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Synchronicity of historical dry spells in the Southern Hemisphere

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Abstract

A shift in climate occurred during the mid-1970s that affected the hydroclimate of the Southern Hemisphere resulting in drying trends across continental regions including Australia, New Zealand and southern and western Africa. There is also anecdotal evidence of other periods of climatic synchronicity in the Southern Hemisphere (e.g. the 1920s and 1940s), indicating that the mid 1970s event may not be anomalous. This paper identifies periods within the last ~120 yr using statistical analysis where dry spells (in terms of annual to multi-decadal rainfall deficiencies) have coincided across the continental Southern Hemisphere in order to characterize temporal consistency. It is shown that synchronicity of dry spells is (a) most likely common over the last 120 yr and (b) associated with changes in the large-scale climate modes of the Pacific, Indian and Southern Oceans. Importantly, the findings presented in this paper have marked implications for drought management and drought forecasting studies in the Southern Hemisphere.

1 Introduction

A number of continental regions in the Southern Hemisphere have experienced a change in climate since the mid-1970s. For example, southwest western Australia is experiencing an extended dry spell that began in the mid-1970s, where austral winter (June–August) rainfall totals have decreased by approximately 20 % (IOCI, 2002). Further, Van Ommen and Morgan (2010) reported a significant inverse correlation between the records of precipitation at Law Dome, East Antarctica and southwest of Western Australia over the instrumental period. In particular, since the mid-1970s rainfall has increased at Law Dome, while rainfall has decreased in southwest of Western Australia. The mid-1970s also corresponds to a period of change in climate for eastern Australia due to changes in ocean-atmospheric processes over the Pacific Ocean (i.e. the El Niño/Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation

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(IPO)) which have resulted in more frequent droughts (Mantua et al., 1997; Power et al., 1999; Wang and An, 2001; Kiem et al., 2003; Kiem and Franks, 2004; Verdon and Franks, 2006). A similar shift in New Zealand's climate around 1976 has also been identified, with the period 1976–1994 characterized by annual rainfall decreases in the north of the North Island and increases in much of the South Island (Salinger and Mullan, 1999). Further, in Southern Africa, overall moist conditions were reported between 1960 and 1970 and since then a switch to drier conditions has been noted (Ngongondo, 2006).

There is also evidence of significant climate shifts in the Southern Hemisphere during the mid-1940s and mid-1920s (e.g. Mantua et al., 1997; Power et al., 1999; Kiem et al., 2003, Kiem and Franks, 2004; Verdon and Franks, 2006), highlighting the fact that the mid-1970s climate shift is not likely to be an isolated event. This apparent connection between rainfall in Australia and East Antarctica, along with the similar timing of climate shifts in Southern Africa and New Zealand, suggests the possibility of synchronicity in dry spells across the Southern Hemisphere. The aim of this paper is therefore to characterize this synchronicity over the last 120 yr (a period when reliable rainfall data is available for the continental regions) and to determine the climate driving mechanism may contribute to this synchronicity.

2 Data

2.1 Gridded data

The NCEP/NCAR (National Centres for Environmental Prediction and the National Center for Atmospheric Research) Reanalysis global gridded data sets, available from the US National Oceanic and Atmospheric Administration (NOAA, www.esrl.noaa.gov/psd/), are used to study the 1970s climate shift in the Southern Hemisphere. The NCEP/NCAR Reanalysis data is derived from a global spectral model with a grid resolution of 2.5° latitude × 2.5° longitude global (144 × 73 grids). As with all reanalysis

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data, this data has various limitations, particularly in the Southern Hemisphere where historical recorded data tends to be sparse (see Trenberth and Guillemot, 1998).

2.2 Station based monthly rainfall data

Station-based observed rainfall data from continental regions south of 30° (Fig. 1) were obtained from the following data sources:

- Australia: monthly station-based rainfall data was obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/data/). Data chosen for analysis was at least 95 % complete and covered the period 1900–2009.

- New Zealand: daily station data was obtained from the National Climate Database of the National Institute of Water and Atmospheric Research (NIWA, http://cliflo.niwa.co.nz/). Data chosen for analysis was at least 95 % complete and covered the period 1920–present. An additional station was chosen for analysis (located at Reefton on the west coast of New Zealand) that contained daily data from 1948 onwards in order to sufficiently represent the west coast of New Zealand. Daily data was aggregated to monthly data prior to analysis.

- South America and Southern Africa: monthly rainfall data for South America and southern Africa was obtained from the Global Historical Climatology Network (GHCN, www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php). The historical GHCN data has previously undergone rigorous quality assurance review (including pre-processing checks on source data, time series checks that identify spurious changes in the mean and variance, spatial comparisons that verify the accuracy of the climatological mean and the seasonal cycle, and neighbor checks that identify outliers from both a serial and a spatial perspective). Despite the level of quality assurance, the rainfall data available through the GHCN for South America and southern Africa is not as complete as data from Australia and New Zealand, with the more recent data being particularly sparse. Station data included varies

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in length with all stations containing data from at least 1920 to 2009 (however two additional stations from Argentina were included that contained data from 1931 onwards (at Puerto Deseado Aero and Rio Gallegos Aero) in order to improve the spatial coverage of the east coast of South America).

2.3 Indices of large-scale climate modes

The four dominant large-scale climate modes operating in the Southern Hemisphere are:

- ENSO (Chiew et al., 1998; Kiem and Franks, 2001; Verdon et al., 2004). In this study ENSO is represented by the Oceanic Niño Index (ONI) from the United States National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (CPC) (www.cpc.ncep.noaa.gov). The ONI is a 3 month running mean of ERSST.v3b SST anomalies in the Niño 3.4 region, centered on 30 yr base periods updated every 5 yr. For historical purposes cold (La Niña) and warm (El Niño) episodes are defined when the ONI exceeds the threshold of $\pm 0.5^{\circ}$ for a minimum of 5 consecutive over-lapping seasons;

- IPO (Power et al., 1999; Kiem et al., 2003; Verdon et al., 2004; Power and Colman, 2006) – a low frequency (15–35 yr) pattern of variability of the tropical and extra-tropical Pacific ocean (refer to Power et al., 1999 for details). Folland et al. (1999) derived an index of IPO variability using a low pass filter of near-global SSTs, while Power et al. (1999) applied a spectral filter with a 13 yr cut-off to the raw IPO to generate a smoothed (or slowly varying) IPO timeseries. Both the raw and the smoothed time series of Power et al. (1999) are used in this study in order to identify epochs of positive and negative IPO;

- Indian Ocean Dipole (IOD; Saji et al., 1999; Ashok et al., 2003; Verdon and Franks, 2005) – in this study the Dipole Model Index (DMI) developed by Saji et al. (1999) is used, defined as the difference in SST anomaly between the tropical

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western Indian Ocean (50–70° E, 10° S–10° N) and the tropical south-eastern Indian Ocean (90–110° E, 10° S–Equator);

- Southern Annular Mode (SAM; Thompson and Wallace, 2000; Thompson et al., 2000; Ho et al., 2012) – in this study the NOAA CPC version of the AAO is used when it exists (i.e. from 1979 onwards) and the Thompson and Wallace (2000) AAO data is used prior to that (1948 to 1978). Overlapping periods (1979 to 2002) of the two versions of the AAO were compared and the difference found to be negligible ($R^2 = 0.95$, $N = 288$).

3 Synchronicity in Southern Hemisphere climate since the mid-1970s

An analysis of changes in the Southern Hemisphere climate was carried out using the gridded data described in Sect. 2.1. Figure 2a shows, for the period 1976–2009, a clear decrease in annual precipitable water in the southwest and southeast of Australia, New Zealand and central South America. This decrease in precipitable water was also associated with an increase in sea level pressure (Fig. 2b) and geopotential height (Fig. 2c) over continental regions located between 30 and 45°. The anomalous high pressure since the mid-1970s would naturally manifest in reduced rainfalls in these regions. The observed increase in zonal winds speeds (Fig. 2d) would also have the effect of pulling storm tracks further south; hence stations located south of 45° show an increase in rainfall, while mid-latitude stations (30 to 45°) have experienced a decrease in rainfall (consistent with CSIRO, 2012).

4 Synchronicity in dry spells across the Southern Hemisphere since 1900

Monthly station based rainfall data (described in Sect. 2.2) was converted to annual totals and ranked from lowest to highest for each individual station. This was carried out for 1, 2, 5 and 10 yr running means. The lowest five rainfall epochs (dry spells) during the period 1900–2009 were then compared for each station to identify any temporal consistencies (Fig. 3).

The dry spells display a strong degree of consistency across the mid-latitudes for the 1 yr through to 10 yr rainfall rankings. It is also clear that there does not appear to be any monotonically increasing trend in dry spells throughout the last century. This is at odds with other studies that suggest drought is projected to increase under anthropogenic warming (e.g. CSIRO, 2007). Rather, based on the results presented here it appears that overall the period 1910 through to 1950 was dry for regions south of 30° (particularly the mid-1920s to mid-1940s), followed by a relatively wet period (i.e. absence of prolonged dry periods) from 1950 through to 1980 and a return to dry thereafter (based on the 5 and 10 rainfall rankings). This is consistent with studies that suggest cyclic activity in wet and dry periods in the historical records (e.g. Erskin and Warner, 1988; Verdon-Kidd and Kiem, 2009; Hastenrath and Polzin, 2011). The occurrence of shorter dry spells (i.e. 1 or 2 yr) is also distributed across the record, with no evidence of a monotonically increasing or decreasing trend. Individual years of significant synchronicity include 1902/1903 (Australia, New Zealand, southern Africa), 1914/1915 (Australia, New Zealand), 1940 (Australia), 1967/1968 (Australia, New Zealand), 1982/1983 (Australia, New Zealand, South America), 1993/1994 (all countries), 2001/2002 (all countries), 2005/2006 (Australia, New Zealand, southern Africa).

5 A case study – was the Federation Drought, experienced in Australia ~1895–1902, just confined to Australia?

Expansion of agricultural regions into regional Australia occurred in the late 1800s after a series of promising rainfall years. Following this, a severe drought gripped northern and eastern Australia which lasted from ~1895–1902 as shown in Fig. 4 (Verdon-Kidd and Kiem, 2009). The Federation Drought, as it became known, was the most severe (in terms of rainfall deficits) of Australia's three iconic protracted droughts, including the

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Big Dry (∼1997–2010) and the World War II Drought (∼1937–1945) (Verdon-Kidd and Kiem, 2009). Station data with records dating back to 1890 were analyzed to determine if the Federation Drought was confined to Australia, or if this dry spell was also synchronous across parts of the Southern Hemisphere (Fig. 5).

Based on the analysis presented in Fig. 5, it appears that the east coast of South America, the east coast of southern Africa, southwest and southeast of Australia and southern New Zealand all experienced a dry spell during this eight year "Federation Drought" period (∼1895–1902). While the exact spatial extent is not clear (due to the reduced number of stations recording rainfall during this time) the results provide compelling evidence of temporal consistency during this time for many regions of the Southern Hemisphere.

6 Climate driving mechanisms forcing hydroclimatic synchronicity

As stated in Sect. 2.3 the main climate driving mechanisms for the Southern Hemisphere are ENSO, IPO, IOD and SAM. For example, ENSO control on climate is known to extend to Australia, South America Africa and New Zealand (e.g. Ropelewski and Halpert, 1996). Similarly, Indian Ocean SST variability has been shown to affect both Australian and African rainfall (Reason, 1999; Saji et al., 1999; Ansell et al., 2000; Ashok et al., 2003; Verdon and Franks, 2006). Table 1 shows the state of the main climate drivers during periods of short term synchronicity in the Southern Hemisphere, as identified in Fig. 3. Timeseries of ENSO, IPO, IOD and SAM are shown in Fig. 6 (see Sect. 2.3 for a description of the indices) along with the common protracted dry epochs across the Southern Hemisphere.

It is clear from Table 1 that ENSO plays a key role in driving Southern Hemisphere synchronicity with seven out of the eight short term simultaneous dry spells occurring during an El Niño event (noting that none occur during La Niña). This is not surprising given the significant role that ENSO plays in controlling climate around the globe (Ropelewski and Halpert, 1996). While the Pacific Ocean is clearly a major driver, Table 1

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shows that short term droughts can occur against a background of either phase of the IPO (i.e. it is the shorter ENSO cycles that dominate annual episodes). It also appears that the Indian and Southern Oceans have a significant influence on this synchronicity at the annual scale. For example, the DMI is positive during five out of the eight short term dry spells (with only one negative DMI event). Further, during the four more recent dry periods SAM has been predominantly positive (corresponding to higher pressure between 30 and 45° S and a southward shift in the westerly winds towards Antarctica) pointing towards the possibility that the SAM may be becoming more important in regulating droughts as it continues to trend positive (e.g. Arblaster and Meehl, 2006).

Figure 6 highlights some important findings regarding Southern Hemisphere synchronicity on decadal to multi-decadal scales. In particular, it is clear that the Pacific Ocean is a dominant driver of protracted dry episodes in the Southern Hemisphere, with the IPO being in a positive phase with an absence of La Niña events during all protracted dry events (as per Kiem and Franks, 2004). However, it is also clear that the Southern and Indian Oceans are also important drivers of this synchronicity. For example, during two of the three extended dry periods shown here the SAM is persistently positive. Note that while SAM is not shown to be positive during the Federation Drought (∼1895–1902) there is some question over the validity of the index used to represent SAM during the earlier part of the record (Ho et al., 2012), further the influence of the SAM is very seasonally dependent for Australian rainfall (Hendon et al., 2007), with opposite effects on rainfall in summer vs. winter which may be negated when analysing annual rainfall. As shown in Fig. 6 the DMI was predominantly positive during the dry period that occurred between ∼1925–1945, contributing to the synchronicity observed during this period, particularly between Australia and Southern Africa.

7 Discussion and conclusions

In this study a number of common periods of hydroclimatic variability in the Southern Hemisphere were identified since the late 1800s, on a short timescale (1 yr) through

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to multi-decadal timescales. For example, across the Southern Hemisphere the period 1910–1950 appears dry on average, followed by a wetter period (absence of dry events) between 1950 and 1970/1980, when a return to dry conditions occurred for much the continental Southern Hemisphere. Furthermore, the analysis presented here indicates that the Federation Drought (~1895–1902), an iconic drought in Australia's history, was not limited to Australia (although the exact spatial extent across the Southern Hemisphere is unclear). It was also shown that the state of the Pacific Ocean (in terms of ENSO and IPO) is crucial in driving large-scale long-term synchronicity of dry epochs. However, the SAM and IOD also play an important role in modulating both short and long term dry events.

Droughts are, and always will be, part of the hydroclimate (particularly of the mid-latitudes) and it is impossible to prevent these natural disasters from occurring. The multi-faceted nature of droughts and the complexities associated with securing the world's water resources in the face of a highly uncertain future requires innovative thinking to improve our understanding and reduce our vulnerability to climate extremes. Therefore, an adequate understanding of the mechanisms that cause enhanced risk periods is essential to effectively manage and minimize the damage associated with droughts when they do occur. This paper represents one step towards identifying controls on major drought periods in the Southern Hemisphere with the aim being to (a) better understand historical and baseline levels of drought risk and (b) better understand which controls are important, and characterize their influence, to inform seasonal to multi-decadal climate forecasting and modeling activities. Any advancement in the ability to forecast, or better model, the onset and termination of drought would clearly benefit a wide spectrum of the community, industry and economic sectors.

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Table 1. Climate drivers during years when dry events coincide across the Southern Hemisphere.

Year	ENSO	IPO	DMI	SAM
1902/1903	El Niño	Positive	Positive	Negative
1914/1915	El Niño	Negative	Neutral	Negative
1940/1941	El Niño	Positive	Positive	Negative
1967/1968	Neutral	Negative	Positive	Negative
1982/1983	El Niño	Positive	Positive	Positive
1993/1994	El Niño	Positive	Positive	Positive
2001/2002	El Niño	Neutral	Negative	Neutral
2005/2006	El Niño	Negative	Neutral	Positive

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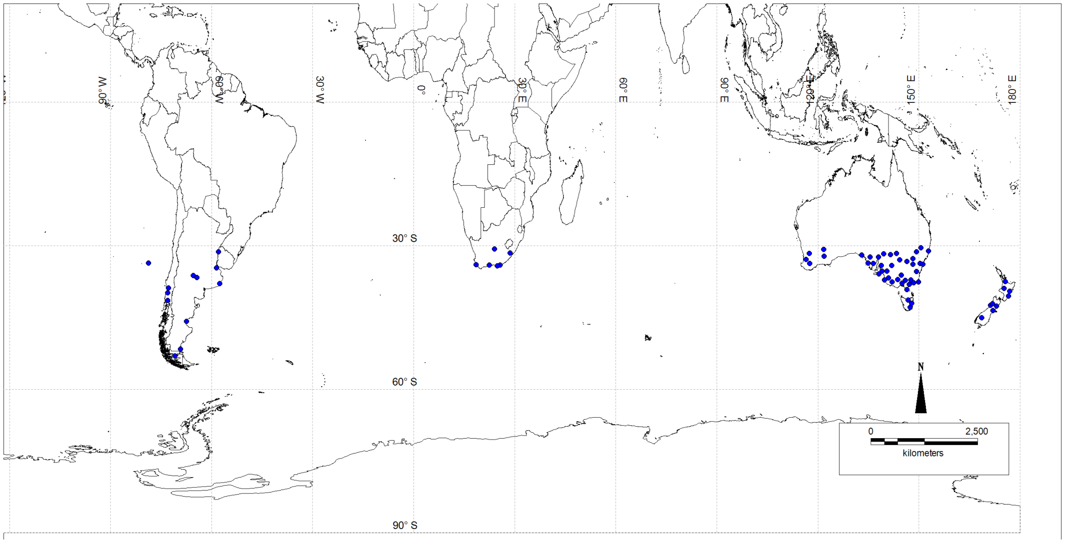

Fig. 1. Location of 73 monthly rainfall stations used in this analysis (blue circles).

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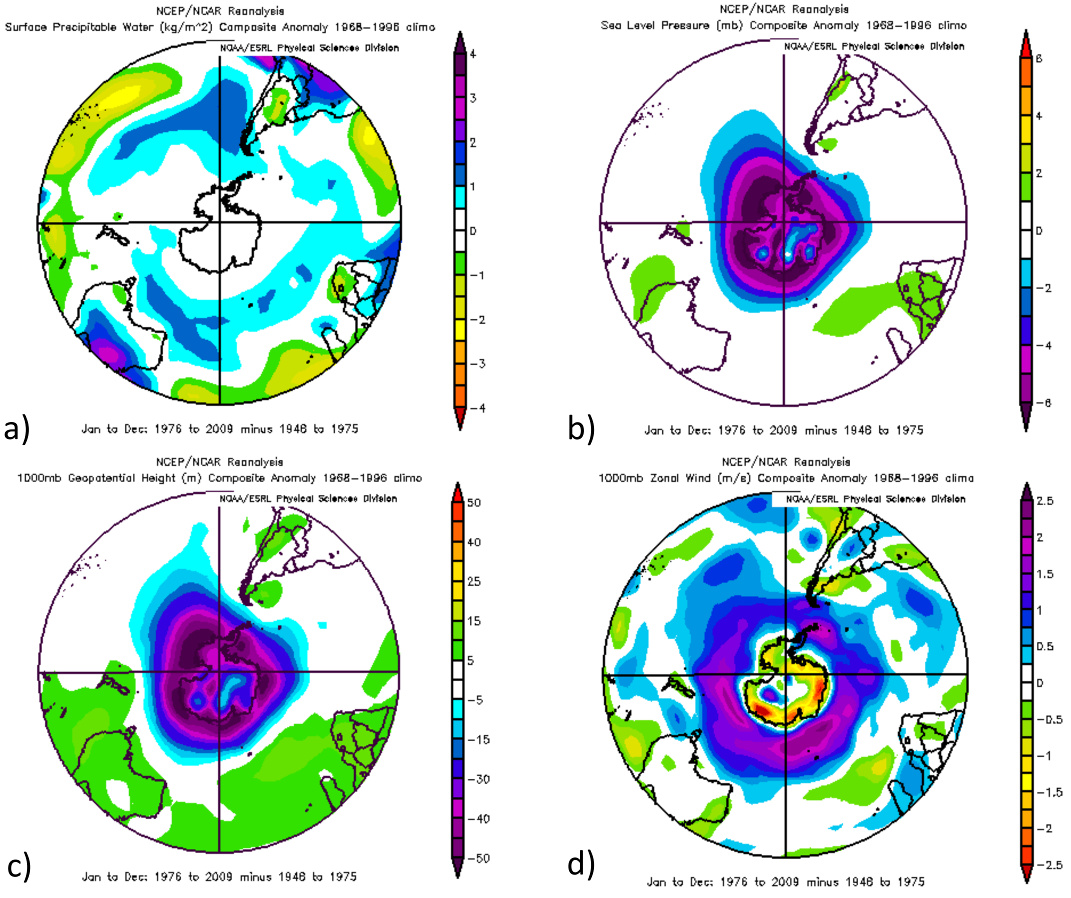

Fig. 2. Differences in **(a)** annual surface precipitable water, **(b)** sea level pressure, **(c)** geopotential height and **(d)** zonal wind anomalies during the period 1976–2009 compared to 1948–1975.

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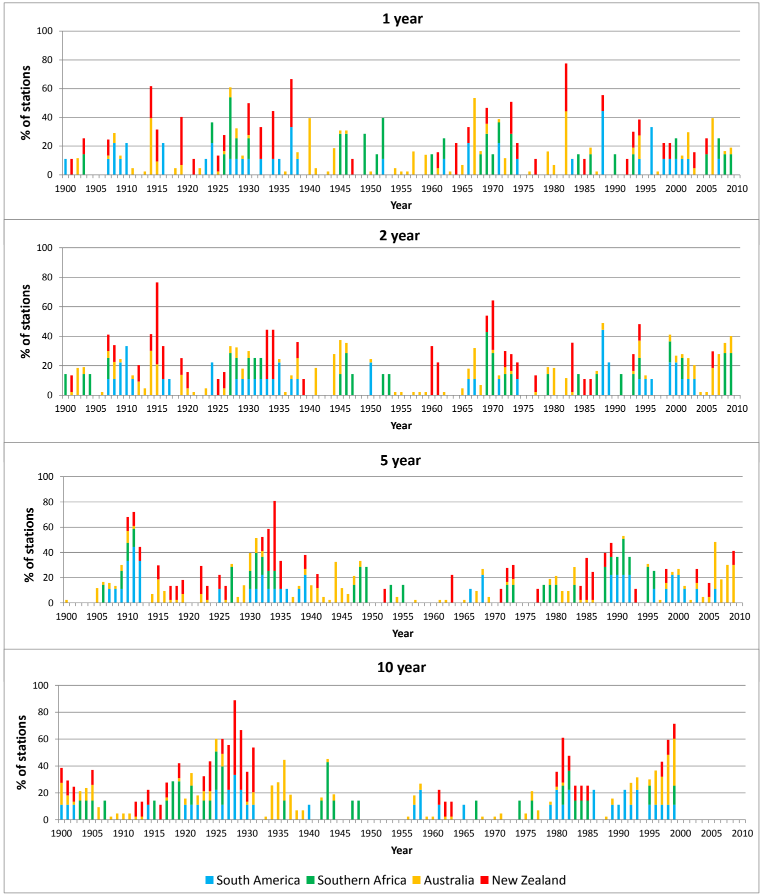

Fig. 3. Total percentage of stations for each continent where the 1–10 yr cumulative rainfall was among the five lowest during the period 1900–2009.

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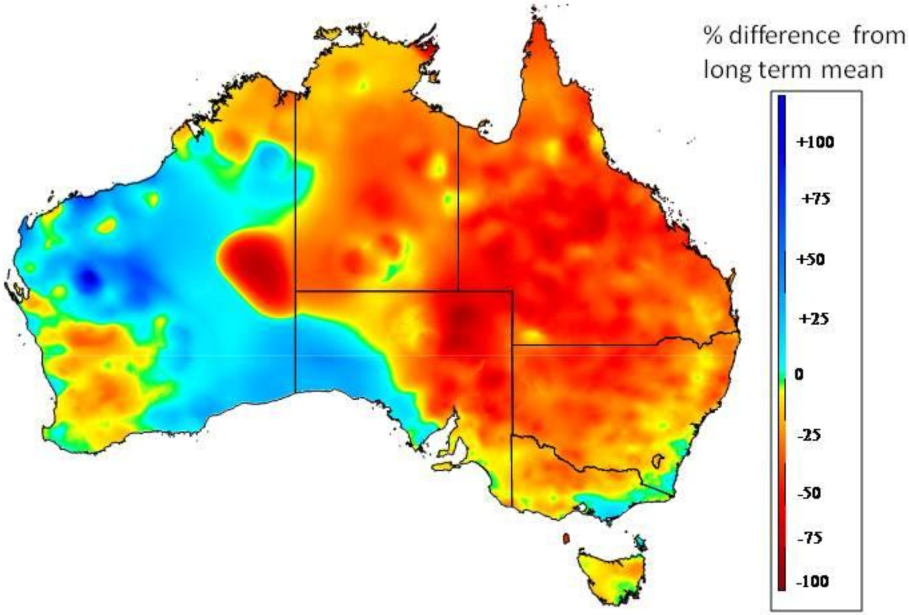

Fig. 4. Spatial extent (in terms of rainfall anomalies) of the Federation Drought (~1895–1902) in Australia (from Verdon-Kidd and Kiem, 2009).

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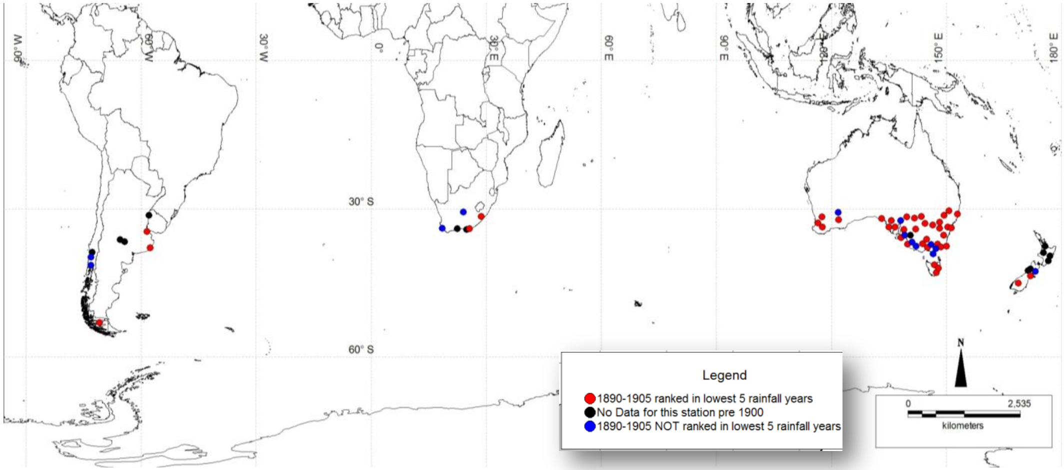

Fig. 5. Stations where the period 1890–1905 was listed in the top five lowest rainfall years (shown in red).

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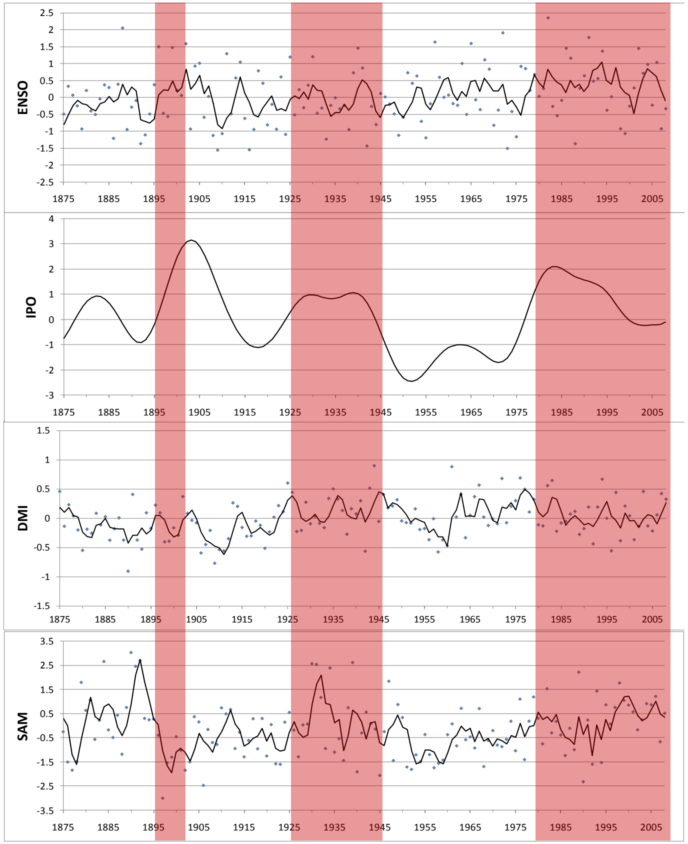

Fig. 6. Historical timeseries of ENSO, IPO, DMI and SAM. Dots represent the mean "annual" value for each index, solid line is the 3 yr moving average, red shaded regions indicate the common dry periods across the Southern Hemisphere.

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