Climatic Change (2007) 83:357–380
DOI 10.1007/s10584-007-9264-1

The climate of Namaqualand in the nineteenth century

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Received: 3 February 2005 / Accepted: 10 January 2007 / Published online: 22 June 2007

Abstract Southern African climatic change research is hampered by a lack of long-term historical data sets. This paper aims to extend the historical climate record for southern Africa to the semi-arid area of Namaqualand in the Northern Cape province of South Africa. This is achieved through extensive archival research, making use of historical documentary sources such as missionary journals and letters, traveller's writings and government reports and letters. References to precipitation and other climatic conditions have been extracted and categorised, providing a proxy precipitation data set for Namaqualand for the nineteenth century. Notwithstanding problems of data accuracy and interpretation the reconstruction enables the detection of severe and extreme periods. Measured meteorological data, available from the late 1870s, was compared to the data set derived from documentary sources in order to ascertain the accuracy of the data set and monthly rainfall data has been used to identify seasonal anomalies. Confidence ratings on derived dry and wet periods, where appropriate, have been assigned to each year. The study extends the geographical area of existing research and extracts the major periods of drought and climatic stress, from the growing body of historical climate research. The most widespread drought periods affecting the southern and eastern Cape, Namaqualand and the Kalahari were *1820–1821; 1825–1827; 1834; 1861–1862; 1874–1875; 1880–1883 and 1894–1896*. Finally, a possible correspondence is suggested between some of the widespread droughts and the El Nino Southern Oscillation (ENSO).

1 Introduction

Much attention is currently being paid to environmental impacts occasioned by complex biophysical and socio-economic influences on the Earth system. The rise in interest

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amongst policy makers in global change, including climate change and development by the G8 and European Union, (IPCC 2001; Steffan et al. 2004; Blair 2005), further illustrate both the urgency for more scientific and political debate on such themes. Previous assessments of climate change, for example, show that parts of Africa will be particularly vulnerable to climate change (IPCC 2001). Some have suggested, based on complex atmospheric modelling and scenarios, that future changes, particularly those associated with climate change and variability (e.g. periods of droughts, floods etc), may possibly be more frequent and more severe for some parts of the world, including parts of southern Africa (e.g. Joubert et al. 1996).

In many areas, however, assessment of whether climate is varying from what is known to have occurred in the past is hampered by a lack of long, historical data sets. This is particularly so in the case of southern Africa, where reliable, meteorological observations only begin in the early 1900s. In this paper we attempt to further extend the work of those who have endeavoured to expand climate history of the region (e.g. Nicholson 1981, 1989, 2000; Vogel 1987, 1989; Nash and Endfield 2002a,b; Endfield and Nash 2002a,b). Such reconstructions may be useful, not only for those interested in climate change, but also for those seeking to better understand environmental changes and their consequences, particularly the interplay between biophysical, socio-economic and socio-cultural systems.

This paper presents a background to the climate of the Namaqualand area and a discussion of the climatic controls of the region, followed by a reconstruction of the climate of the 1800s, as complete as the availability of historical documentary sources would allow. The identifiable extreme climatic events such as drought periods, extended dry and wet years are discussed. The drier and wetter years and drought and flood periods derived in this research are then compared with other documentary-derived climate chronologies (e.g. Vogel 1987, 1989 for the southern and eastern Cape and Nash and Endfield 2002a for the Kalahari, Therrell et al. 2006). Certain identifiable dry, wet and extremely dry periods appear to be widespread, whereas others are more localised, affecting only the Namaqualand region. This study is the first to compare the documentary derived data sets for the whole of the south western Cape and into the Kalahari region. Finally, an attempt is made to identify possible linkages between climate extremes and past El Niño Southern Oscillation high (cold) phase and low (warm) phase events (Lindesay and Vogel 1990; Mason and Jury 1997; Nicholson and Kim 1997). While not attributing direct causation to such phenomena, the *possible correspondence* between identifiable wet and dry periods to ENSO are noted for possible further investigations by others.

2 Background to the study area

The Namaqualand area, with an emphasis on the central Kamiesberg mountainous region was selected for this research because the oldest mission station in the Northern Cape, the Leliefontein station, was located there and thus, we were able to obtain data for a longer period for this area than for any other area in Namaqualand (Fig. 1). Historical climatic reconstructions have been completed for the areas surrounding Namaqualand, the southern and eastern Cape (Vogel 1987, 1989) and the Kalahari (Nash and Endfield 2002a) and so this study provides a useful complement, enabling further identification of past climate, including extreme periods such as droughts and wet spells and allowing the identification of widespread events. The Namaqualand region, moreover, is interesting because it is situated in a marginal region between an area of predominantly winter and predominantly summer

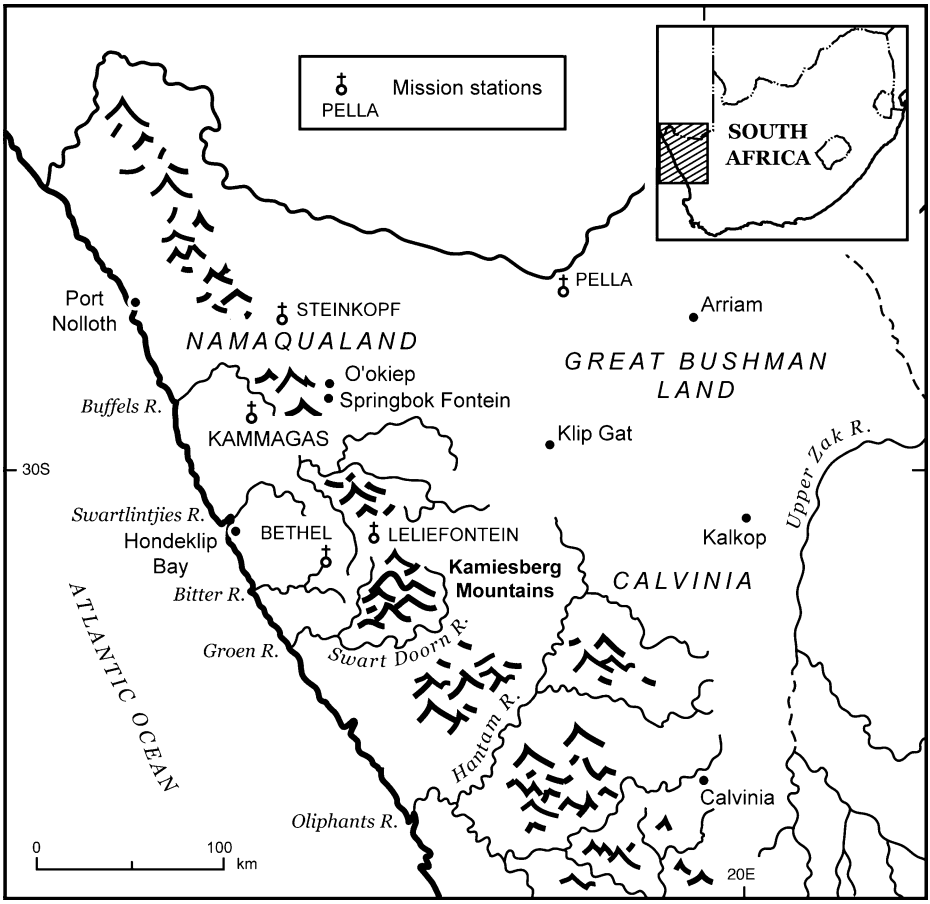

Fig. 1 Map of Namaqualand

rainfall. Finally, although it is not the scope of this paper, this study also formed part of a broader research project into land use and land cover change and adaptation to climate change for the area of Namaqualand (Kelso in preparation). The climate of Namaqualand thus, was reconstructed in order to identify the ways in which the nomadic rural community of Namaqua Khoikhoi were able to adapt and cope with climatic fluctuations at the beginning of the nineteenth century. By the end of the nineteenth century the community were unable to cope with even slight climatic fluctuations.

3 Climate of Namaqualand

The area of Namaqualand in the Western Cape has a desert climate which experiences high diurnal and seasonal temperature ranges. It spans two distinct rainfall regions, the region lying to the west experiencing predominantly winter rainfall, while the region to the east experiences predominantly summer rainfall (Fig. 2) (Weather Bureau 1960; Tyson 1984). The Kamiesberg Mountains, which run through the Namaqualand area, in a roughly north–south direction, form the division between the winter rainfall zone (to the west of and on

the mountains), and the summer rainfall area to the east (Price 1976; Dunne 1988; Kröhne and Steyn 1991; INCO-DP Project 1998). Peak rainfall amounts occur over the mountain belt as a result of the orographic effect.

The rain in this area is low, varying spatially and becoming steadily lower towards the west coast regions, ranging from 50–70 mm per annum. As one progresses eastwards the rainfall increases, with rainfall ranging between 150 and 300 mm per annum (Dunne 1988). Rainfall is moreover, highly variable with incidences having been recorded where the volume of rain which falls in a single heavy thundershower, has been equal to or more than, the annual rainfall total (Schulze 1965).

Namaqualand is an area where periods of extreme rainfall, both low and high, occur fairly frequently (Schulze 1965). Much of Namaqualand, is prone to drought. These droughts usually span a few successive years, the negative impacts worsening as the drought continues. The north-western Cape region, as a whole, experiences highly variable rainfall:

> The position in the north-western Cape .... [is that] only 35% of all annual falls are within ±20% of the normal whilst both dry and extremely dry, and wet and extremely wet years are quite frequent which is shown by the wide "spread" of the percentage about the normal. In other words the annual district rainfall is much more varied and one can expect very large fluctuations from year to year (Schulze 1965, 263).

Periods of climate stress and low rainfall in the Namaqualand area is a result of a combination of the various atmospheric pressure systems, that dominate this region and sea

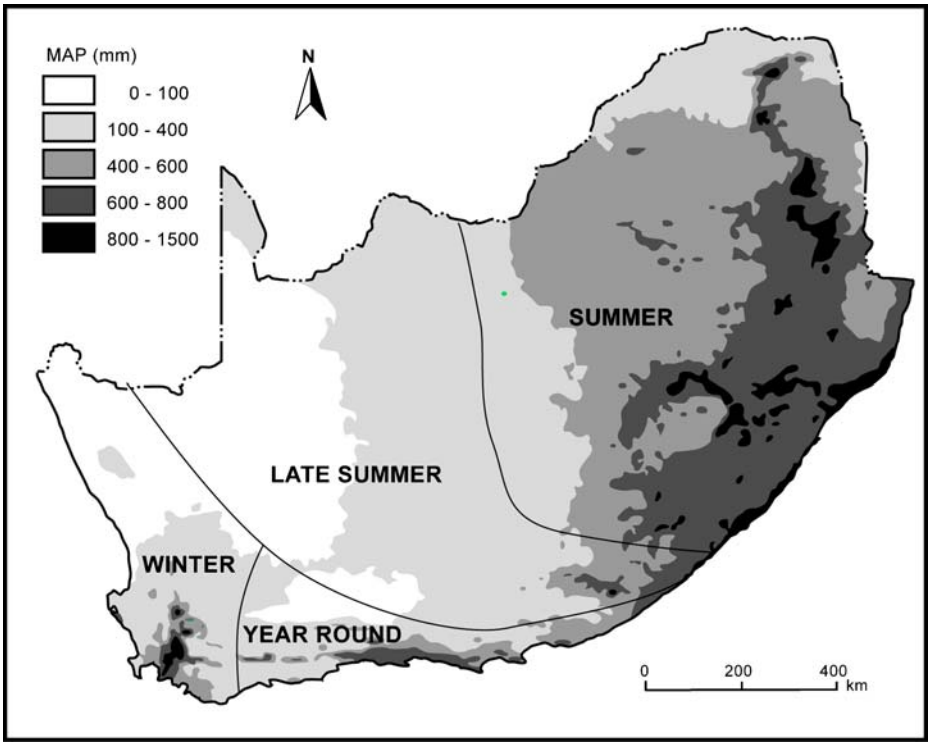

Fig. 2 Rainfall classification of South Africa according to season of maximum rainfall (Adapted after Schulze 1965, 289)

surface temperatures (Kruger 1996). The South Atlantic Anticyclone advects in cold, dry air originating over the Atlantic Ocean. The effect of the cold Benguela current causes less moisture to be advected over the west coast of South Africa, resulting in desert climates developing along the west coast and western interior of the country. Some of the winter rainfall of the western parts of the Northern Cape results from cyclonic rainfall caused by the movement of mid-latitude cyclone systems inland over the south west coast. These systems usually predominate over the western regions of South Africa during the winter season. During the summer season, the mid-latitude cyclone systems usually bypass South Africa to the south of the country and seldom affect rain except along the southern coastal regions of South Africa (Jackson and Tyson 1971; Harrison 1983).

Moisture in the region is associated with both local and wider regional atmospheric controls. Cloud cover over the Namaqualand area averages at less than 2/10 per annum (Jackson and Tyson 1971). Fog and mists also form an important source of moisture in this region. During the night the sea breezes advect in a significant amount of water, which is important for vegetation in the coastal regions (Weather Bureau 1996).

3.1 El Niño Southern Oscillation and the climate of Namaqualand

One of the phenomenon that modulates rainfall in the region is the El Niño Southern Oscillation. Linkages between ENSO and its influence on African rainfall have been shown (e.g. Nicholson and Entekhabi 1987; Ropelewski and Halpert 1987, 1989; Nicholson and Kim 1997; Nicholson 1997; Nicholson and Selato 2000; Nicholson et al. 2001) with the strongest signals in the eastern equatorial and south-eastern parts of Africa (e.g. Ropelewski and Halpert 1987, 1989; Nicholson and Kim 1997). Research on rainfall and ENSO relationships, particularly in attributing cause to southern African rainfall, has shown a high degree of complexity making it difficult to isolate some of the specific dynamical mechanisms (e.g. rainfall inducing systems) that link ENSO to rainfall in the southern African region (e.g. Mason and Jury 1997; Nicholson et al. 2001).

The links between rainfall seasonality (mid- and late-summer) and moisture sources (e.g. moisture derived from mid-latitude and tropical systems) have also been shown to be significant considerations in this region resulting in apparent contrasting and lagged rainfall responses to ENSO in Botswana when compared to parts of South Africa (Nicholson et al. 2001). In late summer, for example, when ENSO has a strong influence on rainfall in Botswana the source of moisture is linked to the Indian Ocean (Nicholson et al. 2001). When the late summer season is dry, during the post-ENSO year, the atmospheric response alters with moisture sources shifting northwards (D'Abreton and Tyson 1995; Nicholson et al. 2001).

The linkages between ENSO and rainfall, as indicated above, are complex with various temporal and spatial adjustments made throughout the various seasons. Attributing direct causality to ENSO, particularly during periods when there are relatively few reliable meteorological records is scientifically problematic. Notwithstanding these problems, there are now some detailed reconstructions of rainfall for parts of the southern African region that enable one to illustrate *possible* associations of periods of extreme drought (or flood) and ENSO. Imputing direct causality to ENSO for such periods of climate stress is, however, not the main purpose in this paper, for this is currently difficult, even despite availability of reliable data and results from complex atmospheric circulation models. Rather, we suggest and show in this paper, that one can identify patterns of extreme climate stress periods derived from documentary sources and with reference to other proxy sources e.g. harvests. Following this, we then offer what appears to be possible associations to notable

ENSO periods that we suggest can be added to the cohort of studies that are slowly emerging for this region. Once a sizeable data set has been derived, informed with several past cases that possibly highlight similar drought and flood cases, then perhaps one can begin to extend the debate and analysis on linkages to causation such as ENSO. Deriving any stronger associations at this stage, we suggest, is based on a rather fragile scientific base.

4 Sources and methods

Having briefly described the current climate, characteristics and atmospheric controls, the focus now shifts to the reconstruction of past climate. As a result of the lack of available measured meteorological data for Namaqualand for this period, historical documentary sources have been used. These sources are qualitative in nature and present certain problems when attempting to isolate climatic information from them. Despite these problems the detail from such data sources including missionary journals, letters, travel writings, and government reports, are invaluable when reconstructing past climates (Ingram et al. 1981; Nash and Endfield 2002a,b; Vogel 1987).

4.1 Documentary sources

A number of different archival sources were used for this study. The sources consulted included various unpublished missionary journals, letters and traveller's writings. Early travellers such as Simon van der Stel (1685), Ensign Rhenius (1724), Carel Fredrik Brink (1761–1762) and Robert Jacob Gordon (1777–1786) wrote journals of their travels through the Namaqualand area and provide scattered records of climate as well as fascinating insights into the livelihoods and social organisation of the local people groups (van der Stel 1932; Brink 1947; Rhenius 1947; Gordon 1988).

For the nineteenth century the missionary journals and letters provide an excellent source of information. Missionaries from the London Missionary Society: Christian Albrecht and Austin Albrecht as well as Mr. Sydenfaden, travelled through Namaqualand and up into the Kalahari region in 1804. These provide some of the first records for the nineteenth century and many of their letters and journal extracts are published in the *Reports of the London Missionary Society*. In 1816 Barnabas Shaw set up a mission station of the Wesleyan Methodist Missionary Society at Leliefontein and this station had a resident missionary until way after the turn of the next century. Many of the writings of these missionaries, as well as those of subsequent missionaries are published in the Wesleyan Methodist Missionary Society publications, which include the *Methodist Magazine*, the *Reports of the Wesleyan Methodist Missionary Society* and the *Missionary Notices*. Many of these missionaries resided at the mission station for long periods of time and grew accustomed to the climate and its changes. Barnabas Shaw himself resided at Leliefontein from 1816–1826 and the missionary who worked with him, Mr. Edwards was there from 1818–1832. They were succeeded by Rev. Jackson, Baillie, Goodman and Tindall and the mission station had a resident missionary throughout the 1800s. The accounts of these missionaries are very useful, as they grew familiar with the climatic conditions of the area, more especially because they introduced agriculture to the local people and continued conducting agricultural activities throughout the century.

For the second half of the nineteenth century government reports and records become a more prolific and valuable source of information. This follows the placing of a Resident Magistrate and Civil Commissioner in Namaqualand in 1856. The Civil Commissioner

resided in Springbok and communicated by letter to all of the districts and mission stations in Namaqualand. Copies of all of these letters were kept and are now held in the national archives in Cape Town. Certain of the Civil Commissioners remained in office for relatively long periods. One notable example is J. Eustace who resided in Namaqualand from 1879 till 1890 and many of his letters are held in letter books, in the archives, in Cape Town. As investigations took place into the status of the mission stations many reports were compiled and these were also used.

Similar methodologies to those adopted in this paper have been used by a number of climatologists and environmental historians in order to reconstruct the climate of particular areas, particularly for periods with no detailed instrumental data available (Ingram et al. 1981; Ballard 1986; Hamilton and Garcia 1986; Quinn and Neal 1987, 1992; Baron 1982; Nash 1996; Nicholson 2001). Examples of such studies relating to parts of the African continent are those done by Nicholson (1979, 1981, 2000, 2001) for the continent Africa as a whole, Vogel for the Cape (Vogel 1987; 1989; Lindesay and Vogel 1990) and Nash and Endfield for the Kalahari region (Endfield and Nash 2002a,b; Nash and Endfield 2002a). Other similar reconstructions have also been used for social and anthropological studies (e.g. Bundy 1979; Ballard 1986). Various international studies have also employed aspects of this methodology for climatic analysis (Metcalfe et al. 2002; Mock 2002; Ortlieb et al. 2002). Such chronologies provide useful supplementary information, particularly where there is a lack of data, for those reconstructing past environments for South Africa (e.g. Dovers et al. 2002). Therrell et al. (2006) recently published the results of their tree-ring reconstructed rainfall data set for Zimbabwe and they found that, with some exceptions, many of the drought periods which they found in their tree-ring studies correlated with those identified by Nash and Endfield (2002a) in their historical documentary studies.

Documentary data provide one of the only continuous sources of climatic information for the area being researched. The missionary sources are extremely valuable in providing a continuous overview of climate in the area and these become even more useful as the missionaries increasingly grow to know and recognise typical climatic conditions, and to identify vagaries and 'different' climate situations. Notwithstanding the value of documentary data to reconstruct past climate, there are a number of associated difficulties, the main problem being the subjectivity to which they succumb. Another difficulty lies in the fact that documentary sources tend to emphasise extreme climatic events, and mention very little about perceived 'normal' climatic conditions. Often the authors, being recent arrivals to the area lack knowledge of the typical climatic conditions, which are usually experienced in the area, and this tends to lead to exaggeration of certain climatic conditions. Despite these problems, the aim of this paper was to identify periods of climatic stress especially long, persistent drought periods and so, despite the difficulties with the data, this chronology will prove useful to environmental historians, sociologists and botanists working in this area, to whom a record of extreme climatic events is valuable.

4.2 Methodological process

The methodology used to reconstruct a chronology of wet, dry and extremely wet and drought periods involved reviewing all available documentary sources for the Namaqualand area. Periods that were extreme (e.g. a prolonged wet or dry spell, usually appeared in several sources hence providing some form of 'triangulation' and corroboration) and enabling a 'degree of objectivity.' Various sources were investigated including materials from the South African national archives located in Pretoria, Cape Town and the archives located at the University of the Witwatersrand. The method used to determine the history of

climate included the following process. All references to climate were noted in chronological order, with dates and exact location captured where this was available. With Namaqualand being a predominantly winter rainfall area, January to December was recognised as the rain year. Many of the references only gave the year and not the exact date and as a result it was felt that accuracy was improved by using the calendar year as the rain year. This is consistent with the work of Vogel (1987), which allowed the comparison of the two studies (Fig. 4).

The references were later analysed and classified according to the climatic events taking place. As these sources are qualitative, the climate can only be broadly classified into categories. Five categories were chosen to be consistent with other researchers in the surrounding areas (Vogel 1987; Lindesay and Vogel 1990; Nash and Endfield 2002a). These included very wet (flood years), wet years, 'normal' climatic conditions, dry years, very dry (drought) years. Reference to repeated dry years and drought and the associated reference to their impacts were identified. This information was then used to compile a graph showing years of drought, dry, normal or wet conditions (Fig. 1).

The following references have been selected to illustrate the approach used. These references come from various letters from the Civil Commissioner in Namaqualand, J.T. Eustace, detailing the 1880–1883 drought and describing the conditions experienced during this drought.

> I know that the last three harvests, have been either very indifferent, very bad or total failures, (C.T., 1/SBK, 5/1/8, Eustace, J.T., Namaqualand, March, 1883).[1]
>
> The most notable event during the year 1883 in this Division was the considerable distress amongst our farming population both white and coloured consequent upon a drought extending more or less over nearly 3 years. (C.T., 1/SBK, 5/1/8, Eustace, J.T., Namaqualand, 11/01/1884)
>
> With regard to all kinds of stock there will be I believe a considerable reduction in numbers, owing to the loss during the late drought. (C.T., 1/SBK, 5/1/8, Eustace, J.T., Namaqualand, 15/04/1884)
>
> I believe the 3 years drought from which this Division suffered in 1880. 1881. 1882 and the poverty – by that drought from which many of the inhabitants of Namaqualand have never recovered is the primary cause of this arrears. (C.T., 1/SBK, 5/1/9, Eustace, J.T., Namaqualand, 27/1/1887).

As can be seen from these sources, the droughts, the years of drought and impacts can be identified. The drought spanned 1880–1883, it affected both the White and the Coloured population negatively causing a decline in stock numbers. There are many other references to this drought period in the sources used, which provide an even more detailed picture than the quotes selected here. Thus it can be seen that the methodology, while not as objective and precise as one would usually prefer in reconstructions of climate, is

[1]Note: Unpublished archival resources used have been referenced using the first letters of the archive collection from which they come. That is, for Cape Town archives they are referenced with the letters C.T., followed by the source number and the volume number of that particular piece of material. For articles from the University of the Witwatersrand archives they are sourced with the letter W., followed by the reference number of the box in which they are to be found. For documents from the Pretoria archives, they are referenced with the letter P., followed by the source number, the volume number and the reference number of the document. Where available this is then followed by the name of the author, place of writing and the date. (Method after Nash and Endfield 2002a).

nonetheless a good surrogate source that can be scrutinized to get a sense of past climate (Ingram et al. 1981).

For certain periods references to a particular climatological condition are prolific but for others there are very few or vague comments in the sources. The number of sources referring to climate for each year ranged from 1 to 20. As a result it was decided that confidence ratings should be awarded for the information for each year in order to allow the reader to easily distinguish data with the greatest certainty (Table 1). The rating for each year was derived from the number of sources consulted for that particular year as well as the number of references to that particular climatological condition and this was used to assign a confidence rating of 1/2/3 to each year (Table 1). The confidence rating of 1 was given where there was only one source referring to the climatic condition. The years with confidence ratings of 1 are therefore questionable. However, it was felt that where the source was reliable, such as a missionary living in the area, it would still be useful to include these in the data set. This follows Ortlieb (2000), conducting similar research in order to construct an historical El Nino sequence, where he argues that to leave out the years in which there was only one reliable source would severely shorten the record available. A more continuous record is also more valuable for comparison with similar research in the surrounding areas and for botanists, environmental historians and others. Nevertheless, a confidence rating of 1 serves as a caution to the reader that this information may be incorrect. The years, which were awarded a confidence rating of 3, were those which had more than three references to them and where the dates and places of these references were very specific, these have been distinguished on the graph for easier reference (Fig. 3).

4.3 Data verification

In Namaqualand the earliest instrumental figures available were recorded in Springbok from 1878. This data set and this was used to test the accuracy of the documentary-derived data set (South African Weather Service). Despite the fact that Springbok is slightly north of the study area and at a lower altitude (Springbok: 991 m and Kamiesberg: 1,448 m), which causes it to receive less rainfall nevertheless preliminary analysis of the data for these two locations for the twentieth century has shown that the general pattern of their wet, dry, normal and drought periods generally coincide. The Springbok data for 1878–1900 was used in order to confirm whether or not the information which had been obtained from the documentary sources was generally correct (Table 2). The mean rainfall for this area is 222.5 mm. In order to identify a meteorological drought the definition of drought after Laing (1992, 1994; Vogel et al. 2000) was used, defining drought as less than 75% of mean annual rainfall. Wet periods were classified as more than 125% of mean annual rainfall and slightly wet or dry periods were between the mean and these figures (Laing 1992; Vogel et al. 2000) (Table 2).

The analysis revealed a correspondence in the climatological periods identified for 11 years out of a possible 19 (Table 2). An analysis of the monthly rainfall data for the 8 years that did not correspond directly, revealed seasonal anomalies during the growing season for 5 of those years. Years 1881, 1891, 1893 and 1989 all received little or no rain during the months of October–December. Year 1884 which the documentary research showed to be a dry year when it was in fact a meteorological drought year, received unusually heavy rainfall during September and October, which are vital months of the growing season, as a result the documentary sources mention that the harvests during this

Table 1 Confidence ratings

Year	Classification	Confidence rating
1817	Drought	3
1818	Wet	3
1819	Dry	1
1820	Drought	1
1821	Drought	3
1822	Wet	3
1823	Wet	2
1824	Normal	2
1825	Drought	2
1826	Drought	3
1827	Drought	3
1828	Normal	2
1829	Insufficient evidence	
1830	Normal	1
1831	Wet	2
1832	Insufficient evidence	
1833	Normal	1
1834	Drought	1
1835	Drought	1
1836	Drought	1
1837	Dry	1
1838	Dry	2
1839	Drought	1
1840	Insufficient evidence	
1841	Insufficient evidence	
1842	Insufficient evidence	
1843	Insufficient evidence	
1844	Dry	2
1845	Drought	2
1846	Insufficient evidence	
1847	Insufficient evidence	
1848	Dry	1
1849	Insufficient evidence	
1850	Insufficient evidence	
1851	Drought	1
1852	Insufficient evidence	
1853	Insufficient evidence	
1854	Dry	1
1855	Drought	1
1856	Drought	2
1857	Drought	2
1858	Insufficient evidence	
1859	Wet	2
1860	Drought	3
1861	Drought	2
1862	Drought	3
1863	Wet	2
1864	Normal	2
1865	Drought	3
1866	Drought	3

Table 1 (continued)

Year	Classification	Confidence rating
1867	Drought	2
1868	Drought	2
1869	Normal	2
1870	Wet	2
1871	Dry	2
1872	Wet	2
1873	Normal	2
1874	Drought	3
1875	Drought	3
1876	Dry	2
1877	Insufficient evidence	
1878	Wet	2
1879	Dry	3
1880	Drought	3
1881	Drought	3
1882	Drought	3
1883	Drought	3
1884	Dry	3
1885	Normal	2
1886	Normal	3
1887	Normal	3
1888	Wet	3
1889	Insufficient evidence	
1890	Dry	1
1891	Dry	2
1892	Insufficient evidence	
1893	Drought	3
1894	Drought	3
1895	Drought	3
1896	Drought	3
1897	Dry	3
1898	Dry	1
1899	Wet	3
1900	Wet	3

1: The value 1 was given when it was felt that the climatic condition assigned was questionable. This was awarded where there was only a single, although definite, reference to a particular condition or there were only references for the surrounding areas and not Leliefontein or Kamiesberg itself. One was also used where only the effects of a particular climatological condition were mentioned and not the actual condition itself, for example harvest failures indicating possible dry conditions.

2: A confidence rating of 2 was given when there was a very definite mention of a particular condition in the sources with clear and accurate date and place given but where the condition was only categorically mentioned in a single source. Here, specific words were looked for in order to indicate a condition, such as 'drought,' 'crop failure,' 'copious rains,' a vague reference to a particular condition was disregarded.

3: A confidence rating of 3 was given to the climatological conditions with a number of references in the sources and where accurate place and dates were given, as well as a description of the impacts. These were the periods of which there could be little question. On the graph showing the climatological periods these have been shaded in order for the reader to easily distinguish them from the others which are more questionable (Fig. 3).

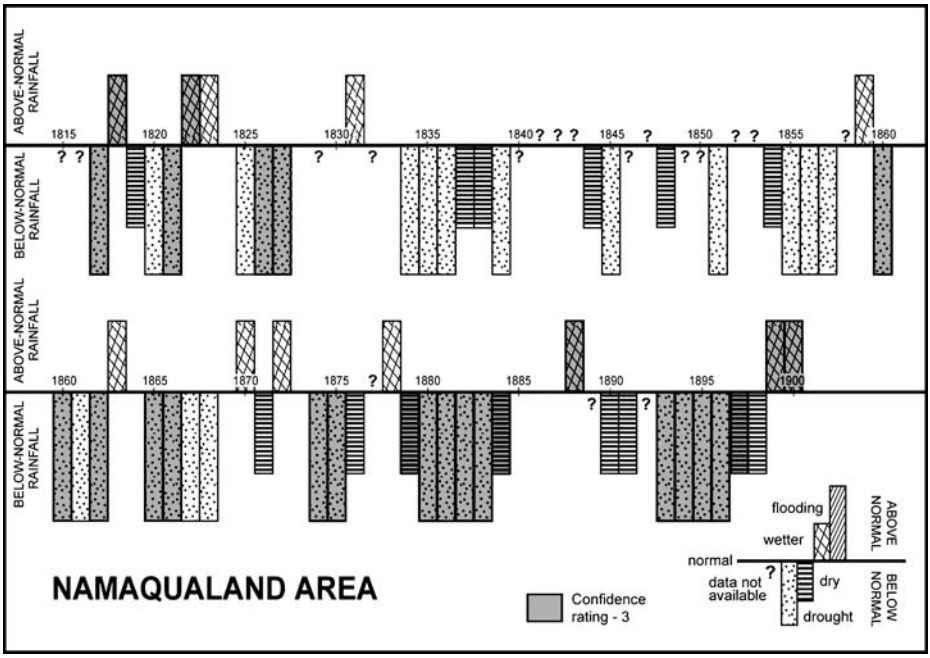

Fig. 3 Climate of Namaqualand in the 1800s

1884 were reasonable, thus causing the error (C.T. 1/SBK, 5/1/9, Eustace, J.T., Namaqualand 1886).

Year 1881 received what would be classified as normal rainfall when looking at the annual rainfall figures, where analysis of the documentary evidence showed it to be a drought year. If however, one looks at the monthly rainfall data, one can see that between September and December only 6.4 mm or rain was received, the normal average for these months is 46.3 mm (South African Weather Service). In this instance then, it is evident that seasonal drought occurred and this, during the season vital for agriculture, therefore it was represented in the sources as a drought year, with widespread crop failures. This error can occur in certain instances when one is converting documentary data into climatological data, for example the effects of a drought might be experienced when the rain falls in the wrong season or time of the year for agriculture and therefore sources might describe it as a drought, whereas annual rainfall figures represent it as a relatively normal year. In this particular case, 1881, the previous year and the following 3 years were meteorological drought years, the sources actually discuss how the rains improved in 1881, but the latter rains failed causing crop failures (Cape of Good Hope 1881, C.T. AG 1538, Tindall, Stellenbosch, 13 June 1890). Therefore the effects of this drought lasted throughout the period causing the various authors to perceive it as a drought year (C.T. AG 1538, Tindall, Stellenbosch, 13 June 1890).

> The year 1881, has, generally, in this division, been one of improvement upon the two previous years .... Owing to the abundance of rain that fell in the beginning of the year in Bushmanland, the chief grazing of this division, stock of all kinds throve well .... We also had fine rains during seed time in the more western and corn-growing districts, and there was, in consequence, a larger breadth of ground broken up and sown than in former years. Unfortunately the rain-fall during the time the seed was in

Table 2 Verification of documentary data with available rainfall data from Springbok

Year	Annual rainfall (mm)	Data verification
1878	315	Correspondence
1879	251.9	No correspondence
1880	178.8	Correspondence
1881	212.6	Seasonal anomaly
1882	62.3	Correspondence
1883	168	Correspondence
1884	130.8	Seasonal anomaly
1885	216.3	Correspondence
1886	214.5	Correspondence
1887	218.9	Correspondence
1888	418.6	Correspondence
1889	151.9	No documentary evidence available
1890	224.6	No correspondence
1891	216.6	No correspondence
1892	344.9	No documentary evidence available
1893	222.9	Seasonal anomaly
1894	203.8	No correspondence
1895	109	Correspondence
1896	132.1	Correspondence
1897	180.9	Correspondence
1898	247.6	Seasonal anomaly
1899	330.6	No documentary evidence available
1900	303.5	No documentary evidence available

Rainfall Data Classification Categories (adapted from Laing 1992, 1994)

Wet more than 278 mm

Slightly wet between 245 and 278 mm

Normal between 200 and 245 mm

Dry between 167 and 200 mm

Drought less than 168 mm

> the ground – a little over an inch, between August and November – was insufficient to bring the grain to maturity; this year's harvest was therefore generally a failure. This is the third year in which the ingathering has been little or nothing, owing to the absence of the latter rains. (Cape of Good Hope 1881).

It is evident from this discussion that the main period of drought was identified using the documentary sources and taken in conjunction with the descriptions of the conditions in 1881, it can be seen that the documentary sources provided an excellent overview of the climate of 1881. Using documentary sources is thus allowing us to correctly identify the periods of climatic stress with only a slight margin of error.

The data verification shows therefore that the data is reasonably reliable and where it is incorrect it is not incorrect by a large margin. In addition to this, analysis of the monthly rainfall showed that 5 of the 8 years that did not correspond experienced seasonal anomalies. The confidence ratings too allow the reader to identify the climatological periods of which the greatest certainty exists (Fig. 1). Thus, despite the difficulties it is felt that this is a useful source of climatic information, more especially as no such record existed previously for this area.

5 Droughts and wet spells in Namaqualand

The earliest records for drought periods in the northern Cape come from sporadic accounts of the area written by travel writers, aiming to travel north to the Copper mountains and later across the Orange River (van der Stel 1932, 1979; van Reenen 1935; Jansz 1935; Wikar 1935).

The earliest recorded drought in the area of the Kamiesberg spanned 1681–1684 and was recorded after Olof Bergh's second expedition attempting to find the Copper Mountains (Ross 1998). This drought ended with good rains in 1685, when Simon van der Stel undertook his first journey to the Copper Mountains (van der Stel 1932, 1979). The 4-year duration of this drought was fairly typical of the droughts in the Namaqualand area, which usually seemed to last for a minimum of 3 and a maximum of 5 years during the 1800s.

For the remainder of the period 1600–1800 the records are very scattered, there are only a few travellers records available. The records become more detailed for the 1800s and therefore this period was chosen for a thorough examination. Certain notable drought periods have been discussed below. The full set of results is displayed in the graph (Fig. 1).

5.1 Droughts and dry years of the 1800s

The earliest records for the 1800s are found in the Reports of the London Missionary Society whose missionaries settled near Warme Bad in Great Namaqualand (southern Namibia). These earlier records are not continuous, therefore it is only possible to establish individual dry years from them, and not to identify periods of drought. Nevertheless the years identified as drier were *1800*, *1804/5*, and *1807*, and *1812* are reportedly (Fig. 1) (London Missionary Society 1804–1808, 1813–1816).

The first major drought periods, of which there are a number of reports in the documentary sources, are *1820–1821* and *1825–1827* (Fig. 3). These droughts are widespread over the Namaqualand areas to the north and east of the Kamiesberg in areas around Pella and Steinkopff, where it spanned the whole period from 1820–1827 (London Missionary Society 1822–1826; Shaw 1970). In the area of Leliefontein in the mountain belt of Namaqualand, this drought was broken into two separate periods with dry conditions experienced in 1820–1821, two wet years occurring in 1822 and 1823, and further droughts in 1825–1827 (Wesleyan Methodist Missionary Society 1826–1828; London Missionary Society 1829; Shaw 1970).

From 1816 the Wesleyan missionary Barnabas Shaw, resided permanently in the Leliefontein area and he describes the initial 2 years of the 1820s drought as follows:

> 10th. [September, 1821].–The failure of our harvest last year was a serious evil; but the loss of our wheat this year also is much more so, and has rendered the distress of some of our poor Namacquas great indeed. (Wesleyan Methodist Missionary Society 1822, 607).

He further describes how the conditions have worsened by *1826*:

> The year 1826 was a time of great scarcity at Lily Fountain, in consequence of the long and continued drought. Several lived chiefly by hunting, and some on bulbs and roots, while others picked up parts of bullock hides, which for years had been thrown about the place. They pounded them for several hours. One evening a Namacqua came to me and said, he had been hunting the whole day, but could obtain nothing. He added, "Mynheer, ik ben drunken van honger, (I am drunk with hunger,) and ready to

faint and fall to the ground." I was enabled to supply him with a little corn, which he received with gratitude and joy. Providentially, I had preserved a good quantity of wheat and barley the preceding year, which I so managed to eke out in small quantities, that none died of hunger. Indeed the Namacquas bore up with amazing patience and fortitude, till the rains commenced, and they obtained supplies of milk from their cows and goats (Shaw 1970, p.95).

Documentary sources provide interesting observations and perceptions of dessication resulting from recurrent droughts (Endfield and Nash 2002a,b). Sir James Alexander, a Captain in British service, took a journey of exploration into Southern Africa, venturing just north of the Kamiesberg region, from 1836 to 1837 (Alexander 1967). He described the perceptions of the local people during the widespread drought of 1834–1836 as follows (London Missionary Society 1834–1837; Wesleyan Methodist Missionary Society 1837; Alexander 1967):

The fountain at the Copper Berg had much decreased within the last 30 years. Formerly a thousand head of cattle could at most times have drank at it; now there was scarcely water enough for a span of 12. The old people said that much less rain had fallen within the latter years, – that there was no sea rains now as there used to be, only thunder storms from the east; but they hoped that the following years would take a turn for the better (Alexander 1967, 138–139).

The drought of *1860–1862* is the first drought for which government assistance was proposed (C.A, 1/SBK, 5/1/2, Judge, Namaqualand, 24 April 1862, Cape of Good Hope, 1862). This drought had severe consequences, particularly for the inhabitants of the various mission stations. As described here in a letter written by the Civil Commissioner of Namaqualand to the Colonial Secretary:

Letter of the Civil Commissioner, Namaqualand, 24 April 1862

From the Revd. Mr. Bailie at Lily Fontein I have had accounts of similar distress among his people–with regard to some of these people I can speak from personal observation. Several of them were lately summoned for debt in my court. They had no means of paying these debts which amounted ... sum of from £1 to £4 or £5 without selling their remaining few cattle. These cattle were however so poor in condition, that there were no chances of finding purchasers except at great sacrifices. One of these natives shortly afterwards started from Lilyfontein with a wagon and +14 oxen with the intention of coming to this place to pay his debt. Seven of the oxen were his own, seven were borrowed. He intended selling as many of his oxen as was necessary to pay his debt and returning with the remainder. But the oxen were in so wretched a condition that they could not perform the journey across the parched country from Lilyfontein to Springbok – Nine of them had died by the time he travelled to the distance of one days journey from Springbok. He could proceed no further. –He therefore came on foot to this place to report the circumstances (C.T., 1/SBK, 5/1/2, Judge, Namaqualand, 24 April 1862).

Another notable drought spanned the years of *1893–1896* (C.T., CO 7373, Chief Inspector of Public Works, 21 December 1895; PWD 2/5/288, Cape Times, 20 January 1896; C.T., SG 3/2/1/31, Resident magistrate, Namaqualand, 21 March 1896; C.T., PWD 2/5/288, Hugo, O'okiep, 18 May 1897). Relief works were set up by the Government on which many mission station residents worked in order to gain an income during the drought (C.T., CO 7373, Hugo, Namaqualand, 29 April 1896). There are prolific reports of extreme distress and starvation in Namaqualand during this drought (C.T., AG 1538, Tindall, Cape

Town, 13 June 1890, 1896; C.T. PWD, 2/5/288, Cape Times, 24 January 1896; C.T., CO 7373, Hugo, Namaqualand, 29 April 1896; C.T., PWD 2/5/288, Cape Times, 6 September 1896).

In a newspaper article entitled *Cry from Namaqualand*, the drought is described as follows:

> A drought, said to be longer than living memory could parallel, had reduced the division to dire straits. For some seasons past the farmers had got no fruits of their toil. Cattle and sheep had perished by the hundred of starvation or thirst. ... and, according to our correspondents, the death of human beings from starvation, the chronicling of which always sends a shudder even through the squalid cities of the old world – is a fact of the moment in the Cape Colony. Our Correspondent draws a pitiable picture of the helpless condition of the people in one part of the division, three years harvestless. ... Some having lost their cattle during the evil that has fallen upon the land, are unable to transport the food supplies which might be obtained at the Government depot, while others having no means of communication with the centre of distribution and so making their necessities known." (C.T., PWD, Cape Times, 20 January 1896).

A Namaqualand resident explains:

> I was born in Namaqualand, but I have never experienced such a time as we are having now. (C.T., PWD, Dixon in Cape Times, 20 January 1896).

The Acting Civil Commissioner of Namaqualand, A.B. Hofmeyr, in a report on the mission stations in Namaqualand, stated that, "[t]here is no doubt that the natives have steadily degenerated and men who some years back were well off and possessed a considerable number of stock, have little or nothing left to-day." (C.T., AG 1538, Hofmeyer, Namaqualand, 6 July, 1905).

5.2 Wet spells of the 1800s

Having traced certain dry years and drought periods attention focuses now upon wetter years. The wetter periods are often more difficult to identify using this methodology. This is most likely a result of the fact that droughts had far more serious negative long-term consequences occurring over a few years, than isolated wetter periods. This again, is probably a result of the fact that their effects are not as negative as those of drought. Drought is a lagged, creeping hazard, the effects of which last for a number of years. Wet periods in these regions are shorter and more sudden and often the sources do not record these in as much detail, although severe weather such as floods will be noted.

Despite these difficulties, the year *1818* stands out as a wet year, with severe storms being experienced on the Kamiesberg (Fig. 3) (Wesleyan Methodist Missionary Society 1819). It is not clear to what extent this excessive rain was experienced elsewhere in Namaqualand, but it certainly occurred in the Kamiesberg. Barnabas Shaw, the resident missionary at the Kamiesberg described it in his journal as follows:

> 12. [May, 1818]. We have actually for the 2 days last past been in the clouds, and the cold is almost insurmountable. The wind has raged most tremendously, and the rain fell almost in torrents.
>
> 18. [May, 1818]. The weather is now more severe than I have ever seen before. We have not only had mist and rain, but the most bitter storms of hail and snow; the wind has also increased to such a degree that we have now a complete hurricane. This storm has had an effect on the house of Brother Edwards (being in an unfinished state,) that it has found its way to the ground, where it must be till the rainy season

shall be over before it can be rebuilt. (Extracts from the journal of Barnabas Shaw in Wesleyan Methodist Missionary Society 1819, 70).

During 1822 and 1823 the Kamiesberg region experienced excessive storms and heavy rains in the winter of *1822* [Fig. 3] (Wesleyan Methodist Missionary Society 1823). The resident missionary at the station describes these storms as resulting from winds from the north–west, indicating that they were advected in from off the Atlantic ocean, which would provide an explanation as to why they did not effect eastern Namaqualand. These storms occurred in most of the winter rainfall area of the Cape Colony (Wesleyan Methodist Missionary Society 1823). The effects of these storms were devastating in Leliefontein, the missionary describes the conditions as follows:

> ... my presence being very soon necessary to repair the buildings which have fallen at Lily Fountain, in consequence of recent hurricanes (Wesleyan Methodist Missionary Society 1823, 118).
>
> Aug. 19th. [1822] Our buildings on our station and also upon the new farm, have also been much injured by the late torrents of rain and wind from the N.W. The church, and smith's shop, have fallen to the ground, and the buildings upon the new farm will all want repair (Wesleyan Methodist Missionary Society 1823, 118).

Years 1831, 1859, 1863, 1864 1870, 1872, 1878 and 1899 all appear to have had good rains (Fig. 3) (Wesleyan Methodist Missionary Society 1832–1834, 1860; Cape of Good Hope 1871–1873, 1878; C.T., CO 7373, Studer, Bowesdorp, 23 October 1899).

Year 1888 in particular was mentioned as having exceptional rainfall

> Our rainfall last year was very much in excess of any previous year, certainly within my knowledge, now extending over 10 years – many rivers which had not been flowing for years, ran for some months, the veldt was everywhere good, and I have never seen stock of all kinds in better condition, and were it not for the present low price of grain in this Division I should say the farming interests had no cause for complaints – unfortunately in good seasons the supply is in excess of the local demand – and the transport to the only port available for chief corn growing districts – Hondeklip Bay – owing to the heavy road almost precludes its use (C.T., 1/SBK 5/1/10, Eustace, Namaqualand, 6 May 1889).

6 Discussion and observations

Several drought periods and wetter periods have emerged from a detailed study of a variety of documentary sources. The drought periods identified in this study have been compared with those identified in other similar studies conducted for the same period for the Cape Province (Vogel 1987); the Kalahari region (Nash and Endfield 2002a); Zimbabwe (Therrell et al. 2006) and for Africa as a whole (Nicholson 1989). Possible Links between ENSO and droughts in Namaqualand have also been identified.

6.1 Comparison of the droughts and wet spells in Namaqualand with those found in similar studies

The years in which the droughts were found to be the most widespread and occurring in the Kalahari region, the southern Cape, the eastern Cape and Namaqualand were those from

1820–1821; 1825–1827; 1834; 1861–1862; 1874–1875; 1880–1883 and 1894–1896 (Vogel 1987; Nash and Endfield 2002a) (Fig. 4, Table 3). These droughts began and ended in different years in different areas, but the years cited above are those of common reference in all four areas. Certain of the wetter years identified also coincide in a number of the sources. Vogel (1987) identified the years *1822–1824; 1831 and 1859* as wetter years in the southern Cape (Table 1), while the wet years of *1863–1864 and 1899* coincide with those identified by Nash and Endfield (2002a) in the Kalahari.

Recently a tree-ring reconstructed rainfall data set for Zimbabwe for the 19th century was compiled. The authors compared their findings to the documentary derived data set for the Kalahari (Nash and Endfield 2002a). It was found that there was good correlation between the tree-ring reconstructed data and that from documentary derived data.

> "Contemporary historical sources in the Kalahari region (Botswana) report drought conditions in these areas that were often coincident with episodes shown in the reconstruction" (Therrell et al. 2006, 681).

Certain widespread drought years, which were concurrent between the tree-ring reconstructed data set, the Kalahari data and the Namaqualand data were 1857–1858, 1860–1862, 1882–1883, 1893 and 1895–1896. The years that coincide between the three studies formed some of the most severe drought periods in Namaqualand for the second half of the 19th century. The unusually high rainfall of 1899 and 1900 also correlated with the tree-ring data set (Therrell et al. 2006).

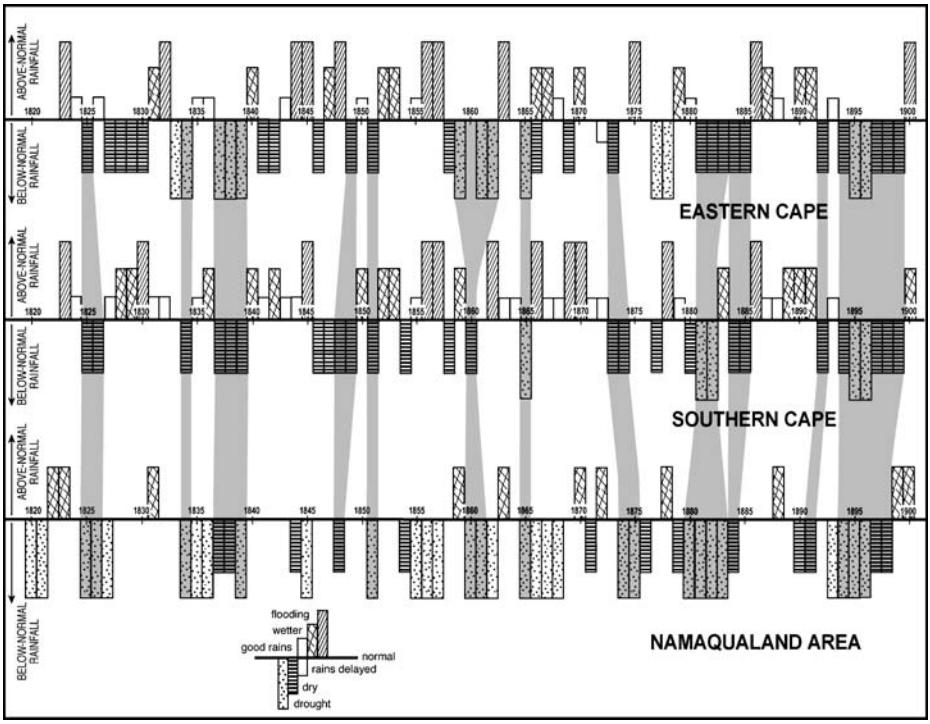

Fig. 4 Climatic conditions in Namaqualand compared with those of the Southern and Eastern Cape 1820–1900

Table 3 Correlation of ENSO low phase events with drought periods in Namaqualand for the nineteenth century

El Niño events	Strength	Namaqualand dry/drought years	Droughts identified for surrounding areas
1817	M	1817	
1819	M	1819–1821	
1821	M	1819–1821	Kalahari
1837	M	1834–1839	Eastern Cape
1844–1846	M/S	1844–1845	Kalahari
1857	M	1855–1857	Kalahari
			Eastern Cape
			Zimbabwe
1861	M	1860–1862	Kalahari
			Zimbabwe
1862	W	1860–1862	Kalahari
			Eastern Cape
1866	M	1865–1868	Kalahari
			Southern Cape
			Eastern Cape
1871	S	1871 (Latter rains failed)	
1880	W	1880–1883	Kalahari
			Southern Cape
			Zimbabwe
1884	S	1880–1884	Kalahari
1891	VS	1890–1891	
1897	M	1893–1898	Kalahari

The documentary derived rainfall data set for Namaqualand was correlated with historical ENSO low phase events (Quinn and Neal 1987, 1992; Ortlieb 2000). Column 4 identifies when these corresponded with those in surrounding areas (Vogel 1987; Nash and Endfield 2002a; Therrell et al. 2006)

Another important feature of rainfall, which is identified in a number of sources is the failure of what are referred to in the sources as the 'latter rains.' As part of Namaqualand falls into the winter rainfall region the rains which are important for agriculture are those, which fall in the months of September, October and November while the seed is in the ground. In certain years the rains during the middle months of winter are good, allowing for good grazing, but if the so called 'latter rains' do not fall, the harvests fail. The sources identify this as occurring in 1871, 1872, 1880 and 1881 (Cape of Good Hope 1871–1872, 1880–1881).

As the Namaqualand area spans part of the winter rainfall area of the north-western Cape, as well as part of the summer rainfall area of Bushmanland, it is possible that it could have experienced certain drought and wet periods in common with those of both the Kalahari region and the Cape Province. Key, however, is the very noticeable concurrence between all sources consulted for the years *1825–1826; 1833–1835; 1839; 1860–1862, 1865, early 1880s and 1894–1897* (Vogel 1987; Nash and Endfield 2002a). These were extensive years of drought with devastating effects across much of South Africa.

6.2 Droughts in Namaqualand and El Niño Southern Oscillation events

In this study for the Namaqualand region, while not trying to over attribute cause to wet and dry periods, attempts are made to see whether the dry spells identified here correspond to those already identified in previous work on ENSO. It should be noted that not all droughts

in Southern Africa have been linked to El Niño events and droughts can result from other causes, such as intensified anti-cyclonic circulation over southern Africa (Mason and Jury 1997). However, there does seem to be some overlap between certain droughts and the years in which ENSO events have taken place.

The historical climatic chronology derived for the Namaqualand area was compared to the ENSO, low phase events identified by Quinn and Neal (1992) and Ortlieb (2000) (Table 3). The Quinn and Neal record has been cited prolifically, being until recently, one of the only continuous historical records of ENSO. However the validity of this record has been challenged Ortlieb and Macharé (1993; Ortlieb 2000). As a result, both records were used for this analysis, but where the more recent Ortlieb record conflicted with that of Quinn and Neal (1992), the Ortlieb record was given preference (Table 3). Both records identify the low phase events and include a grading of the strength of this event which has been included on the table (Table 3).

Correspondence between 14 drought phases in Namaqualand in the 1800s and low phase ENSO events were identified and in nine of these cases these droughts were widespread affecting surrounding areas too (Table 3). Some severe drought periods in Namaqualand, notably those of 1819–1821; 1834–1839; 1844–1845; 1855–1857; 1860–1862; 1865–1868; 1880–1884 and 1893–1898 stand out as noticeable drought periods which coincide with ENSO events. Another point worth attention is the fact that each of these dry periods also occurred in the Kalahari region (Nash and Endfield 2002a). These findings are neither exhaustive nor conclusive however they may provide some initial points of departure for further detailed studies in ENSO-related research.

6.3 Value of the data set

Despite the limitations of documentary derived data, it is nevertheless felt that this data set is extremely valuable. First, it extends the historical climatic record for southern African into a region not previously researched, that of Namaqualand. Second, it fills a spatial gap between the historical climate studies for the southern Cape and those of the Kalahari region, thus enabling the identification of widespread drought periods the extent of which was not previously recognised. This will be of use to historians, botanists and sociologists conducting research in Namaqualand. Third, it provides an historical climate record which may assist further research into possible links between El Nino events and droughts in southern Africa and extend these back into the nineteenth century.

In addition, availability of this kind of data set allows environmental historians to conduct more detailed research into human-environment linkages. It allows us to evaluate the role of climate, and particularly periods of climate stress, in increasing the vulnerability of a local community, in this case the Leliefontein community of Namaqualand. Access to a climate record for the nineteenth century enables study into whether the climate stresses for the community have changed from the nineteenth to the twentieth century and to assess the role of climate in contributing to impoverishment of this rural community. In addition to this, a climatic background allows research into livelihood changes and other factors, which may have increased the vulnerability of this local community. This is especially important in a semi-arid area where climatic variability is so closely tied to the livelihoods of the local community. A climate data set for the nineteenth century thus allows for a more detailed local level study of drivers of land-use change and factors, which enhance vulnerability of local communities (Kelso in preparation). Many researchers have asserted the necessity for such local level studies that include the role of climate in an integrated environmental history (Beinart and Coates 1995; McCann 1999; Jones et al. 2001; Oldfield et al. 2000;

Beinart 2002; Carruthers 2002). Until now, much of this kind of research has taken place from a purely historical perspective ascribing little importance to the role played by climate and potentially that played by climate change, in affecting local level changes in communities. This kind of local-level climatic data set is therefore seen as hugely valuable in both historical climate research and environmental history.

7 Conclusions

The Namaqualand region is a marginal area that suffers from low and unreliable rainfall with frequent periods of drought. In this paper we have attempted to reconstruct a documentary-derived chronology thereby extending the length of the meteorological data record for this area. Notwithstanding the severe limitations to such research, not least subjectivity in interpretation, several distinctive periods of prolonged dry and wet spells emerge.

The dry years and periods of drought (denoted in italics below) identified for Namaqualand during the nineteenth century were: *1682–1684; 1762; 1805; 1807; 1812; 1817; 1820–1821; 1825–1827; 1834–1836; 1844–1845; 1855–1857, 1860–1862; 1865–1868; 1874–1875; 1880–1883; 1893–1896.* The wetter years were more difficult to identify as there is not as much written about them in the sources. Despite this, the following years were identified as wetter years:*1818; 1822–1823; 1831; 1859; 1872; 1878; 1888, 1899 and 1900*. The most widespread drought years, which coincide with those identified in other similar studies were the droughts of 1820–1821; 1825–1827; 1834; 1861–1862; 1874–1875; 1880–1883 and 1894–1896 (Vogel 1987; Nicholson 1989; Nash and Endfield 2002a).

The drought periods were also compared to ENSO low phase events in order to identify possible coincidence between the droughts and their possible intensification resulting from ENSO events. The drought or dry years which were found to *possibly correspond* with ENSO low phase events were *1819–1821; 1834–1839; 1844–1845; 1855–1857; 1860–1862; 1865–1868; 1880–1884 and 1893–1898*.

The reconstruction of past climate extremes and their impacts enables some understanding and appreciation of the spatial and temporal extent of these events and enables an improved appreciation of past events, their magnitude, frequency, spatial spread and associated impacts:

> ‘By interweaving the many elements that make up climate research, and by continuing to compare and correlate different indicators, our understanding of climates of the past and the present will continue to illuminate and instruct us, and help us prepare for the challenges of future climates’ (Jones et al. 2001, 6).

Of particular value in this paper are the derived sequences of severe droughts and wet spells, particularly those that seem to have been widespread across the country. Despite problems of subjectivity and interpretation of data, this chronology should provide a useful datum for others, such as historical–ecological researchers and those interested in ‘drivers’ of land-use change, to help frame further research into the causes and consequences of global environmental change.

Acknowledgements This research was carried out with the partial assistance of a grant from the European Commission (Contract no. ERBIC18CT970162).

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