1900). Wet years include those classified as +1/+2 in Fig. 3, and dry years as −1/−2. Extreme rain-years (i.e. +2/−2) are shown in bold. For El Niño (La Niña) years, rain-years after 1860–61 in which JFM and/or AMJ rainfall was below (above) normal are italicised. Annual ENSO status is based on Table 9 in Gergis and Fowler (2009)

	El Niño	Neutral	La Niña
Dry rainy season	**1837–38**, 1853–54, 1857–58, ***1865–66***, ***1868–69***, ***1876–77***, ***1877–78***, 1878–79, *1881–82*, *1884–85*, ***1888–89***, **1889–90**, ***1896–97***, 1897–98, ***1899–1900***	1869–70, 1883–84, **1895–96**, 1898–99	1849–50, 1857–58, **1861–62**, **1862–63**, *1868–69*, *1871–72*, *1878–79*, **1886–87**, **1887–88**, **1896–97**
‘Normal’ rainy season	1838–39, 1846–47, *1860–61*, 1866–67, *1874–75*, *1891–92*	1842–43, 1859–60, 1882–83	1841–42, 1851–52, 1860–61, 1866–67, 1867–68, *1873–74*, 1874–75, 1875–76, 1891–92, *1894–95*
Wet rainy season	**1847–48**, 1848–49, 1852–53, 1856–57, 1858–59, **1864–65**, 1885–86	1854–55, 1855–56	1843–44, **1847–48**, 1848–49, 1850–51, *1863–64*, ***1864–65***, *1870–71*, 1872–73, *1879–80*, *1880–81*, ***1890–91***, ***1892–93***, **1893–94**
Unclassified rainy season	1844–45, 1845–46	1839–40	1840–41

The dry years encompassed five very dry/drought episodes, including those of the early 1860s and late 1890s. However, the majority of wet or normal La Niña summers after 1860 exhibited above average rainfall during JFM and/or AMJ, echoing the pattern observed in 20th century data (Nicholson and Selato 2000). Such complexity can arise during La Niña if the frequency of high rainfall systems such as cut-off lows is altered (Singleton and Reason 2007).

Taken as a whole, our results suggest that the relationship between El Niño and rainfall in southeast Africa remained relatively stable, at least for the latter half of the 19th century. However, as Washington and Preston (2006) suggest, Pacific SST conditions do not appear to have been a simple determinant of anomalously wet conditions over the study area. As with El Niño, the impacts of La Niña upon rainfall in southeast Africa are likely to have been confined to those events that produced SST anomalies in both the Atlantic and Indian Oceans (Nicholson and Selato 2000).

4 Rainfall variability within the summer rainfall zone over the last 200 years

Reconstructed ONDJFM rainfall variability across the southern African SRZ is shown in Fig. 4, together with associated uncertainties. The reconstruction (Fig. 4a) includes all the

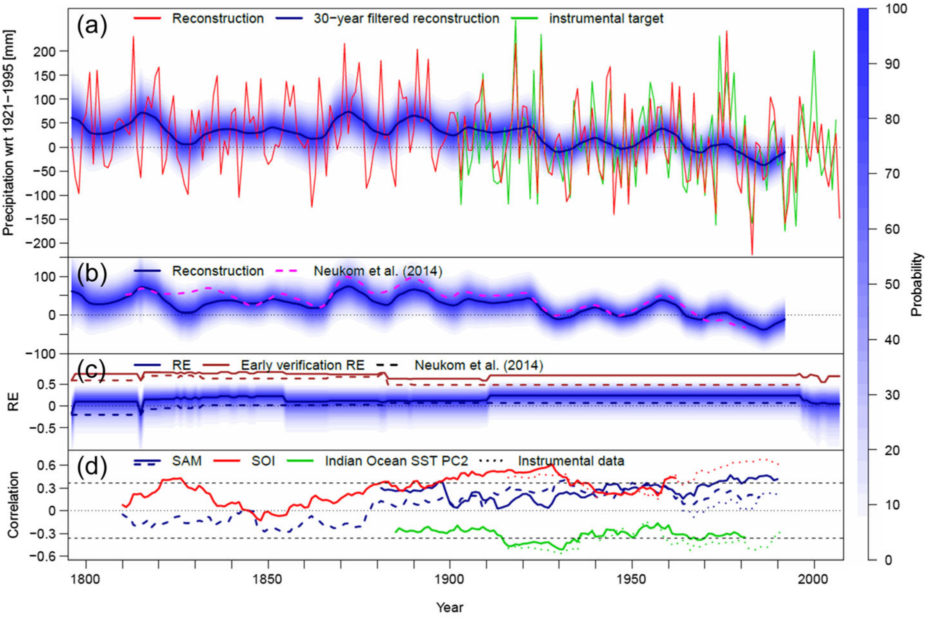

Fig. 4 (**a**) Southern African summer rainfall zone (SRZ) precipitation reconstruction for 1796–2007 on interannual (*red*) and 30-year filtered (*blue*, with uncertainty bands shaded) timescales. Unfiltered instrumental data are shown in *green*; (**b**) 30-year filtered data compared to the SRZ reconstruction of Neukom et al. (2014; *pink*); (**c**) Distribution of RE values of the reconstruction ensemble members (*blue shaded*, *dark blue line* is the median), early verification RE (*brown*) and the corresponding data of Neukom et al. (2014; *dashed*); (d) 30-year running correlations of the SRZ reconstruction with reconstructions of the Southern Annual Mode (SAM) index (*blue dashed*; Villalba et al. 2012; *blue*; Jones et al. 2009); Southern Oscillation Index (SOI, *red*; Stahle et al. 1998) and second principal component of Indian Ocean SSTs (IOPC2, *green*; HadISST data; Rayner et al. 2003). The *dotted lines* represent the correlations between the corresponding instrumental data. Data are plotted at the 15th year of each 30-year period

proxies used in Neukom et al. (2014), the new KZN rainfall chronology presented here, and the ships' log-based reconstructions from Hannaford et al. (2015). The baobab tree-ring data of Woodborne et al. (2015) are excluded from the final reconstruction, as they do not introduce additional signal and lead to lower verification skill (see section S3.3).

The new reconstruction advances that which is presented in Neukom et al. (2014), in that the time range covered is extended further into the past (back to 1797) and towards the present (up to 2007). Figure 4a indicates that rainfall in the SRZ has varied on a roughly bi-decadal timescale over the last 200 years, supporting the work of Tyson (1986), Reason and Rouault (2002) and others. It also shows that the long-term rainfall decrease in the SRZ identified by Neukom et al. (2014) has continued into the 21st century. The trend is, however, slightly weaker than in that study, since the newly added proxy data suggest a marginally drier 19th century (Fig. 4b). Modest downward trends in rainfall during the latter 20th century have been identified in Botswana, Zimbabwe and western South Africa from instrumental data (see Niang et al. 2014); our reconstruction confirms that this drying began much earlier.

Relatively dry intervals are reconstructed during the pre-instrumental period at around 1827 and 1862, the latter of which was the driest year of the 19th century. This confirms the results presented in Section 3. The wettest periods of the 19th century are reconstructed around 1815, 1872 and 1890, with 1813 being the wettest year in the multi-proxy reconstruction. Figure 4c illustrates that the inclusion of new proxy data increases the reconstruction skill, both for the ensemble mean and early verification Reduction of Error (RE) measures (section S3). Studies targeting earlier periods of the 19th century, and underrepresented areas such as present-day Malawi, Namibia, Mozambique and Zambia, will further increase the robustness of the reconstruction.

Figure 4d shows the 30-year running correlations of SRZ rainfall with important large-scale climate indices. These include the Southern Oscillation Index (SOI), SAM and the second principal component of Indian Ocean SSTs, an important driver of SRZ rainfall (Neukom et al. 2014). The comparison of these indices remains very similar to the relationships reported by Neukom et al. (2014). The SOI and the Indian Ocean SSTs have a stronger influence on SRZ rainfall than the SAM in both instrumental and reconstructed data. While the correlation coefficients for most indices are relatively consistent over time, there are breakdowns in the SOI-SRZ rainfall relationship from c.1830–1875 and c.1930–1960. The timing of these breakdowns is in accordance with analyses of instrumental and palaeodata from elsewhere around the Indian Ocean (e.g. Zinke et al. 2004; Adamson and Nash 2014; Ashcroft et al. 2015), suggesting a basin-wide weakening of ENSO teleconnections during the mid-19th and mid-20th centuries.

5 Conclusions

This paper has presented the first combined annual and seasonal reconstruction of rainfall variability over southeast Africa for the 19th century. The results indicate that the region was affected by severe or multi-year drought on eight occasions between 1836 and 1900 (the austral summer rainy seasons of 1836–38, 1861–63, 1865–66, 1868–70, 1876–79, 1883–85, 1886–90 and 1895–1900). In addition, six severe or multi-year wet periods were identified (1847–49, 1854–57, 1863–65, 1879–81, 1890–91 and 1892–94). The timing of these events shows close agreement with independent reconstructions of 19th century rainfall variability for other parts of the southern African SRZ. A comparison of our results with the ENSO chronology of Gergis and Fowler (2009) suggests that the relationship between El Niño and rainfall in southeast Africa was relatively stable, at least for the latter half of the 19th century. El Niño conditions appear to have had a more consistent modulating effect upon rainfall compared to La Niña. The inclusion of the results of this study, plus two recent annually-resolved ships' logbook-derived reconstructions of southern African rainfall, within a new multi-proxy rainfall reconstruction, confirms the importance of ENSO and Indian Ocean SSTs for modulating rainfall in the SRZ. The multi-proxy reconstruction further highlights that summer rainfall in the SRZ has been progressively declining over the last c.200 years.

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SUPPLEMENTARY MATERIAL

Seasonal rainfall variability in southeast Africa during the nineteenth century reconstructed from documentary sources

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S1. Historical documentary sources

The sources of historical material used for this study are shown in Table 1 in the main manuscript. Documents describing the landscape and climate of former Natal and Zululand first appear in the late 18th and early 19th centuries. Increased numbers of detailed written accounts are available from the 1820s onwards, after Europeans settled at Port Natal, now Durban (Bird, 1888). However, it was not until after 1836, when the first mission stations of the American Board of Commissioners for Foreign Missions were established near Port Natal and at inland locations in Zululand (Lulat, 2008), that descriptions of the climate and environment of the region become plentiful. As a result, the rainy season of 1836-37 is the starting point for the chronology presented here. Other mission stations were established from the early 1840s by organisations including the Wesleyan Methodist Missionary Society (Pritchard, 2013), Norwegian Mission Society (Hale, 1997), Hermannsburg Missionary Society (Lüdemann, 2000) and the Society for the Propagation of the Gospel (Pascoe, 1901). Pietermaritzburg, the administrative capital of the Natal Colony under British rule, also saw significant growth from the 1840s, and along with this the availability of colonial documents; these included statistical summaries and annual *Blue Books* from 1863 onwards. A number of regional newspapers were also established in the mid-19th century. Of these, the *Natal Witness* – first printed in February 1846 and the oldest continuously published newspaper in South Africa – was the most important for this study.

S2. Reconstructing rainfall variability from documentary sources

Each of the collections in Table 1 was analysed using standard historical climatology methods (e.g. Nicholson, 1979, 1981; Brázdil et al., 2005; Nash and Adamson, 2014). All information on climate or climate-dependent phenomena within individual documents was recorded verbatim and, if necessary, translated into English. The range of information included direct references to rainfall, storms and dry periods, plus indirect indicators of rainfall variability such as reports of droughts, floods and harvest quality/quantity. For each observation, the author, place of publication, location referred to, date written, and date range referred to was recorded in a database. Occasional instrumental rainfall, temperature, wind and pressure data were also included within issues of the *Natal Witness* from 1850 onwards (Nash and Adamson, 2014) – these were used to supplement qualitative materials. A total of 7220 quotations or other observations were recorded (Figure S1).

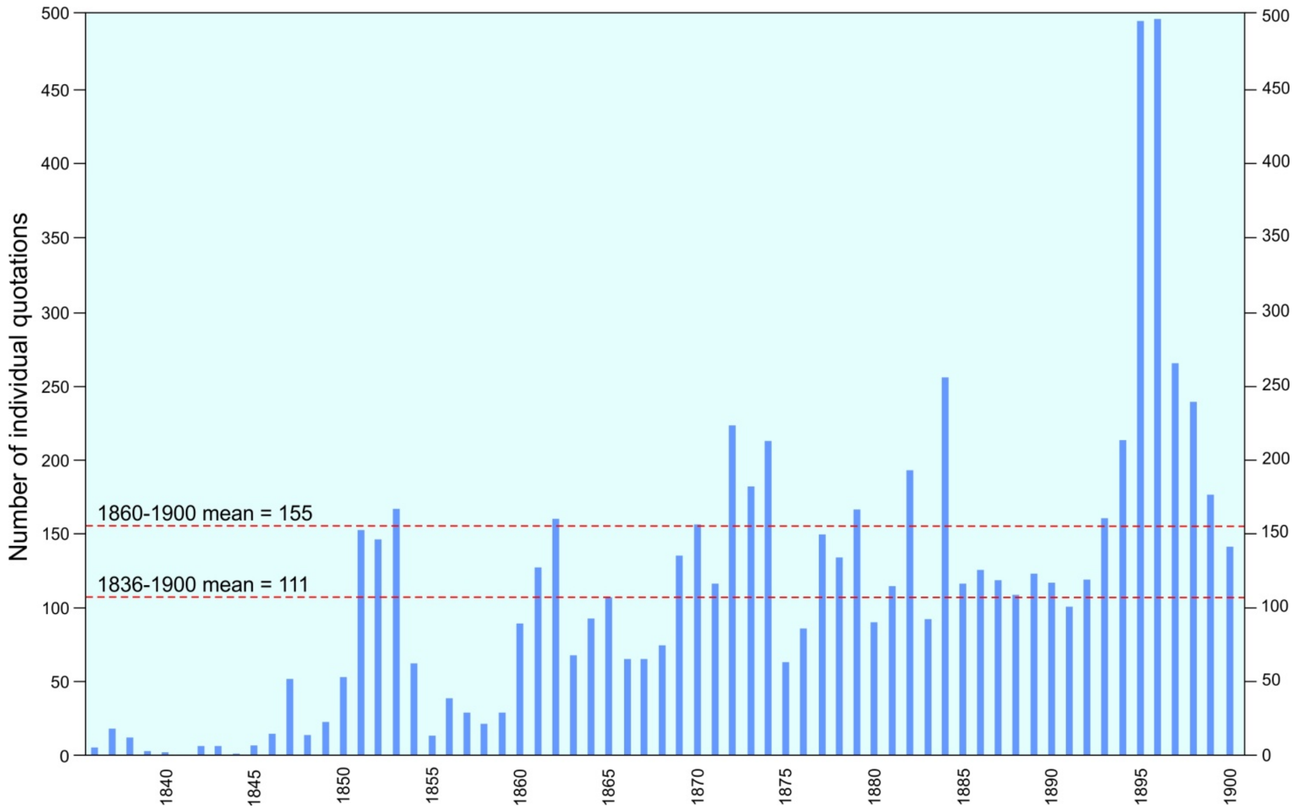

Figure S1. Number of individual quotations describing rainfall or rainfall-related conditions within documentary sources.

Upon the completion of archive work, individual quotations were sorted chronologically by July-June ‘rain-year’ (spanning the austral summer rainy season) and by location, to facilitate the reconstruction of rainfall conditions across the region as a whole. Relatively few quotations were available for the rain-years 1836-37 to 1859-60 (Figure S1), so it was only possible to generate annual classifications for this period. However, on average, 155 quotations per year were available for the rain-year 1860-61 onwards, providing sufficient data to permit seasonal (JAS, OND, JFM, AMJ) rainfall reconstruction.

Collections of quotations for each rain-year or season were analysed qualitatively to generate a five-point classification of rainfall conditions from +2 (very wet/floods) to -2 (very dry/drought). Following previous studies (e.g. Vogel, 1989; Nash and Endfield, 2002; Kelso and Vogel, 2007; Nash and Endfield, 2008; Nash and Grab, 2010), classifications of +2 or -2 were only awarded where observers described extreme wet or dry conditions, often with significant environmental and/or socio-economic impacts, during a major part of the rain-year or season. To generate annual rainfall classifications from seasonal data, the seasonal scores for individual rain-years were summed, averaged and rounded to the nearest whole number, a common approach used in historical climate reconstructions (e.g. Brázdil et al., 2005). Scores for OND and JFM were double-weighted to reflect the contribution of rainfall during these seasons to annual totals. As an illustration, analysis of quotations for 1886-87 yielded seasonal scores of -1 (JAS), -2 (OND), -1 (JFM) and 0 (AMJ), giving a weighted total of -7 for the rain-year, a -1.75 seasonal average, and a classification of -2.

A criticism often levelled at documentary-based climate reconstruction is that the analytical process is dependent upon the interpretation of qualitative descriptions, and hence may be subject to investigator bias (Brázdil et al., 2005; Nash and Adamson, 2014). To counter this, the seasonal series for 1860-61 to 1899-1900 were constructed independently by two of the authors (DJN and KP) and then compared. Of the 160 seasonal classifications during this period, 59% of scores were identical, 34% within one class and 7% within two classes. In general, there was greatest agreement during extreme years and least for seasons where conditions fluctuated around ‘normal’; this is to be expected given that documentary sources capture extreme events most effectively (Brázdil et al., 2005). Only four of the seasonal scores generated opposing signs (e.g. +1 versus -1). Further analysis indicated that these were seasons with large spatial differences in rainfall intensity across the study area. The results presented in section 3 of the main manuscript are the agreed final classifications, developed through negotiation between the two assessors.

Following Kelso and Vogel (2007), each annual classification was allocated a confidence rating from 1-3. This reflects both the number of quotations and the quality of information about rainfall conditions contained. A rating of 1 (low confidence) was awarded to rain-years where there was either a limited number of sources or the quality of information was low – several rain-years in the 1830s and early 1840s fall within this category. In contrast, a rating of 3 (high confidence) was awarded to rain-years which had multiple date- and place-specific references to rainfall conditions, and where the level of detail within the majority of quotations was high. All rain-years from 1859-60 onwards fall within this category.

S3. Multi-proxy rainfall reconstruction for the summer rainfall zone

The methodology used to reconstruct rainfall variability across the SRZ was identical to that used by Neukom et al. (2014), which incorporated all published annually-resolved climate records from southern Africa and surrounding oceans that spanned all or part of the 19th and 20th centuries. For the SRZ, these included three documentary-derived series (from Vogel, 1989; Nash and Endfield, 2002; Nash and Endfield, 2008; Nash and Grab, 2010), three coral δ18O and/or Sr/Ca series (Zinke et al., 2004; Zinke et al., 2009), and a single tree-ring width series (Therrell et al., 2006). The results of the current study, two rainfall series for Mthatha (Eastern Cape) and Royal National Park (KZN) derived from ships’ logs (Hannaford et al., 2015), and a baobab tree-ring isotope series from north-eastern South Africa (Woodborne et al., 2015) were added as part of the current reconstruction.

S3.1. Extension of the KwaZulu-Natal rainfall chronology to present

To allow for a calibration within a multi-proxy setting, the new documentary time series presented in the main manuscript needed to be extended to the present. This extension was performed using a "pseudo-documentary" approach (Mann and Rutherford, 2002; Pauling et al., 2003; Xoplaki et al., 2005; Küttel et al., 2007; Neukom et al., 2009; Neukom et al., 2014). This approach has been used successfully to extend five other documentary rainfall time series from southern Africa (Neukom et al., 2014). To allow direct comparison with these records, we use the same approach as in Neukom et al. (2014). For a detailed description of the methodology and its advantages and limitations we refer readers to Neukom et al. (2009).

In a first step, we identified the instrumental data that were most representative for the documentary time series of KwaZulu-Natal. To allow for a comparison, instrumental data needed to extend back in time at least to AD 1900, the year when the documentary time series ends. Within the province of KwaZulu-Natal, there are four stations from the GHCN database (Peterson and Vose, 1997) that fulfil this criterion (Table S1).

The station Umzimkulu does not show a good overlap correlation with the documentary data and the overlap period is very short. This station was therefore not included in further analyses. The three other stations show relatively high correlations with the documentary data (Neukom et al., 2014). While Pietermaritzburg Botanic Gardens extends back to 1860, it has many missing data in the 19th and 20th centuries. Durban Botanical Garden shows the highest correlations but also has some missing data.

To reduce the number of missing values in the instrumental data and obtain a regionally representative dataset, we built a composite of the three stations Durban Botanical Garden, Pietermaritzburg Botanic Gardens and Kokstad. First, the data were annualised over the July-June hydrological year, the same as the documentary data. To account for differences in mean and variance, Durban and Kokstad were then scaled to the mean and standard deviation of the Pietermaritzburg station over the period 1901-1964, where the number of missing values is low across these three stations. Note that for the generation of pseudo-documentary data, the unit of the instrumental data does not play a role, as the data are transferred to indices. Third, the three station data were averaged. The resulting composite covers the period 1860-1999 (with missing values between 1865 and 1869), resulting in 35 years of overlap with the documentary data (Figure S2). The overlap correlation is $r=0.69$ ($p<<0.01$), which exceeds the values of all other documentary series from the region (Neukom et al., 2014), confirming the high quality of this new documentary record.

Table S1: Instrumental data available for KwaZulu-Natal province extending beyond AD 1900. Station names, coordinates, time period covered, Spearman correlation with documentary data in the overlap period (*cor*) and length of the overlap period (*n*).

Station name	Lat (°S)	Long (°E)	Start	End	*cor*	*n*
Durban Botanical Garden	29.85	31.00	1871	1995	0.73	27
Umzimkulu	30.27	29.93	1885	1982	0.18	7
Pietermaritzburg Botanic Gardens	29.60	30.43	1860	2000	0.62	17
Kokstad	30.53	29.43	1882	1997	0.63	14

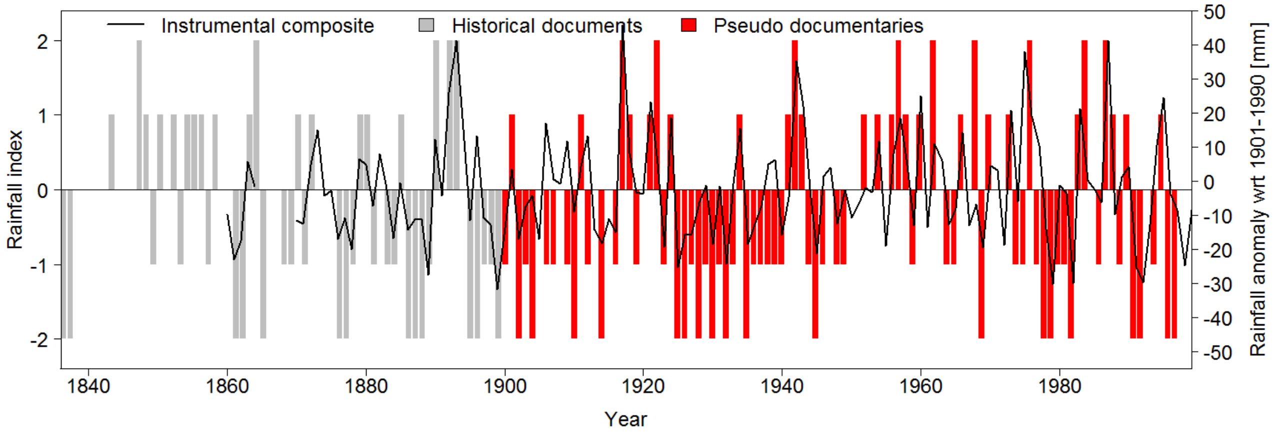

Figure S2: KwaZulu-Natal documentary record (grey bars), instrumental composite (black line) and one realisation of pseudo-documentary indices (red bars).

The instrumental composite was then degraded to pseudo-documentaries using the following steps. First, the overlap correlation (r=0.69) was used to define the signal-to-noise ratio (SNR) for the degrading process (Mann et al., 2007):

$$SNR = \sqrt{\left(\frac{r^2}{1 - r^2}\right)}$$

The corresponding amount of white noise was then added to the instrumental composite data, to avoid over-weighting this record in a multi-proxy calibration. Neukom et al. (2009) have shown that using white noise for degrading yields synthetic time series that are comparable to "real" documentaries.

In a next step, the degraded instrumental data were transformed to the unit of the documentary data (i.e. indices ranging from -2 [very dry] to +2 [very wet] – see main text).

The thresholds for assigning rainfall amounts to the different index categories were derived based on the overlap characteristics with the documentary time series; the number of years allocated to each category remained the same for the original and newly created pseudo-documentary data. The corresponding fractions in the 35-year overlap period are 27.5% for category -2, 25% for category -1, 22.5% for category 0, 15% for category +1 and 10% for category +2. For a discussion of different categorisation methods, we refer to Neukom et al. (2009) and Neukom et al. (2014).

The degrading and categorisation process was repeated 1000 times to create an ensemble of pseudo-documentary records for use in the multi-proxy reconstruction (see below). Each of these pseudo-documentary time series were then spliced to the original documentary data to form a time series covering 1836-1999.

S3.2. Extension of the Hannaford et al. (2015) rainfall reconstructions to present

To extend the ships' log-based rainfall reconstructions for Mthatha and Royal National Park (Hannaford et al., 2015) to present, we use the same degrading approach as above to create an ensemble of 1000 pseudo-proxy data. The instrumental data were degraded based on the correlation values reported in Hannaford et al. (2015): r=0.78 for Mthatha and r=0.67 for Royal National Park. Note that these data were directly spliced to the reconstructions (without categorisation as used for the documentary data, see above), because the reconstructions are provided in the same unit (mm) as the instrumental data.

S3.3. Multi-proxy reconstruction details

We updated the SRZ October-March rainfall reconstruction of Neukom et al. (2014) by adding additional proxy datasets; the extended documentary time series from KwaZulu-Natal (this study), the ships' log-based rainfall reconstructions of Mthatha and Royal National Park (Hannaford et al., 2015) and the baobab tree-ring isotope data of Woodborne et al. (2015). We used the same reconstruction target and method as Neukom et al. (2014) to obtain reconstruction results that are directly comparable. In the following we provide a brief description of this method; for full details we refer readers to Neukom et al. (2014).

The proxies were calibrated over the 1921-1995 period, with the 1911-1920 interval kept for independent early verification of results. The proxy matrix was infilled over the 1921-1995 period using the composite plus scale method (Neukom et al., 2011; Neukom et al., 2014).

The reconstruction was performed using nested principal component regression (Cook et al., 1994; Luterbacher et al., 2002; Neukom et al., 2011). We used an ensemble approach to quantify reconstruction uncertainty (Neukom et al., 2010; Wahl and Smerdon, 2012; Neukom et al., 2014). The reconstruction was thereby repeated 3000 times and, for each realization, five key reconstruction parameters were randomly perturbed: (i) One of the proxy datasets was removed from the predictor matrix; (ii) The proxy principal components (PCs) were truncated in a way that the retained PCs explain between 50% and 90% of the variance of the full predictor matrix; (iii) A calibration period of 35-50 (non-successive) years between 1921 and 1995 was selected, and the remaining 25-40 years used for verification; (iv) The weight of each proxy record in the PC analysis was scaled with a factor of 0.67 to 1.5; (v) For each documentary record and ships' log reconstruction, one of the 1000 realisations of pseudo-documentary data was chosen (see section S3.1). We use the ensemble mean of these 3000 reconstruction as our best estimate reconstruction.

The total reconstruction uncertainties were defined as the combined calibration and ensemble standard error (SE), calculated as $SE = \sqrt{\sigma_{res}^2 + \sigma_{ens}^2}$ with σ_{res} denoting the standard deviation of the regression residuals (calibration error) and σ_{ens} the standard deviation of the ensemble members (ensemble error).

We quantified the reconstruction skill based on the reduction of error measure (RE; Cook et al., 1994). The RE is defined as $RE = 1 - \frac{\sum_{i=1}^{n}\left(xinst_i - xrecon_i\right)^2}{\sum_{i=1}^{n}\left(xinst_i - x_{calib}\right)^2}$ $\mathrm{RE} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{xinst_i} - \mathrm{xrecon_j})^2}{\sum_{i=1}^{n}(\mathrm{xinst_i} - \mathrm{x_{calib}})^2}$ $RE = 1 - \frac{\sum_{i=1}^{n}\left(xinst_i - xrecon_i\right)^2}{\sum_{i=1}^{n}\left(xinst_i - x_{calib}\right)^2}$, with *xinst* denoting instrumental values and *xrecon* the reconstructed values for each year *i* of the verification period. *xcalib* is the calibration period mean of the instrumental data. The RE tests whether the reconstruction has more predictive potential than the calibration period climatology (*xcalib*). If the reconstruction has skill, then its RE values lie between 0 and 1 (a hypothetically perfect reconstruction), while RE values <0 have no predictive skill. We calculated an RE value for each ensemble member over its individual verification period (blue shading in Figure 4c in the main manuscript, ensemble median in bold blue). Additionally we calculated the early verification RE (brown in Figure 4c).

To calculate the early verification RE, the ensemble mean reconstruction (average of the 3000 member ensemble) was verified against the instrumental target over the 1911-1920 pre-calibration period. The ensemble reconstruction was repeated three times. First, only the new documentary data from this study (KZN) were added to the reconstruction of Neukom et al. (2014; N14). Second, the Hannaford et al. (2015) ships' log reconstructions

(H15) were additionally included and third, the Woodborne et al. (2015) baobab tree-ring isotope data (W15) were added. Figures S3-S5 compare the results of these three reconstructions. While all reconstructions are within the uncertainty range of the original Neukom et al. (2014) reconstruction, there are some clear differences, particularly in the pre-1860 period (see also main text). Comparison of the different reconstructions shows that the largest changes are introduced by the Hannaford et al. (2015) marine data that lead to drier conditions throughout the 19th century.

Figure S5 shows that adding the KZN and H15 data introduces additional skill to the reconstruction. In contrast, the W15 data do not improve the results; the RE values get slightly lower. This is not surprising given that the baobab tree-ring record is not significantly correlated with our reconstruction target (r=-0.13, p=0.24). We therefore use the N14 & KZN & H15 version of the reconstruction in the main manuscript.

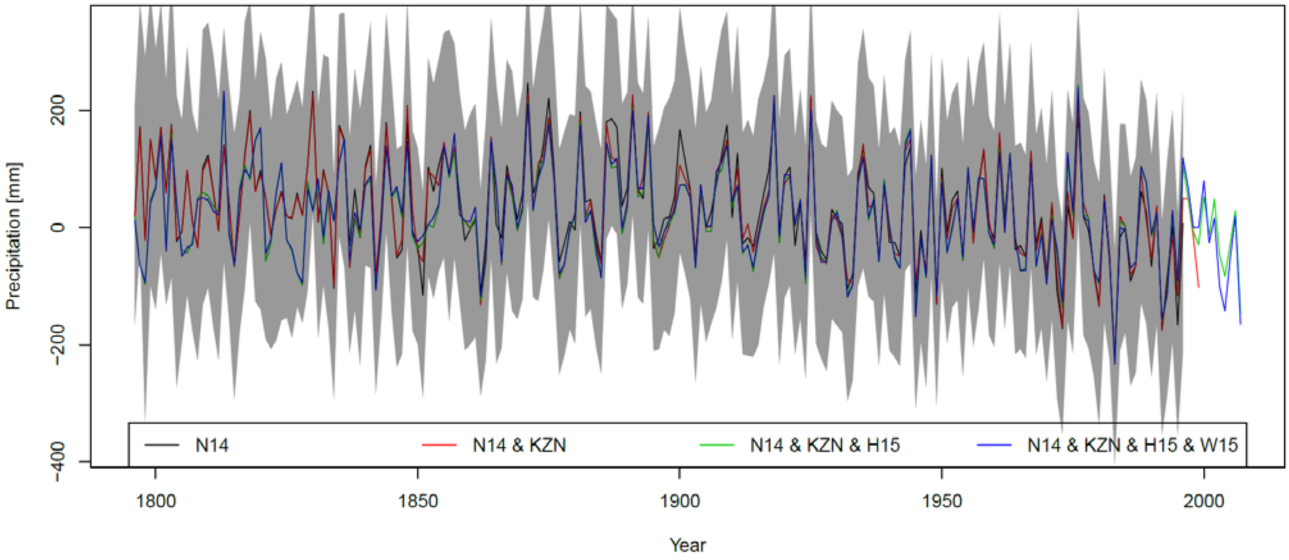

Figure S3: SRZ rainfall reconstruction based on different proxy datasets. Black: Original reconstruction of Neukom et al. (2014, N14) with grey shaded 2SE uncertainty bands. Red: N14 & KZN; Green: N14 & KZN & H15; Blue: N14 & KZN & H15 & W15.

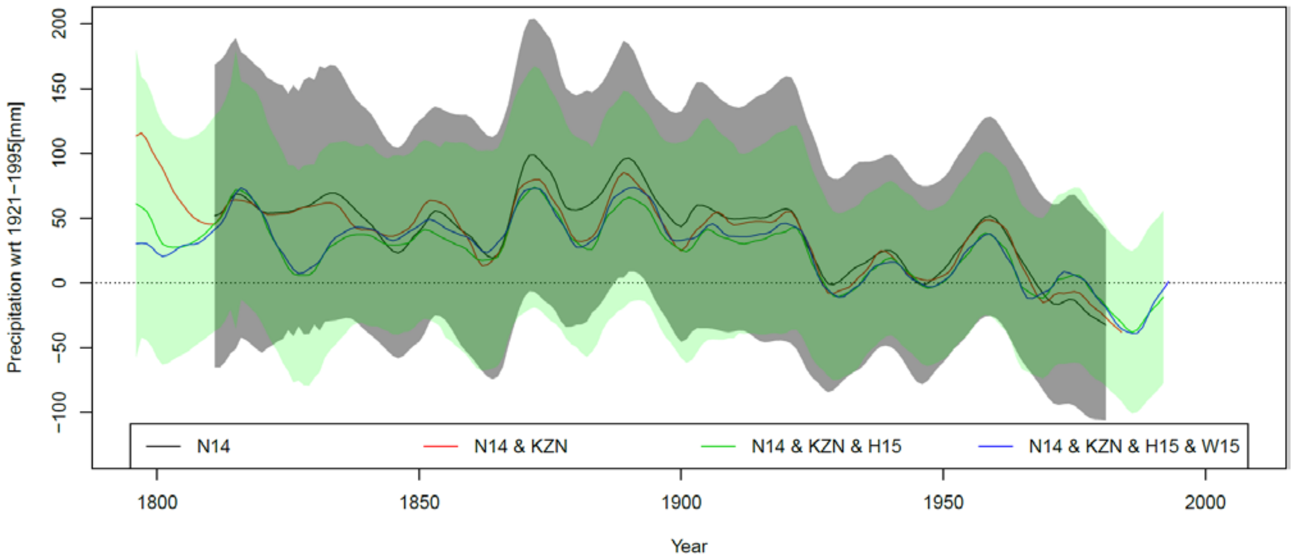

Figure S4: Same as Figure S3 but for 30-year loess filtered data. Green shading is 2SE for the filtered N14 & KZN & H15 reconstruction as used in the main text.

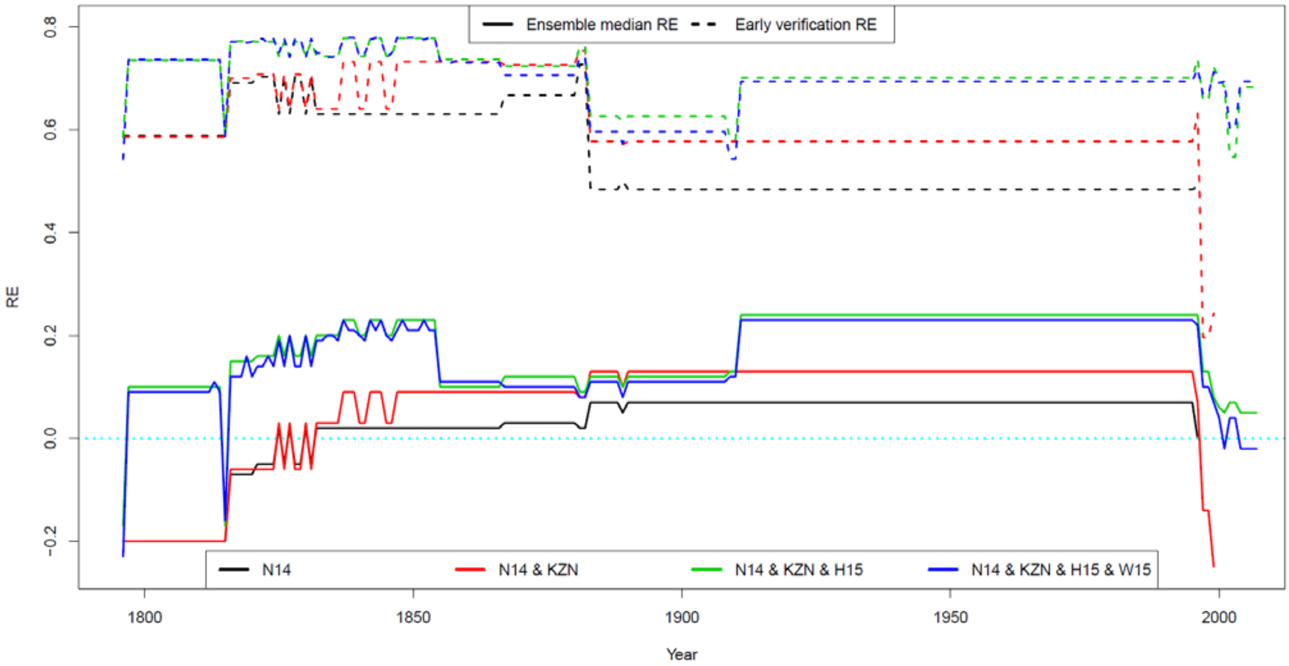

Figure S5: Ensemble median RE (solid lines) and early verification RE (dashed lines) for the different reconstructions shown in Figure S3.

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