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Research paper

Early-nineteenth century southern African precipitation reconstructions from ships' logbooks

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Abstract

Atmospheric circulation in the oceans surrounding southern Africa plays an important role in determining its precipitation. This study uses wind information recorded in ships' logbooks in order to statistically reconstruct summer and winter season precipitation at four southern African weather stations from 1796-1854. The reconstruction was obtained by first relating gridded 8° x 8° NCEP-DOE reanalysis seasonal mean wind vectors in the adjacent oceans to station precipitation. Over a 30-year calibration period (1979-2008), significant correlations between wind and precipitation at Cape Town, Mthatha and Royal National Park showed particular correspondence with those areas with the greatest concentration of logbook observations. Principal Component Regression was used to assess the potential of the dominant patterns of variability in the wind vectors as predictors to reconstruct precipitation. Cross-validation in the calibration period gave confidence that precipitation could be reconstructed at several stations across South Africa, meaning the regression relationships derived in the calibration period could be applied to the gridded seasonal mean logbook data to produce reconstructions of precipitation from 1796-1854. The reconstructions show a degree of correspondence with other regional datasets. For instance, the decade beginning in 1810 was the wettest of the period at Mthatha and Royal National Park, while the 1820s were the driest. At Cape Town, the 1820s were the wettest decade, with drier conditions observed in the 1830s. An index of west-east circulation in the summer season revealed correspondence with two documentary reconstructions of El Niño events and increased westerliness, though this did not always result in drier conditions. Attention is also drawn to the remaining 3000 yet to be digitised English East India Company logbooks which would provide a high-resolution picture of atmospheric circulation back to 1700 in the region under consideration.

Keywords

Ships' logbooks, precipitation reconstruction, southern Africa, climate change, nineteenth century, El Niño

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Introduction

Extended knowledge of inter-annual rainfall variability provides an important context for long-term climate change. Instrumental climate records in southern Africa (Figure 1), however, only become significant in quantity towards the late-nineteenth century, limiting the availability of extended time-series for this region. While natural proxy records from sources such as tree-rings and lake diatoms, and written records from historical documents have added to knowledge of this past variability, their quantity across the African continent and Southern Hemisphere as a whole is sparse in comparison to other regions.

One source of historical climate data with an extensive spatial coverage and high temporal resolution are the meteorological observations held within the ships' logbooks of the European former colonial powers, which have received growing attention in recent years (see for example García-Herrera et al., 2005a; Wheeler and García-Herrera, 2008). Since the release of the Climatological Database for the World's Oceans (CLIWOC), these marine data have been used to reconstruct a range of climatological phenomena. Wind observations in particular have been used in reconstructions of the North Atlantic Oscillation (Jones and Salmon 2005), North Atlantic sea-level pressure fields (Küttel et al., 2010), and atmospheric circulation in the English Channel (Wheeler et al., 2010). Furthermore, in the Southern Hemisphere, Neukom et al. (2013) used gridded CLIWOC-ICOADS wind data (Küttel et al., 2010) from 1834 onwards to provide an independent verification for a 200-year southern African multi-proxy precipitation reconstruction. This paper incorporates observations from the English East India Company (EEIC) (Brohan et al., 2012) and CLIWOC datasets in order to statistically reconstruct seasonal station precipitation in southern Africa from 1796-1854.

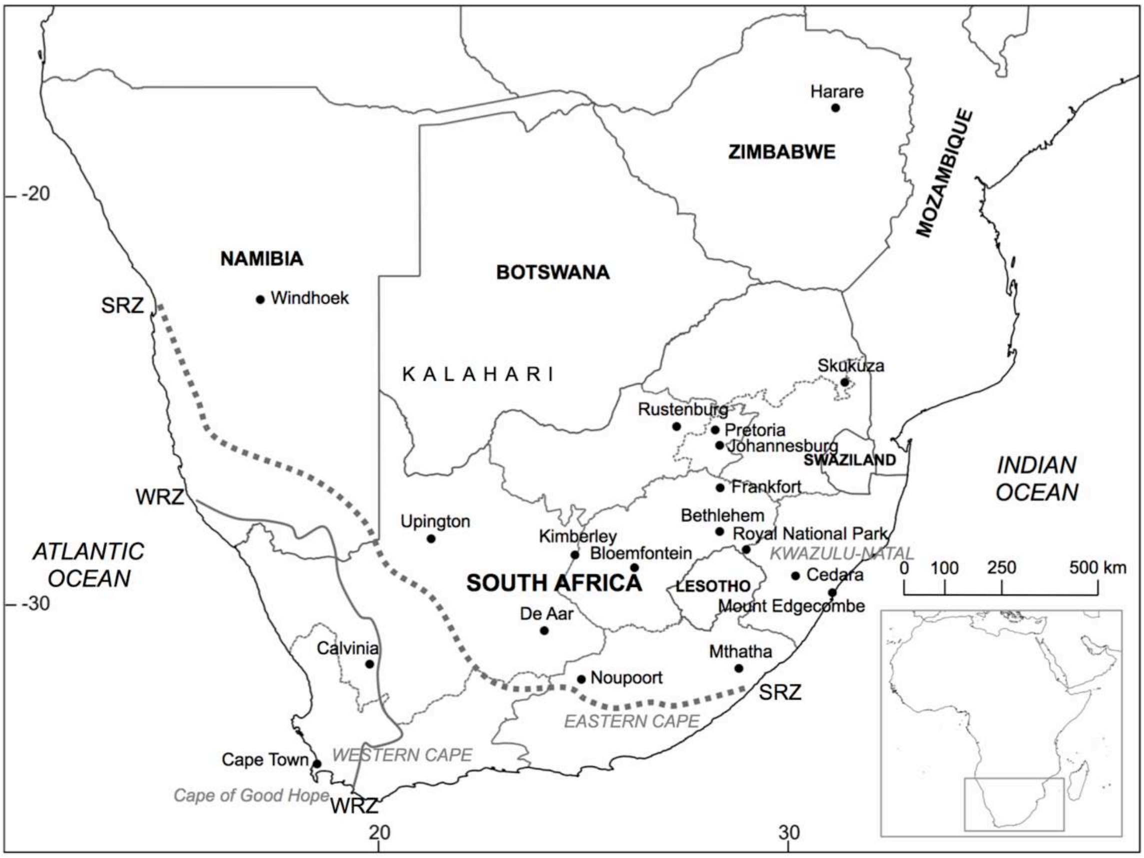

Figure 1. Map of southern Africa. Dots indicate station precipitation records used in the study. The dotted line indicates the Summer Rainfall Zone extent, the solid line shows the Winter Rainfall Zone extent.

Situated at the interface of the temperate, subtropical and tropical climate zones, as well as the Indian, Atlantic and Southern Oceans, southern Africa is influenced by several atmospheric and oceanic systems. These are shifts in the Inter-Tropical Convergence Zone (ITCZ), the mid-latitude westerlies, sea-surface temperatures (SSTs) and the development and position of continental and oceanic anticyclones. Moreover, these modulating influences are reflected in climate modes such as the El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Southern Annular Mode (SAM) and their interplay (Nash and Endfield, 2002; Neukom et al., 2013).

Rainfall distribution in this region has a marked seasonality, with two main zones making up the annual rainfall cycle (Fig 1). In the east and the interior the Summer Rainfall Zone (SRZ), defined as where ≥66% of mean annual precipitation falls between October and March, receives precipitation associated with the southern edge of the ITCZ and easterly airflow from the Indian Ocean (Nash and Grab, 2010; Stager et al., 2013). In the southwest, the comparatively small Winter Rainfall Zone (WRZ), with ≥66% of its precipitation falling between April and September, receives its rainfall from temperate frontal systems as the westerlies migrate equatorward each winter (Chase and Meadows, 2007; Reason and Jagadheesha, 2005). Between these two zones is a narrow area that receives year-round precipitation (Chase and Meadows, 2007). Pronounced spatial variability in rainfall totals is present in the SRZ, where the dominance of anticyclonic conditions means that much of east and central South Africa derives its moisture from air masses moving in from the southwest Indian Ocean. Its distribution, however, is strongly influenced by topographic variations. As these air masses move westward, much moisture is lost over the SRZ due to orographic effects associated with the eastern highlands. This manifests in a pronounced east to west gradient in rainfall levels, further enhanced by the arid conditions arising from the cold Benguela current off southwest Africa.

As a result of these influences, high inter-annual variability of rainfall levels exists. Wetter or drier seasonal conditions are predominantly associated with changes in the frequency, intensity and persistence of rainfall-producing weather systems (Mason and Jury, 1997; Ratna et al., 2013). In the SRZ, synoptic-scale tropical-temperate trough systems and their associated cloud bands are a dominant contributor to seasonal rainfall. A major moisture source for tropical-temperate trough development is via easterly winds from the adjacent Indian Ocean, with strengthened easterly winds resulting in stronger moisture fluxes toward southeast Africa (Ratna et al., 2013). Inter-annual variability in the WRZ, in contrast, is influenced by the strength of the winter storm systems forming over the South Atlantic and Southern Ocean (Chase and Meadows, 2007).

As regional rainfall-producing systems are in turn related to changes in atmospheric circulation around southern Africa (Mason and Jury, 1997; Todd et al., 2004; Williams et al., 2007), the marine observational data held within ships' logbooks provide a unique means of statistically reconstructing past precipitation variability. Although the coastal areas of the region are particularly sensitive to these influences, it is important to note that the logbooks capture regional atmospheric circulation rather than maritime climate alone, and thereby offer reconstruction potential further inland, as is later shown by the calibration and validation statistics. By providing direct measurements, logbooks possess a significant advantage over proxy-based sources. They also differ from other documentary sources as they recorded information on airflow and circulation variations over a wide spatial area, factors important in any explanation of changes in past precipitation patterns (Wheeler et al., 2010).

The next section describes the data sources used, their pre-processing and the reconstruction methodology. The results section analyses the reconstruction skill of the wind data and presents the findings from the rainfall reconstructions, while the discussion compares the results to other regional precipitation records and documentary reconstructions of El Niño events.

Data and methods

Wind direction and wind speed observations from ships' logbook data were used to statistically reconstruct seasonal precipitation at southern African weather stations from 1796-1854. As there is no overlap of the early-nineteenth century logbook data with the instrumental station measurements, reanalysis data were first used to determine the statistical relationship between wind and precipitation in the area.

Data

Reanalysis data. The wind data used to assess the relationships between wind and precipitation were taken from the NCEP-DOE Reanalysis 2 dataset (Kanamitsu et al., 2002). The reanalysis assimilates available observations, including pressure, temperature, and humidity using model forecasts, providing a physical picture of the climate at consistent time-steps from 1979 onwards. The climatological variables used in the study were the u- (west-east) and v- (south-north) components of the wind. These were selected as the most common weather observations in the logbooks are wind direction and force. The u- and v-wind components were re-gridded to an 8° x 8° latitude-longitude grid. Similarly to Gallego et al. (2005) Jones and Salmon (2005) and Küttel et al. (2010), this resolution was chosen in order to obtain a balance between incorporating as high a data density as possible in the corresponding logbook data, without obscuring or oversimplifying the spatial relationships between marine wind and continental rainfall. Both a 2° x 2° and 5° x 5° resolution were tested in a sensitivity study (not shown), and while the spatial extent of significantly correlated grid boxes was slightly wider, the coverage of the logbook data in each grid box was inadequate to produce seasonal aggregations. The spatial domain used was also determined by the availability of digitised logbook data in the historical period (Figure 2; Figure S1); this is discussed in the ships' logbook wind data section.

Station data. The station precipitation records were obtained from both the South African Weather Service and the Global Historical Climatology Network. Stations were only selected which had complete precipitation records for the period 1979-2008 (Figure 1; Table S1). This period was chosen as many station records have significant gaps in the preceding decades. This applies to much of KwaZulu-Natal and the portion of the Eastern Cape that falls within the SRZ, areas which are particularly sensitive to variability in atmospheric circulation over the oceans (Mason and Jury, 1997; Tyson and Preston-Whyte, 2000). Additionally, given that this recent period marks the beginning of satellite data entering the reanalysis, and a higher input of observational data, it is likely that the data are of a superior quality to that which precedes it. To select the stations where marine wind influences are significant, the 8° x 8° seasonally resolved NCEP-DOE wind vectors within the study domain were correlated with the station data. Both datasets were detrended before correlation. Of the total 19 stations with significant correlations at $p < 0.05$ (Figure 1), 15 are located within the South African portion of the SRZ, with two stations in the WRZ. This gives a relatively wide spatial coverage of areas most influenced by tropical-temperate systems and the westerly storm tracks, with several stations located in most of the South African provinces.

Ships' logbook wind data. The keeping of logbooks by ship officers was an important duty. All matters relating to the navigation of the ship were recorded at daily or sub-daily intervals, helping to ensure that the ships could transport goods as quickly and safely as possible (Ward and Wheeler, 2013). Few such matters were more critical than the wind, weather and state of the sea, which played a large part in determining the speed and direction of the ship. Recently, digitisation of this climatic information in the thousands of logbooks held in archives in the UK, Spain, Netherlands and France resulted in the development of the CLIWOC project (García-Herrera et al., 2005a; Können and Koek, 2005). The current version 2.1 of this database holds 281,920 records between 1662-1855, with 99.6% of available data falling between 1750-1855.

In addition to CLIWOC, the later digitisation of 891 EEIC logbooks provided a further 273,000 records of a similar spatial extent between the years 1789-1834.

Similarly to the distribution of modern marine data, observations from these digitisation projects cluster predominantly along established strategic routes, leaving certain areas, such as the Atlantic and Indian Oceans densely covered with data points, and others, like the Pacific, data deficient. One route covered in both datasets was the voyage from England to India and China, which generally took around two years. Before the opening of the Suez Canal in 1869, sailing ships travelling between England and the Indies had to follow a route constrained by the global wind fields. This meant sailing southwest through to the Southern Hemisphere westerlies, rounding the Cape of Good Hope, and then using either the Mozambique Channel or the westerly winds between 35-40°S before sailing north to India or China (Figure 2). The return voyage was a direct route round the Cape using the easterly trades, north west into the mid-Atlantic and then to England with the westerlies (Brohan et al., 2012). The oceans surrounding South Africa are consequently among the global areas with the highest data density, while the fact that the routes necessarily followed circulation systems makes the data suitable for reconstructing circulation-related variables, offering a previously unprecedented insight into the weather and climate of the late-eighteenth and early-nineteenth century.

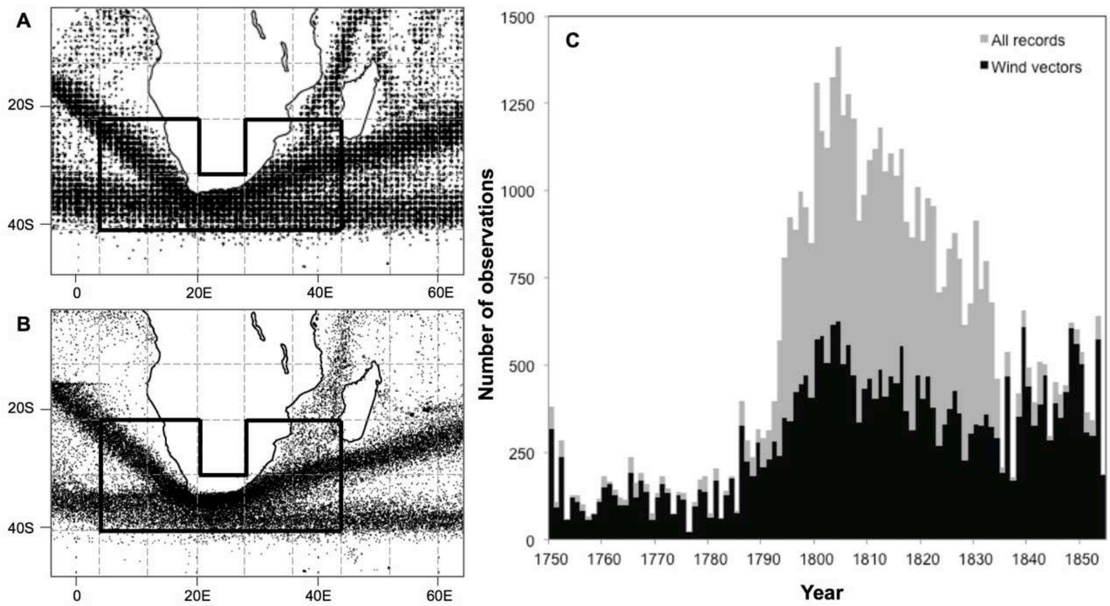

Figure 2. A) distribution of English East India Company observations (1789-1834). B) distribution of CLIWOC observations (1750-1854), the solid line indicates the gridded 8° x 8° domain of the study. C) annual frequency of logbook observations within the domain, showing all records (grey) and records with complete wind vector information (black).

The spatial domain was determined by the availability of logbook observations. Following the methodology of Gallego et al. (2005), Jones and Salmon (2005), Küttel et al. (2010), and Neukom et al. (2013) the logbook observations were averaged and aggregated to seasonally resolved 8° x 8° grid boxes to ensure that meaningful wind information of a high enough density was present, and were thereafter transformed into the u- and v-components of the wind. The domain thus covered the oceanic areas between 25-41°S and 4-52°E. A total of 56,042 records were obtained in this area between 1750-1854 from the combined datasets. Only records with complete information on date, coordinates, wind direction and wind speed were used, lessening the total to 31,367. This high number of missing wind direction and/or speed records (Figure 2) is only present in the EEIC data, where budget constraints meant that digitisation priority was given to the pressure and temperature data in the logbooks (Brohan et al., 2012). Nevertheless, the wind vector data incorporated from the EEIC collection provides a significant amount of data for the early-nineteenth century where data density was previously insufficient (Neukom et al., 2013).

The observations recorded in logbooks were generally taken at the local noon. Three categories common to all observations are wind direction, wind speed and general descriptions of the state of the weather, the first two of which are of particular interest. These records were converted to the International Marine Meteorological Archive format (Woodruff, 2007), requiring several corrections which were made prior to release of the data.

Each of the observations are spatially and temporally referenced by date and coordinates. Longitudes, typically determined by dead-reckoning, were corrected to present-day coordinates. Wind direction was usually recorded on a 32-point magnetic compass, using expressions such as north-west-by-west. As instrumental data these contain little ambiguity, but were converted from the magnetic north to the true north (see Brohan et al., 2012; Wheeler et al., 2010). Wind speed observations are prone to a higher degree of subjectivity in their recording as they were estimated by reference to the state of the sea. Standardised vocabulary for assessing wind force was not in place until the adoption of the Beaufort Scale in the 1830s, yet even prior to this sailors were consistent in their description of the winds (Ward and Wheeler, 2013; Wheeler, 2005). This meant that wind force terms could be quantitatively re-expressed in modern Beaufort force equivalents using the multilingual CLIWOC wind force dictionary, and then to 10-m winds in ms^{-1} (see Wheeler, 2005; Wheeler and Wilkinson, 2005). Of the descriptive wind speed terms in the CLIWOC database, 99% could be converted to Beaufort Scale equivalents, while this figure was around 80% for the EEIC data. Statistical investigation into the quality of these data by comparing observations from vessels sailing in convoy was performed by Wheeler (2005), the data were found to be highly reliable. For further details on wind direction and speed measurements and their corrections and conversions, the reader is referred to García-Herrera et al. (2005b); Wheeler and Wilkinson (2005) and Brohan et al. (2012). The digitised data from the EEIC do also provide some instrumental records, including thermometer and barometer observations. These data will not be considered here, however, as the pressure data, which may be used to infer precipitation, are generally too sparse to be used in a reconstruction.

Logbook data pre-processing. As previously stated, the oceans adjacent to southern Africa are relatively well-covered with logbook observations in comparison to oceanic areas surrounding most other landmasses. Nevertheless, using spatially and temporally variable data requires careful data pre-processing. Figure 2 displays the inter-annual variability in the number of CLIWOC-EEIC records. From 1796 onwards the available wind vector records in the study domain mostly exceed 300 annual observations, with peaks of well over 500 records around the turn of the nineteenth century and in the late 1840s. Minimum availability is observed in the 1830s, though most of this is accounted for by less austral winter voyages, meaning observations in the austral summer months remain generally consistent throughout the period. Intra-annual availability of observations is also variable. October has consistently low numbers of records, and therefore was omitted from the SRZ reconstructions, which consist of the austral summer months of November-March. This did not significantly alter summer rainfall totals as there is generally less rainfall in October than all other months in the SRZ rainy season. Six months (April-September) were used for the WRZ.

Given the inter-annual variability in the quantity of observations, it is important that a compromise is reached between maximising the number of seasonally-resolved grid boxes, and increasing the signal-to-noise ratio of the wind data (Küttel et al., 2010). This means that the true wind conditions are assumed to be well-captured by the available records at a specific grid box during a particular year. To reduce the noise component due to undersampling, Küttel et al. (2010) and Neukom et al. (2013) used a threshold where only seasons with at least three records in each 8° x 8° grid box were used. In this case, owing to the increased data coverage with the additional EEIC data (see Figure S1), grid boxes are only included where an absolute minimum of one-tenth of seasonal days have observations. Where this was not the case, grid boxes were longitudinally interpolated from adjacent grid boxes exceeding this threshold based on the difference between their corresponding 1979-2008 mean in the NCEP-DOE reanalysis data. Higher thresholds were tested, but these did not improve the resolved variance in the reconstructions (not shown).

Precipitation reconstructions.

To establish regression models between wind and precipitation at various southern African stations, reanalysis wind data were used. The wind data were tested for suitability as precipitation predictors by correlating the gridded NCEP-DOE wind vectors against each of the station records obtained (Figure 1) over the period 1979-2008. Both of these datasets were first detrended to avoid potential spurious correlations due to timeseries having unrelated trends. The four stations with the highest r values from the correlation for u-wind are shown in Figure 3, while v-wind gave less significant results for the majority of stations and was consequently omitted (not shown). The plots are consistent with the discussion in the first section, and show that strengthened easterliness (lower u-wind) in the southwest Indian and southeast Atlantic Oceans is correlated with increased precipitation in the 'rain-year' months of November-March at SRZ stations. By contrast, strengthened westerliness (higher u-wind) in the southeast Atlantic is significantly correlated with higher precipitation in the WRZ rainy season months of April-September. These results show an influence of large-scale atmospheric circulation on precipitation in these regions, and link to wind speed and direction over adjacent oceanic areas. Importantly, these grid cells correspond with those in the path of the major shipping routes, and are thus suitable predictor variables to allow for statistical reconstructions.

For each station, the grid boxes significantly correlated at $p < 0.05$ were selected for the reconstructions. Principal Component (PC) analysis was performed over these areas, meaning the variables were reduced to a dataset containing fewer variables which separated the dominant patterns of spatial variability from unnecessary noise, and importantly were not correlated. Non-detrended seasonal mean u-wind data were used to perform the PC analysis in the domain, as the statistical relationships derived here are later applied to the seasonally aggregated logbook wind data. The first PC explains most of the variance in the significantly correlated areas of the u-wind data for each station record at 73% for Mthatha, 85% for Royal National Park, 78% for Mount Edgecombe, and 53% for Cape Town (Table S1 gives the full list). It also gives the highest correlation values with station precipitation. Principal Component Regression (PCR) was then used to reconstruct precipitation (see Luterbacher et al., 2002 for a full outline of this technique). The calibration with the predictand was performed over the period 1979-2008, where the greatest number of stations with complete records is available. For independent verification of the reconstruction, cross-validation was used (Wilks, 2005), as the 30-year period would be inadequate if a substantial portion of it was reserved for a validation sample. This technique repeatedly divides the data into calibration and short validation data subsets, meaning the PCR was performed 30 times, each time estimating a different year not included in the calibration data. Two years on either side of the validation year were left out, meaning that the reconstructed time step is uncorrelated with all time steps used for model calibration. The final model for the reconstructions was therefore calibrated using data for each of the 30 years, which were concatenated to produce a validation record. The performance of the statistical reconstruction was first assessed by calculating Reduction of Error (RE) skill scores (Cook et al., 1994). RE scores range from $-\infty$ to $+1$, where 1 indicates perfect agreement with the predictand, the station data, 0 means that the reconstruction is as good as the climatology, and negative RE scores indicate that the reconstruction contains no meaningful information. Second, the reconstructed timeseries from the wind data were correlated with the observed precipitation.

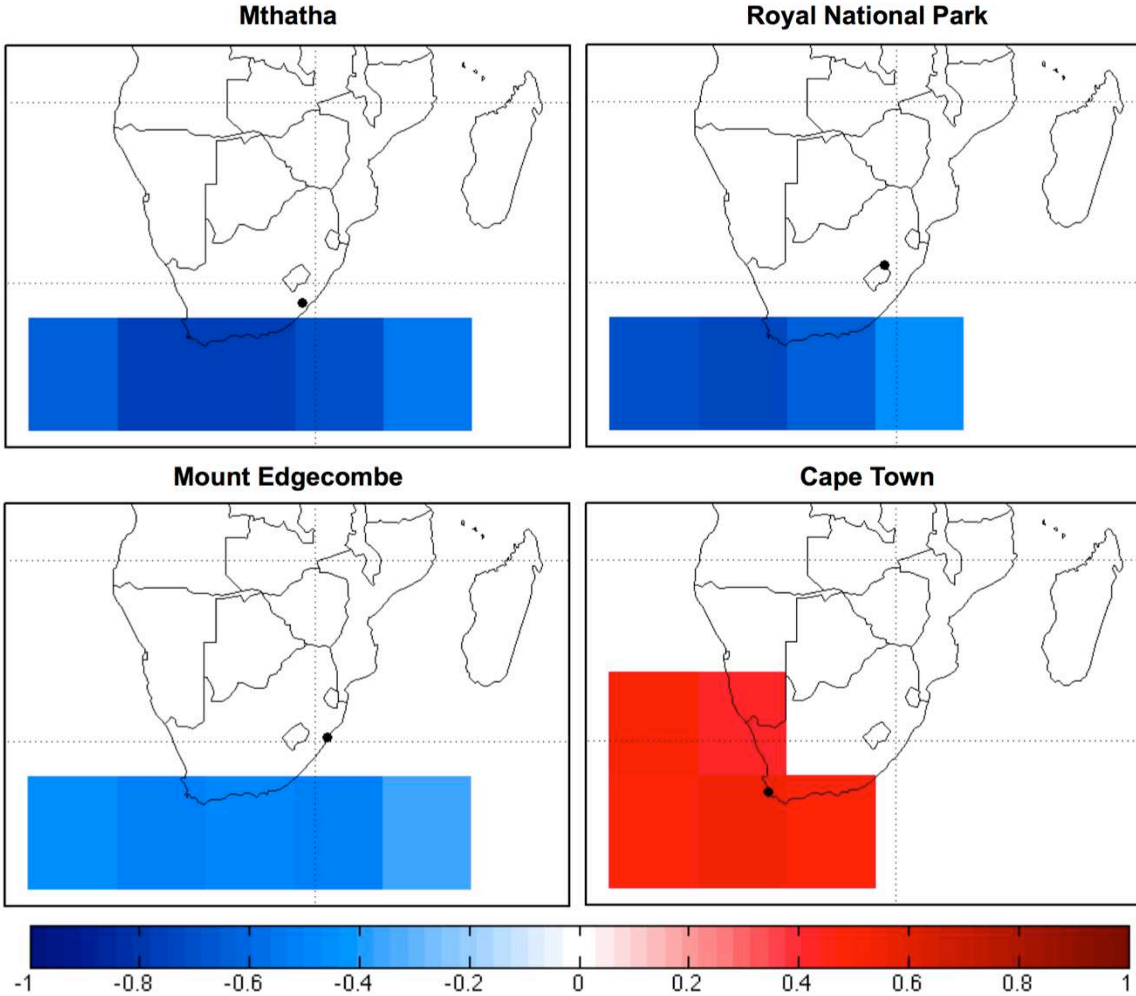

Figure 3. Correlation of the detrended NCEP-DOE Reanalysis 8° x 8° u-wind and detrended station precipitation 1979-2008. Only squares with statistically significant correlations ($p < 0.05$) are shown. Note that Cape Town uses winter rainfall months (AMJJAS).

Results

Reconstruction skill.

The reconstruction skill of u-wind is spatially variable. The highest RE scores are observed for those stations with the greatest number of significantly correlated grid boxes included as predictors, with Cape Town and Royal National Park each having values ≥0.4, and Mthatha >0.6 (Figure S2 and Figure 4). While Royal National Park is considerably further inland than Cape Town or Mthatha, the data recorded in the logbooks capture not only maritime climate, but the regional atmospheric circulation which is important for precipitation at this station (Mason and Jury 1997; Reason and Jaghadeesha 2005). Weaker, though positive RE values were observed further inland, with only Windhoek displaying no reconstruction skill. This is most likely due to the greater influence of the strength of the southeasterly trades in the eastern South Atlantic on precipitation at Windhoek, an area which was excluded from the analysis domain. Reduced reconstruction skill is likely to be a consequence of other forcing mechanisms and local effects explaining precipitation variability which the PCs do not capture, while most of the inland stations are much drier than those in the coastal and south-east areas of South Africa. Similarly to the RE, the highest correlation coefficients are observed at Mthatha ($r = 0.78$), Cape Town ($r = 0.63$) and Royal National Park ($r = 0.67$). these stations were chosen to be reconstructed, but nine other stations also have significantly correlated timeseries' at $p < 0.05$ (Table S1).

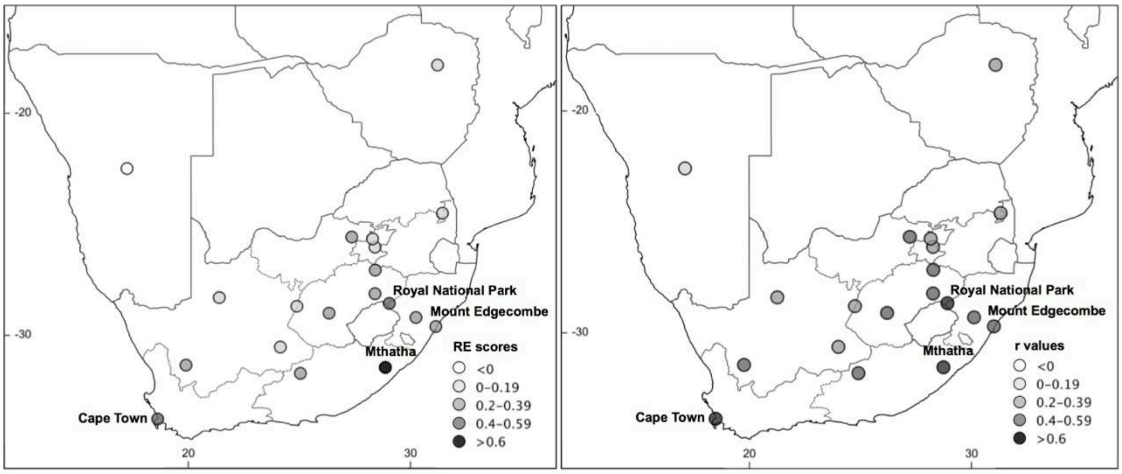

Fig. 4 Calibration period-derived Reduction of Error skill scores (left) and correlation coefficients (right) for selected stations across the Summer and Winter Rainfall Zones.

Precipitation reconstructions

The summer season precipitation reconstructions for Mthatha and Royal National Park, derived from applying the statistical relationships established in the calibration period to the logbook data, are shown in Figure 5. The axis years are dated by the November and December months but refer to the entire SRZ 'rain-year'. The thin black line shows the inter-annual values, while the thicker black line is the 7-year running mean. The grey error bars are confidence intervals, which cover the true value with a probability of 95%. They are defined as ±1.96 standard deviations of the residuals from the model calibration as during the calibration period about 95% of the true precipitation values lay inside an interval of this size. As just one 8° x 8° grid box was the difference between the predictor networks for the two SRZ stations in Figure 5, the reconstructed inter-annual values are very similar, while the reconstruction for Mount Edgecombe displayed an identical curve to Mthatha as the predictor network was the same and is therefore not shown.

Although all decadal anomalies for the SRZ stations are within the error bars relative to the 1979-2008 mean (±147.6 mm),. t-tests were conducted to test whether the difference in mean decadal conditions is significant. For the SRZ stations, the decades beginning in 1810 and 1820 were statistically significantly different ($p < 0.02$), with the 1810s being wetter than the 1820s, while no significant difference was found between the other decades. The most severe dry conditions (exceeding -1 standard deviations from the 1979-2008 mean) were 1796-97, 1805-06, 1820-21, 1826-28, 1829-30, 1831-32, and 1841-42. The wettest years (exceeding +1 standard deviations from the 1979-2008 mean) were 1812-13, 1818-20, 1830-31, 1835-36, and 1845-46.

At Cape Town (Figure 5), in the WRZ, conducting t-tests on the decadal differences revealed that the 1820s and 1830s were significantly different ($p < 0.025$); the 1820s being wetter than the 1830s, although three years in the 1830s had too few wind observations to reconstruct precipitation. No significant difference was found between the other decades in the period. Pronounced dry conditions (below -1 standard deviations from the calibration period mean) were reconstructed in the WRZ rain season in 1806, 1808, 1812, 1818, 1820, 1832, 1836, 1840 and 1847. Wetter conditions (exceeding +1 standard deviations from the calibration period mean) were observed in 1801, 1804, 1813, 1824, 1827, and 1849 and 1850.

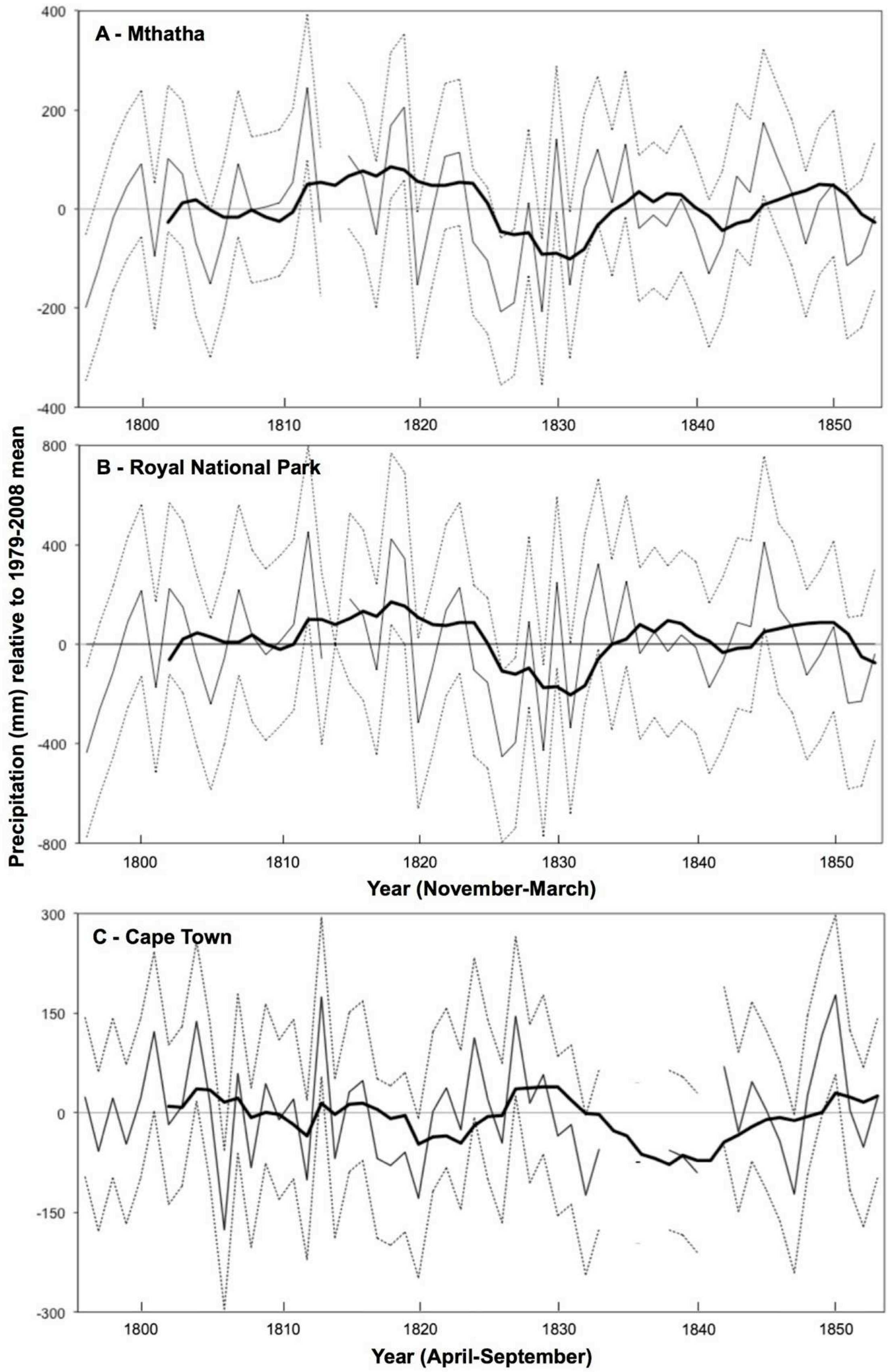

Figure 5. Reconstructed 1796-1853 November-March precipitation for A) Mthatha, B) Royal National Park, and C) reconstructed April-September precipitation for Cape Town. The thin black line indicates the inter-annual precipitation given as the difference from the 1979-2008 mean (note the difference between the three y axes). The thicker black line is the 7-year running mean. The thin grey lines show the 95% confidence intervals. The SRZ station years are dated by the Nov/Dec.

Examination of the changing variability in the reconstruction period was conducted by calculating the 7-year running standard deviation. For the Mthatha reconstruction (Figure 6), f-tests revealed 1820-21 to 1836-37 as a period with consistently high rainfall variability, being significantly different at $p < 0.001$ from periods between 1803-04 to 1819-20 and 1837-38 to 1853-54, where reduced rainfall variability was observed. For Cape Town, variability was fairly constant throughout the reconstruction period (Figure S3). In order to further examine the wind patterns associated with the reconstructed precipitation variability, summer and winter indices of atmospheric circulation were produced.

Atmospheric circulation

Indices of atmospheric circulation within the grid box domain of influence for the reconstructions were constructed by aggregating the wind direction observations to the four cardinal compass points, as demonstrated by Wheeler and Suarez-Dominguez (2006). These combined to produce measures of the proportional frequency of days with winds blowing from the east and west, giving further insight into the circulation dynamics influencing precipitation (Figure 6 and Figure S3). This technique also yielded some extra wind information from the EEIC data, as some of those data with only wind direction *or* wind speed records could be utilised where this was not possible in the reconstructions.

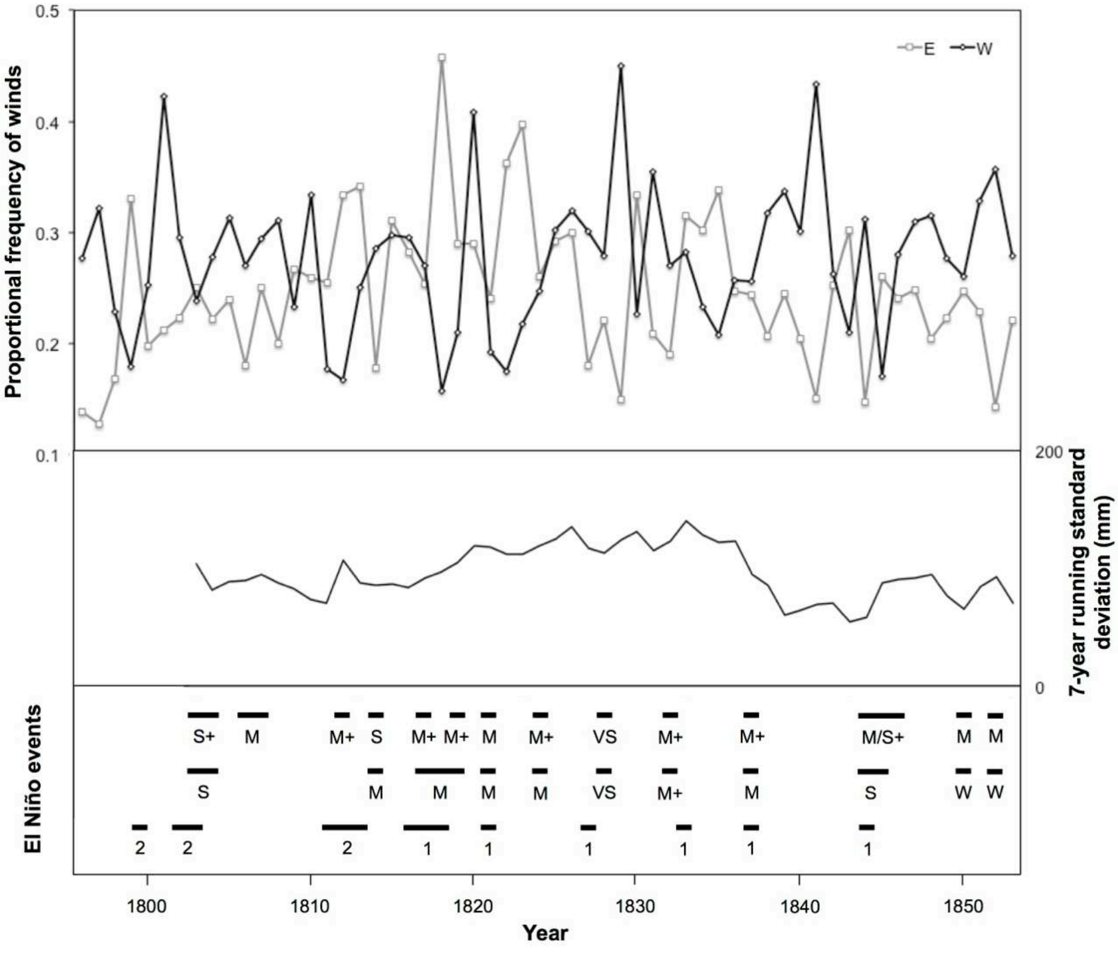

Figure 6. Proportional frequency of November-March zonal winds in the leading Principal Component for the Mthatha grid boxes (upper panel), 7-year running standard deviation for precipitation at Mthatha (middle panel), and El Niño events identified by Quinn and Neal (1995) (top), Ortlieb (2000) (middle) and Garcia-Herrera et al. (2008) (bottom): M – moderate, S – strong, VS – very strong (lower panel); 1: possible El Niño and 2: probable El Niño.

Figure 6 shows the proportional frequency of winds from the east and west in the area of the leading PC for Mthatha (shown in Figure 3). As previously outlined, when the easterly component of the wind is stronger, precipitation at Mthatha is higher, while increased westerliness is associated with reduced precipitation. From the beginning of the reconstruction period to 1810-11, westerliness exceeds easterliness in all except three years. This situation is reversed in the period 1810-11 to 1824-25, where 10 out of 15 years are characterised by a higher proportion of winds from the east. Following this, easterliness exceeded westerliness in only six of the years to 1853-54. The period of increased reconstructed precipitation variability between 1818-19 to 1836-37, identified in the running standard deviation, can therefore be linked to highly variable shifts in the zonal wind. In comparison, the winter season wind direction index (Figure S3) shows a relatively consistent proportional frequency of westerly and easterly winds throughout the period. These findings are now discussed in comparison with other regional rainfall reconstructions and possible ENSO forcing.

Discussion

Comparison with other regional records

The precipitation reconstructions can be directly compared with other southern African records of early-nineteenth century rainfall variability with inter-annual resolution. The records selected for comparison with our analysis are the multi-proxy records for the SRZ and WRZ (Neukom et al., 2013), which are made up of various documentary, instrumental and natural proxy records, the semi-quantitative documentary-derived rainfall records for Lesotho (Nash and Grab, 2010), the Eastern and Southern Cape (Vogel, 1989), and the Western Cape proxy-documentary wetness index produced by Nicholson et al. (2012). Those for the SRZ are compared with the Mthatha reconstruction in Figure 7.

Though correlation between SRZ records is statistically insignificant, the comparison of records reveals some correspondence on both inter-annual and decadal scales. The period to 1810 had two major dry spells, the summers of 1796-97 and 1805-06, which are picked up by both records. The latter is also noted by Eldredge (1992) in the contemporaneous written accounts from KwaZulu-Natal. Although wetter conditions are observed in both the logbook and multi-proxy records between 1810-20, little inter-annual correspondence is present excluding the normal conditions in 1811-12 and the wet summer of 1818-19. The 1820s was the driest decade in the period in both the logbook reconstruction and the SRZ multi-proxy record, although the latter still received slightly above average precipitation. The drier years in the Mthatha record are towards the late 1820s, which agrees with the Eastern Cape record (Vogel, 1989). The drier years in the multi-proxy reconstruction, however, are shown to be at the beginning of the 1820s, while very little correspondence is observed with the Lesotho chronology beginning in 1824. Improved coherence between records is observed in the 1830s, particularly with the multi-proxy and Lesotho records. The summer of 1830-31 was wet at Mthatha and in the multi-proxy reconstruction, while wet summers were observed in these records in 1832-34 and 1835-36. In the late 1830s, normal to relatively dry conditions prevailed at Mthatha and in the multi-proxy record. Agreement with the Lesotho record is shown in the relatively dry summer of 1837-38, while the documentary Eastern Cape chronology gives very dry conditions for these years. The 1840s showed reasonable correspondence between records, with the drier summer of 1842-43 reflected in all four records being followed by three wetter summers (1842-46), each of which are picked up by the multi-proxy record, two by the Eastern Cape record, though only one by the Lesotho chronology. Relatively drier conditions are registered in each record except for the Eastern Cape at the beginning of the 1850s. In addition, two of the three southern Africa-wide droughts identified by Kelso and Vogel (2007) in this period were reflected in the SRZ logbook reconstructions, those in 1820-21 and 1825-27.

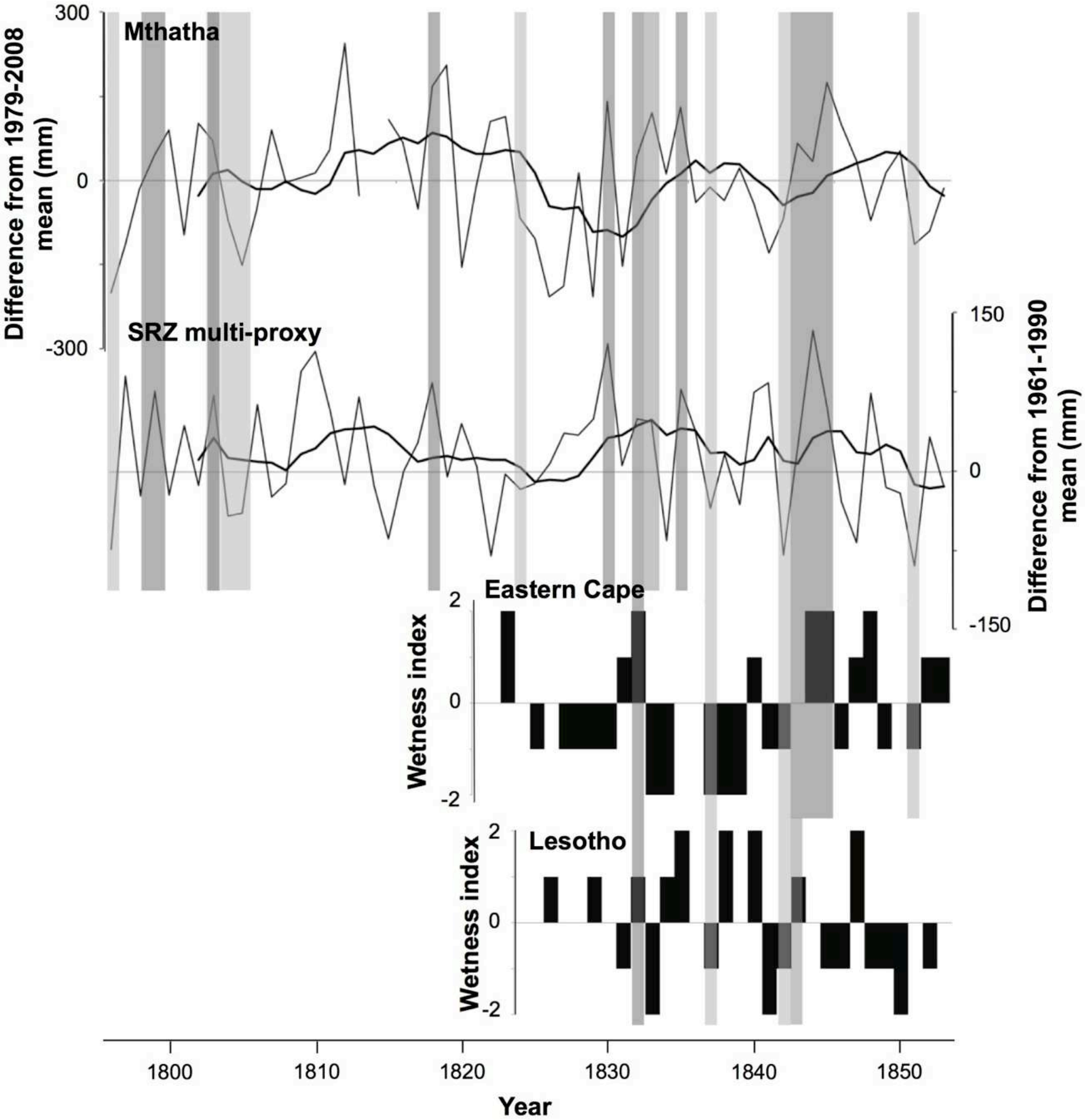

Figure 7. Comparison of the Mthatha reconstruction and other Summer Rainfall Zone reconstructions. The Summer Rainfall Zone multi-proxy is from Neukom et al. (2013), the Eastern Cape and Lesotho records are reconstructed from documentary evidence by Vogel (1989) and Nash and Grab (2010) respectively. The scale of the documentary reconstructions ranges from 2 (wet) to -2 (dry). The darker shaded bars extending across the plots indicate inter-annual correspondence of wetter conditions in the records, and the lighter bars correspondence of drier conditions. Note the difference in reference mean periods of the logbook and multi-proxy reconstructions.

The regional comparison of records for the WRZ is shown in Figure 8. Again, a statistically insignificant correlation is present between the Cape Town and multi-proxy record, which for the overlapping period is comprised of the Die Bos tree-ring record (Dunwiddie and Lamarche, 1980) and two documentary datasets (Kelso and Vogel, 2007; Vogel, 1989). Lower frequency variability indicated by the 7-year running mean shows slightly better correspondence, with both records showing a decrease in precipitation in the 1830s, and increasing precipitation towards the end of the record. The longest other contemporaneous inter-annual record from the WRZ is the proxy-documentary record marked as region 84 in the wetness index by Nicholson et al. (2012). Correlating the wetness values with the logbook reconstructed precipitation record gives a weakly significant value of $r = 0.23$ ($p < 0.10$).

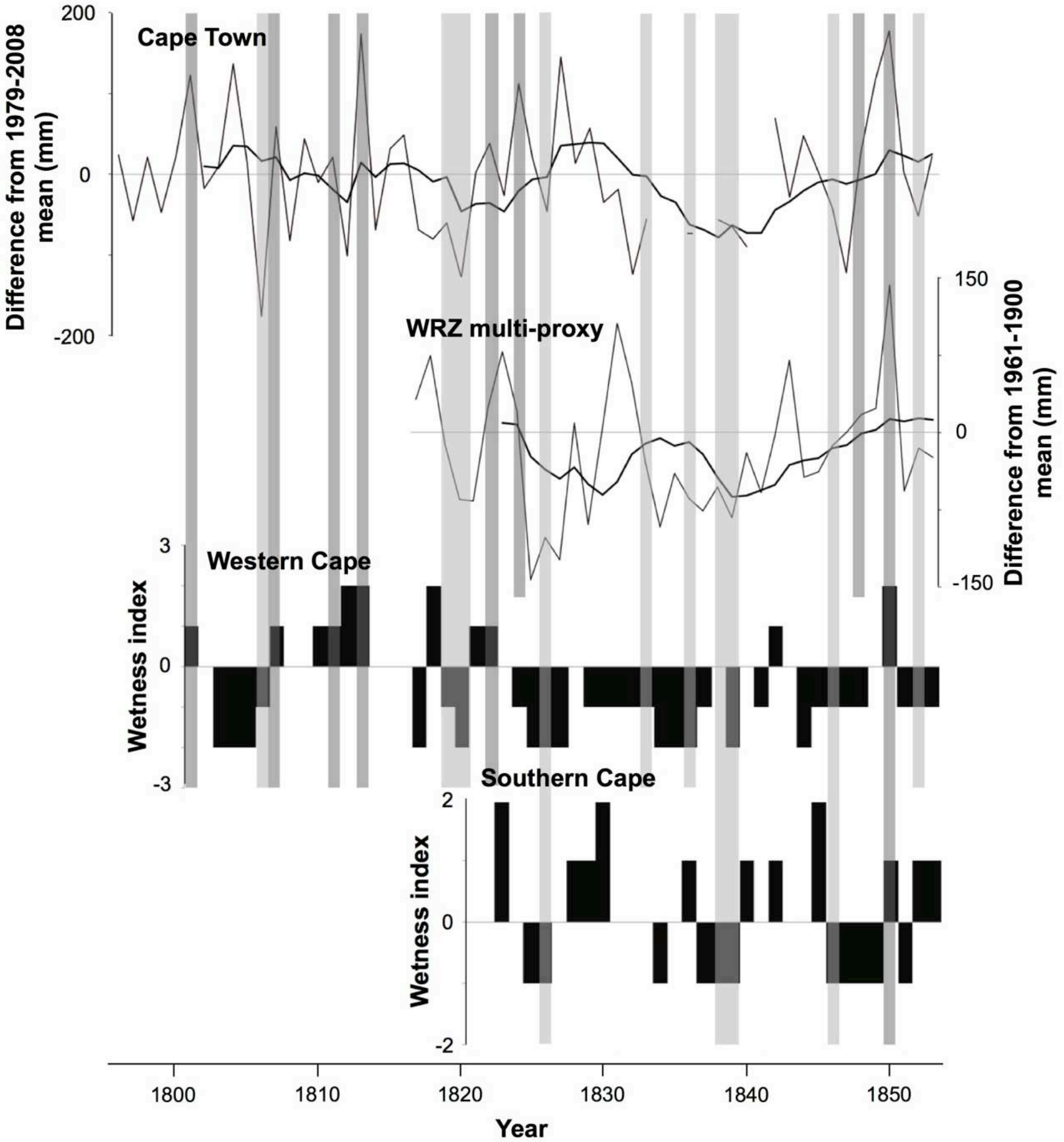

Figure 8. Comparison of the Cape Town reconstruction and other Winter Rainfall Zone reconstructions. The Winter Rainfall Zone multi-proxy is from Neukom et al. (2013), the Western Cape and Southern Cape records are reconstructed from documentary evidence by Nicholson et al. (2012) and Vogel (1989) respectively. Note that the scale of the documentary reconstruction for the Nicholson et al. (2012) reconstruction ranges from 3 (very wet) to -3 (very dry), while that of Vogel (1989) ranges from 2 (wet) to -2 (dry). The darker shaded bars indicate inter-annual correspondence of wetter conditions in the records, and the lighter bars drier conditions. Note the difference in reference mean periods of the logbook and multi-proxy reconstructions.

Relatively normal precipitation relative to the 1979-2008 mean prevailed at Cape Town until 1812, with two anomalously wet years (1801 and 1804) and one very dry winter (1806), two of which are picked up by the Western Cape proxy-documentary record (Nicholson et al., 2012). Relatively dry conditions were present until 1821, with notably drier conditions occurring in the available WRZ records at this time shown in Figure 8 in the winters of 1819 and 1820. Conditions were relatively wet until 1824, with coherence between the Cape Town and multi-proxy records observed in 1822 and 1824. The multi-proxy and documentary reconstructions then show a three-year dry period, in which two of these years are not reflected in the logbook reconstruction. Little agreement is present between records from 1829-1832, however, the mid- and late-1830s show the greatest correspondence between records, with very dry conditions occurring in most years. Unfortunately, some winters were unable to be reconstructed from the logbook data as the data density was poor, though those that were reconstructed were consistently lower than the 1979-2008 mean. Conditions were relatively variable towards the end of the reconstruction, with some dry years, notably 1846, reflected across each of the records. 1850, a very wet year in the WRZ, was also reflected across each of the four records shown.

Although some correspondence is found between the records, inter-annual variability often differs, with occasional notable differences between certain reconstructions. A major reason for this may be that the multi-proxy data are composed of very different sources influenced by various forcing mechanisms across a wide spatial area, each of which may have a local bias. For instance, in the SRZ, the tree-ring chronology from Zimbabwe by Therrell (2006), representative of ITCZ-forced precipitation levels, and the Ifaty Reef Indian Ocean coral record by Zinke et al. (2004), sensitive to changes in sea-surface temperatures, were combined with documentary records from Lesotho, the Eastern Cape, and the Kalahari. Although a general coherence of summer rainfall totals across the SRZ exists, inter-annual variability between areas is present. Although the WRZ is smaller, inter-annual variability between documentary records still exists. Despite the relatively high RE values and correlation coefficients in the calibration period, a limitation of this approach is that there may also be other mechanisms of precipitation variability reflected in the other records that are not captured by the regression relationships with the wind data, such as intensified anticyclonic circulation over southern Africa (Mason and Jury, 1997). Moreover, the logbook reconstruction itself is based upon spatially and temporally variable data incorporated according to pre-processing criteria, it is therefore also possible that changes in wind speed may be more rapid than that captured by the sample, although by using seasonal means it is hoped that this may be minimised. Certainly, the potential to increase the data density by incorporating the yet to be digitised EEIC logbook observations would further improve the reconstructions.

Droughts in the SRZ and ENSO events

ENSO warm events, or El Niño events, are associated with drought over areas of southern Africa, with a strong response in the south-east (Nash and Grab, 2010; Rocha and Simmonds, 1997). This is particularly evident in the summer immediately after an El Niño event, with the greatest rainfall reductions occurring between January and March (Nicholson and Kim, 1997; Nicholson et al., 2001). According to Mason and Jury (1997) and Tyson and Preston-Whyte (2000), El Niño events are followed by a northward shift of the westerlies in the southern African sector, leading to a diminution of moisture convergence and a dominance of dry conditions.

Relating patterns in summer atmospheric circulation to the semi-quantitative documentary reconstructions of ENSO warm events by Quinn and Neal (1995) and Ortlieb (2000) (Figure 6), some noteworthy patterns emerge. Although not attempting to over-attribute cause, 14 of the 18 El Niño years identified by Quinn and Neal (1995) in the period of the logbook reconstruction coincided with an increase in or above average westerliness the following summer, while this number was 11 out of 15 for the revised chronology by Ortlieb (2000). Furthermore, the only El Niño event in the time period identified as ‘very strong’ in both records, in 1828, coincided with the highest proportional frequency of westerliness and the second driest year in the record. Given the high concentration of El Niño events reported in both documentary records between 1814 and 1832, it may also be possible that this is linked to the increased inter-annual rainfall variability calculated in the 7-year running standard deviation (Figure 6). Despite this association with the two chronologies listed above, less correspondence is observed with El Niño events reconstructed in the most recent documentary chronology by García-Herrera et al. (2008), with only four out of 14 summers following El Niño events having increased or above average westerliness. As inferred by the difference in correspondence, discrepancies exist between El Niño events in the records, including a suggested overestimation of events by Quinn and Neal (1995) due to both inappropriate interpretation of documents and the inclusion of reports from areas where ENSO teleconnections are uncertain (García-Herrera et al. 2008). The level of correspondence between El Niño events and summer westerliness, therefore, is dependent on the record used for comparison.

In addition to discrepancies between records, it is important to note that while most El Niño events recorded in Quinn and Neal (1995) and Ortlieb (2000) appear to coincide with increased westerliness, they do not always result in reduced rainfall at Mthatha or Royal National Park. A total of 11 out of the 18 years following El Niño events in the Quinn and Neal (1995) record are marked by a decrease in precipitation, while this figure is eight out of 15 for the years identified by Ortlieb (2000). Furthermore, in both records, only three out of the seven severely dry years noted in the results section - 1805-06, 1820-21, and 1829-30 - are in years following El Niño events in both records. That two out of these three events, however, are rated as 'strong' and 'very strong' perhaps suggests that the incidence of stronger ENSO warm events is more likely to result in such severe decreases in precipitation in south-east southern Africa, while a weaker atmospheric response and consequently weaker precipitation anomaly is generally present in events of a moderate strength. This also suggests that whilst El Niño events appear to have an important influence on atmospheric circulation according to two of the chronologies, the precise nature of the relationship may be more complex, and that they are not the only cause of drier conditions in southern Africa (Nash and Grab, 2010; Nicholson, 2000). Furthermore, as the Southern Hemisphere westerlies shift poleward in La Niña events (L'Heureux and Thompson, 2006; Seager et al., 2007), it is possible that the consequences of La Niña conditions are captured in the wind data in years with increased easterliness (Figure 6). However, the resultant wetter conditions may be under-recorded in the documentary records, which is a common issue in reconstructions from written sources (Kelso and Vogel, 2007; Nash and Grab, 2010).

Conclusion

By establishing statistical relationships between wind and precipitation using reanalysis data, this study has presented precipitation reconstructions at selected southern African weather stations for the period 1796-1854. Results for the SRZ stations showed that the 1810s was the wettest decade of the period, while the 1820s was the driest. At Cape Town in the WRZ, the reconstruction revealed the 1820s to be the wettest decade, while the 1830s, although having some missing years, was shown to be the driest decade of the time period. A degree of correspondence was registered between the logbook reconstruction and other records, although frequent differences in inter-annual observations were registered. These discrepancies may be due to the spatial extent of certain records, or their sensitivity to alternative or local forcing factors. Nevertheless, the SRZ reconstruction did pick up two of the three southern Africa-wide drought episodes identified by Kelso and Vogel (2007) in 1820-21 and 1825-27.

Identification of causation in past rainfall variability should be treated with caution. However, comparison of the El Niño records by Quinn and Neal (1995) and Ortlieb (2000) revealed that in all but four of the El Niño years identified by each record respectively, westerliness in the following summer increased or was above average for the period. Despite this, the strength of atmospheric response following El Niño events differed, and not all events were followed by markedly dry summers. Reduced correspondence was present with the independent chronology of García-Herrera et al. (2008). This therefore cautions against strong causal linkages with documentary-reconstructed El Niño events in this period without further investigation.

By providing highly-resolved and reliable observations for the oceans surrounding southern Africa, the logbooks have offered new and independent insight into the past atmospheric circulation and precipitation patterns in the region. That the logbook data are not proxy-based but are the result of direct observations, recorded to a common standard, is a significant advantage, the value of which has been demonstrated in this study. Extraction and digitisation of wind data in the remaining 3000 logbooks in the British Library archive would not only enhance the resolution of the reconstruction in this time period, but would most likely enable the reconstruction to be extended back to the beginning of the eighteenth century.

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Online supplementary material

Table S1. Reconstruction statistics for each station significantly correlated with NCEP-DOE u-wind (1979-2008).

Station	Mean annual precipitation (mm)	Grid boxes	Explained variance	r (first PC)	RE	r (validation time series)
Bethlehem	698.43	4	85, 12, 2, 1	-0.5108	0.27	0.5262
Bloemfontein	551.94	3	36, 33, 30, 0	0.5791	0.22	0.4852
Calvinia	201.99	2	90, 10, 0, 0	0.5370	0.21	0.4872
Cape Town	541.61	5	53, 32, 9, 5	0.6703	0.40	0.6338
Cedara	839.23	4	73, 18, 7, 2	-0.5473	0.22	0.4802
De Aar	332.05	2	95, 5, 0, 0	-0.4481	0.12	0.3624
Frankfort	664.27	5	70, 21, 6, 0.2	-0.6279	0.2	0.4725
Harare	690.01	3	64, 33, 0.2, 0	-0.4627	0.08	0.3177
Johannesburg	745.78	2	64, 36, 0, 0	-0.4902	0.13	0.3853
Kimberley	412.81	1	100, 0, 0, 0	-0.3685	0.09	0.3117
Mount Edgecombe	962.84	5	78, 17, 4, 1	-0.5824	0.26	0.5107
Mthatha	657.01	5	73, 15, 1, 0	-0.8125	0.61	0.7801
Noupoort	380.65	2	95, 5, 0, 0	-0.5440	0.23	0.4807
Pretoria	657.87	4	68, 18, 10, 4	-0.5501	0.1	0.3588
Royal National Park	1223.11	4	85, 12, 2, 1	-0.6763	0.43	0.6556
Rustenburg	575.84	2	72, 28, 0, 0	0.5177	0.22	0.4744
Skukuza	586.55	1	100, 0, 0, 0	-0.3813	0.05	0.2772
Upington		3	66, 19, 13, 2	-0.4690	0.1	0.3502
Windhoek	342.79	1	100, 0, 0, 0	-0.3910	-0.04	0.1661

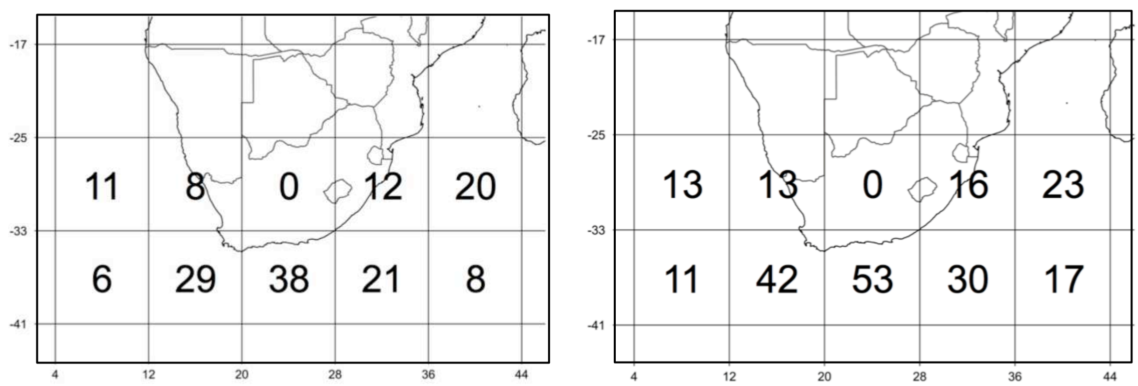

Figure S1. Left: average number of NDJFM records in each 8° x 8° grid box between 1796-1854. Right: average number of AMJJAS records in each 8° x 8° grid box.

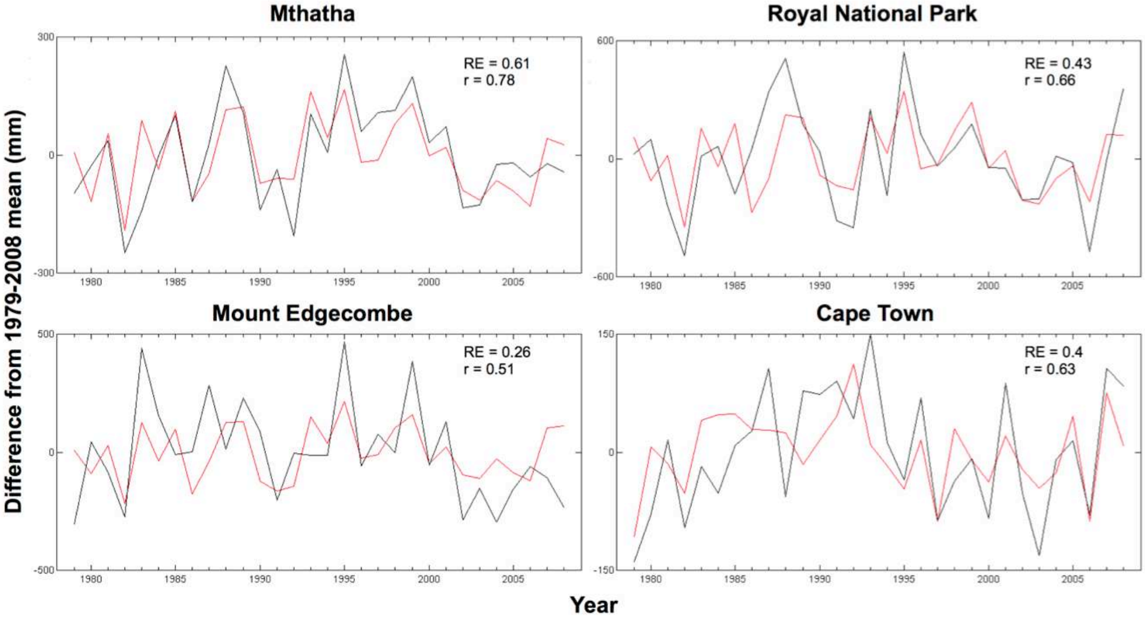

Figure S2. Reconstructed (red line) and observed precipitation (black line) from NCEP-DOE u-wind 1979-2008 at four stations with the highest RE values.

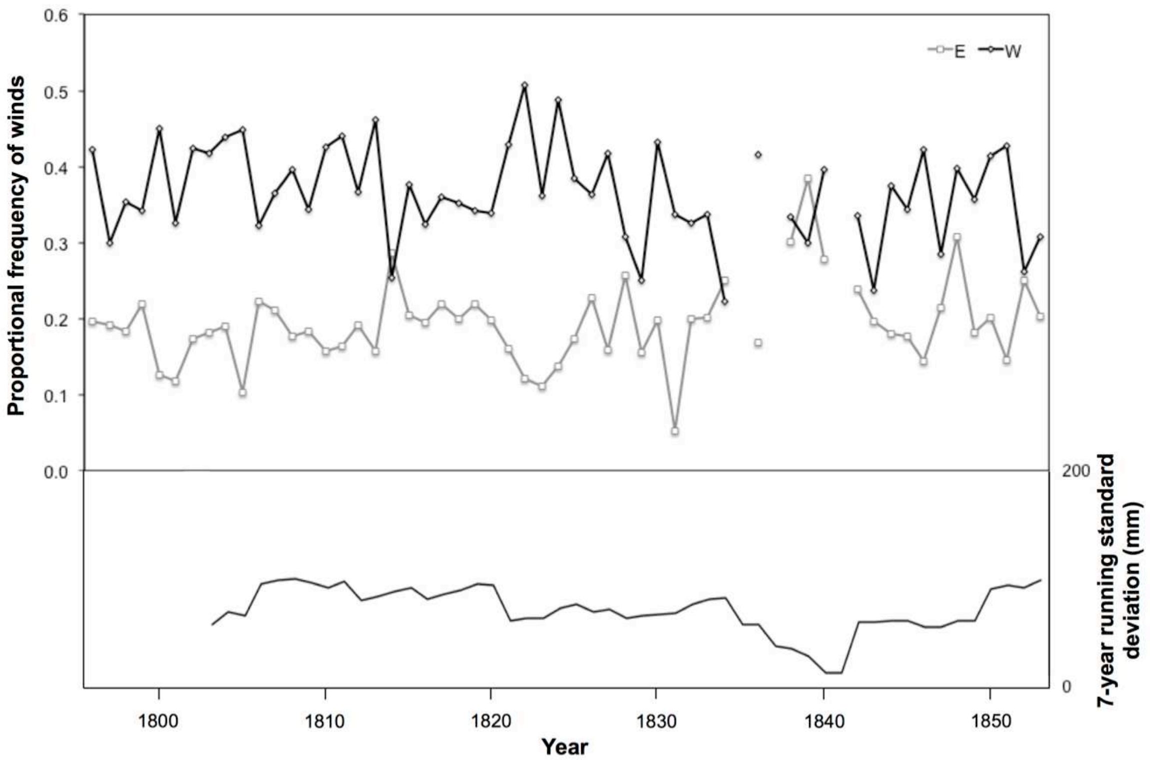

Figure S3. Proportional frequency of April-September zonal winds in the leading Principal Component for the Cape Town grid boxes (upper panel), and 7-year running standard deviation for precipitation at Mthatha (lower panel).