Temporal changes in annual rainfall in the "Top End" of Australia

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Abstract CUSUM (cumulative deviations from the mean) analysis of up to 136 years of annual rainfall at 15 stations in the northern part of the Northern Territory (Australia) revealed alternating periods of above- and below-average rainfall that persisted for at least 6 years to many decades. The Kruskal-Wallis and Mann Whitney tests were used to show that consecutive time periods were usually statistically significantly different to each other. Furthermore, the wet periods were statistically identical to each other, as were the dry periods, but non-consecutive wet and dry periods were significantly different. The time and duration of these alternating wet and dry periods varied from station to station. Alternating, sub-decadal to multi-decadal, wet and dry periods also appear to be manifested in the streamflow record and have significant implications for water resource assessments, river channel dynamics and landscape processes.

Key words alternating flood- and drought-dominated regimes; CUSUM; non-parametric statistics; Top End of Australia

INTRODUCTION

Climate change is an important issue worldwide, especially where decreasing rainfall and/or increasing temperatures are likely to significantly reduce agricultural production. This is especially the case in the Top End of Australia (Fig 1) where annual rainfall is concentrated during the monsoonal season (December to March) and where annual rainfall decreases substantially to the south. Previous research in the Top End has highlighted that annual rainfall is bimodal, consisting of alternating periods of low and high rainfall (Carter, 1990; Mollah *et al.*, 1991), which Erskine & Townley-Jones (2009) have called alternating flood- and drought-dominated regimes. All low and high rainfall periods in the Top End had approximately the same average rainfall and persisted for time periods of between 5 and 29 years (Carter, 1990).

This alternation between high and low rainfall must be recognized for the purposes of managing water resources; especially as cycles may be closely related to El Niño-Southern Oscillation (ENSO), Inter-decadal Pacific Oscillation (IPO) and/or Indian Ocean Dipole (IOD) signals. Verdon *et al.* (2004) reported that, for eastern Australia, rainfall is much greater during the La Niña phase of ENSO than during El Niño. Rainfall also tended to be higher during the negative period of the IPO compared to the positive period. Both impacts are also reflected in streamflow increases (Verdon *et al.*, 2004). The negative phase of the IPO magnified the already enhanced La Niña rainfall and streamflow (Verdon *et al.*, 2004).

The purpose of this paper is to determine temporal changes in annual rainfall at long-term stations in the Top End of Australia, which is defined as the area of the Northern Territory, north of Newcastle Waters (Fig. 1). Specific objectives are to apply non-parametric statistical approaches used in water resources assessments (Helsel & Hirsch, 1992; Kampata *et al.*, 2008) to determine whether there have been repeated vacillations between two different mean rainfall states over the last 130 years, as speculated by Nicholls & Lavery (1992). The approach adopted here differs from that used by Verdon *et al.* (2004) in that rainfall periods are not deliberately split at La Niña and/or IPO negative phases but the complete annual rainfall record is analysed independently of ENSO/IPO/IOD events.

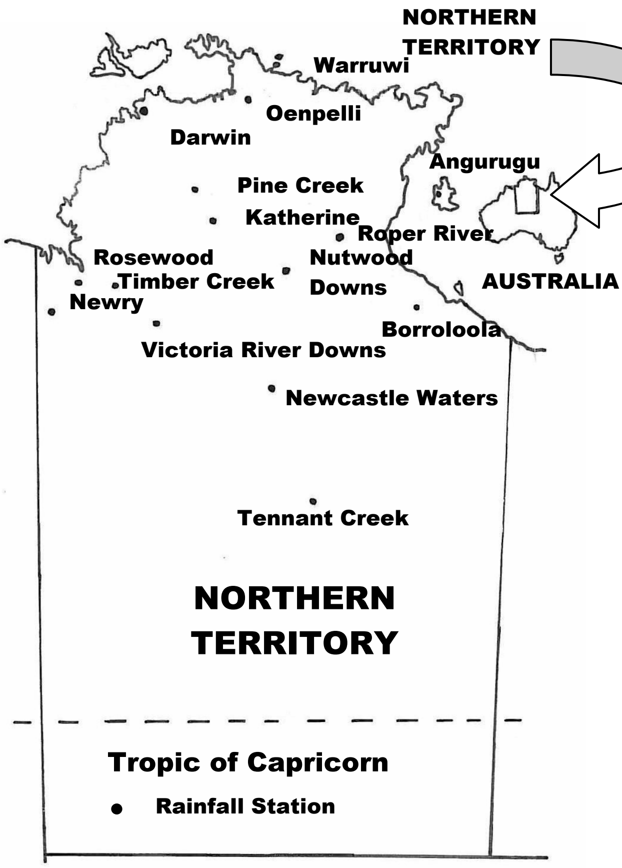

Fig. 1 Location of rainfall stations analysed for temporal changes in the Top End of Australia.

DATA

Lavery *et al.* (1992) produced a long-term data set of 191 Australian rainfall stations which can be used with confidence in studies of climate change because the record of each station is free of any suspected discontinuity or non-climatic trend, and because no station had missing data. However, within the Top End, there are only three such stations (Oenpelli, Pine Creek and Katherine). Lavery *et al.* (1992) explicitly recognized that a major drawback of their data set was its poor geographic coverage. Although Lavery *et al.* (1997) extended their earlier work to identify 341 high-quality, long-term rainfall stations throughout Australia, only an additional two stations were listed for the Top End (Darwin Airport and Warruwi). Furthermore, the complete data sets mentioned by Lavery *et al.* (1992, 1997) have not been added to the Bureau of Meteorology's archive for each station (http://www.bom.gov.au/climate/data). For example, Bennett (2005) lists a complete monthly record for Katherine Council, but we had to estimate 13.1% of the annual values to fill the gaps in the Bureau's archive (Table 1). Our stations were selected to provide adequate spatial and temporal coverage of the Top End (Fig. 1). No records have been composited by combining two stations, as practised by Lavery *et al.* (1997). Our data sets have sample sizes of between 68 years (1942–2010 at Darwin Airport) and 136 years (1874–2010 at Katherine Council). All annual rainfall data held by the Bureau of Meteorology for 15 stations in the Top End of Australia (Fig. 1) were downloaded from the Bureau's archive. Missing annual values were estimated by least squares linear regression with neighbouring stations. All of the following analyses were conducted for the water year, August to July inclusive, to avoid splitting the wet season between different calendar years. August usually has the lowest mean monthly rainfall at each station.

METHODS

To determine temporal changes in rainfall, the following steps were undertaken (Helsel & Hirsch, 1992; Kampata *et al.*, 2008):

(a) intervention analysis (CUSUM),
(b) step change analysis (Kruskal-Wallis test), and
(c) detailed comparison of time periods (Wilcoxon Rank Sum test).

Intervention analysis

Intervention analysis was carried out using the cumulative sum technique (Page, 1957; McGilchrist & Woodyer, 1975) to detect changes in mean value of a sequence of ordered time observations. The computed CUSUM at any time is given as:

$$s_i = \sum_{i=1}^{i} \left(x_i - \bar{x}\right) \quad (1)$$

where x_i is the regularly spaced observation.

Rainfall changes must persist for at least five years to define different periods so as to conform to earlier analyses for the Top End by Carter (1990). From plotted CUSUMs, temporal changes were identified at peaks and troughs separated by at least five years, as shown in Fig. 2(b) for Katherine. For this initial analysis of temporal trends, we used as many long-term records as possible and did not concentrate on a common period of record at all stations.

Step change analysis

The Kruskal-Wallis test was the non-parametric test used to determine differences in median for three or more time periods representing different interventions. Data are ranked from smallest (1) to largest (N). Ranks are then used to compute the test statistic. If the null hypothesis is correct, the average rank for each time period should be similar. If the alternative hypothesis is true, the average ranks for some time periods would be different. The null hypothesis is that no change has occurred in the time series or that the samples for different time periods come from the same population. The null hypothesis is rejected if the p-value is less than 5%.

Detailed comparison of time periods

The Mann Whitney test is one of the most powerful of the non-parametric tests and was used to determine if annual rainfall for each time period identified by CUSUMS belongs to the same distribution. Ranks are used to calculate the test statistic. The null hypothesis is that no change has occurred in rainfall distributions between the various time periods or that the samples come from the same population. The null hypothesis is rejected if the p-value is less than 10%. The higher probability level of 10% was chosen because of the often short record lengths and the high variability characteristic of Australian hydrology.

RESULTS

Figure 2(a) shows annual rainfall at Katherine between 1873–74 and 2009–10. A five-year moving average has been fitted to the data in Fig. 2(a) to highlight temporal trends. Annual rainfall at Katherine oscillates between a high and a low state. These trends are similar to those recognized by Mollah *et al.* (1991) based on a 15-year moving average. The CUSUMs have been plotted in Fig. 2(b) for Katherine. Time periods with a positive slope indicate higher rainfall, periods with a negative slope indicate lower rainfall and periods with zero slope indicate constant rainfall (Carter, 1990). For Katherine, the CUSUM trends (Fig. 2(b)) also support oscillations between two different means. However, the duration of each mean state is highly variable, ranging from sub-decadal to multi-decadal.

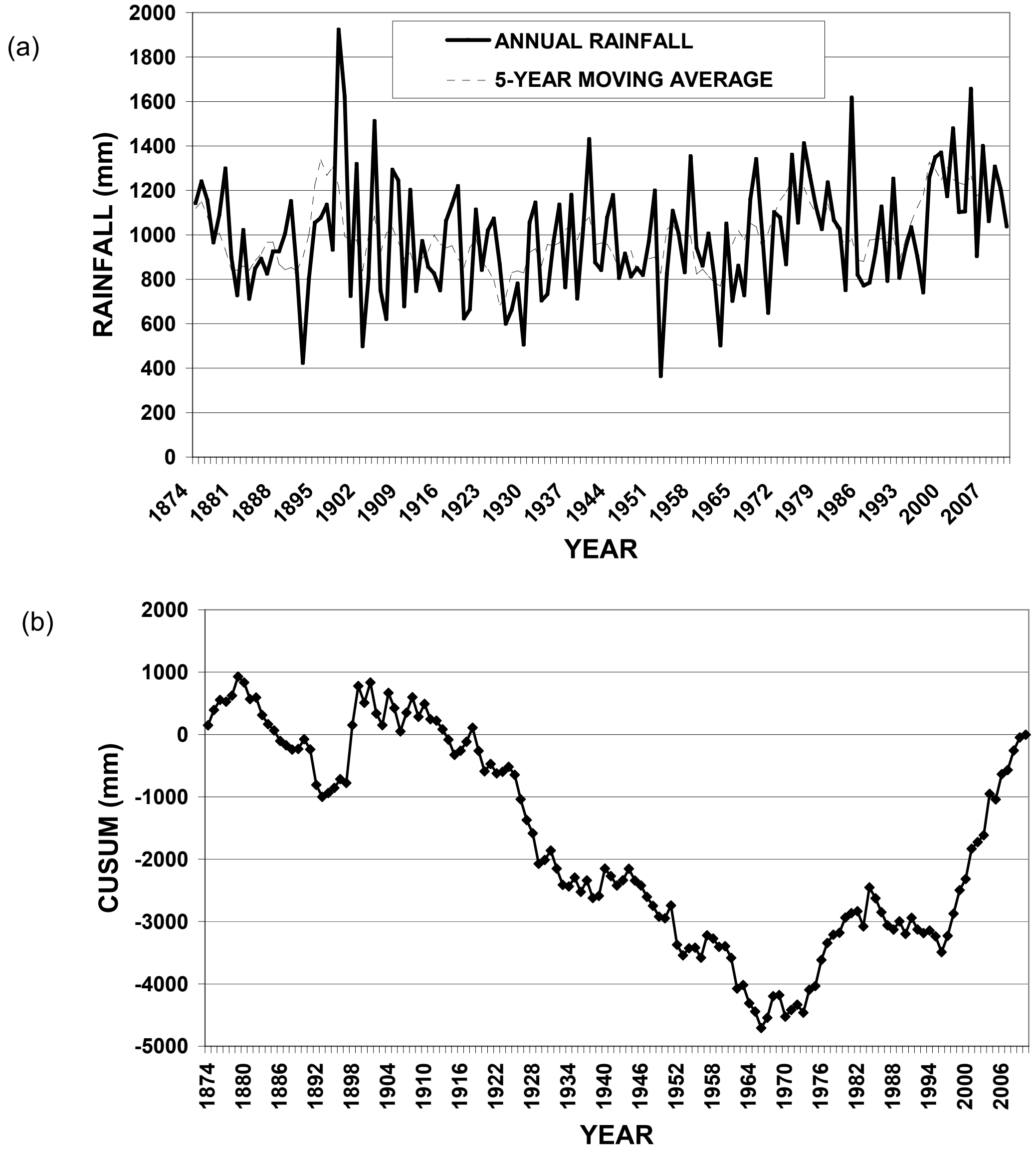

Fig. 2 (a) Annual rainfall with 5-year moving average at Katherine Council (Station Number 14902), and (b) CUSUM plot for Katherine Council. See Fig. 1 for location of station.

The results are summarized in Table 1. Different periods of mean rainfall (high *versus* low) were identified by different slopes of the CUSUM plot separated by distinct peaks or troughs at all stations. However, the time of the change from one rainfall mean state to the other was highly variable between stations right across the Top End. Modal years of change were 1951–1954 and 1984–1987 but only 7 of the 15 stations exhibit a change of rainfall within these two time periods. Other switch times are less common across the Top End. Clearly it has not been possible to identify simultaneous rainfall changes throughout the Top End and, therefore, it is not possible to determine changes in annual rainfall for the same periods of record.

Kruskal-Wallis test results indicate that at least one of the identified time periods has a different distribution to the other time periods at the 0.018% level or less at all 15 stations in the Top End. Mann Whitney test results indicate which time periods are statistically significantly different to each other in terms of annual rainfall (Table 1). The results in Table 1 only show comparisons between consecutive time periods. Of the 64 time periods compared, annual rainfall is not

Table 1 Results of Mann Whitney test for comparison of annual rainfall for specified time periods at 15 rainfall stations in the Top End of the Northern Territory, Australia. Significance levels cited for comparison with preceding time period.

Station name and number	Period of record	% Estimated record	Median annual rainfall (mm)						
Darwin PO (14016)	1870–1962	7.5	1593.0 (1870–1898)	1417.5** (1899–1909)	1608.3* (1910–1923)	1429.7* (1924–1953)			
Darwin Airport (14015)	1942–2010	0				1472.4 (1942–1966)	1933.5*** (1967–1977)	1684.0* (1978–1996)	1917.5 (1997–2010)
Oenpelli (14042)	1910–2009	11.0		1629.5 (1910–1918)	1270.6*** (1919–1954)	1436.1** (1955–1972)	1726.4* (1973–1984)	1277.1** (1985–1993)	1619.5*** (1994–2006)
Warruwi (14401)	1916–2009	16.0		1527.6 (1916–1921)	1075.7*** (1922–1952)	1461.5** (1953–1959)	1115.8** (1960–1979)	1250.7 (1980–2000)	817.2*** (2001–2009)
Pine Creek (14933)	1875–2006	26.5	1117.9 (1875–1893)	1403.6*** (1894–1899)	970.2*** (1900–1915	1251.9* (1916–1926)	1005.6** (1927–1953)	1250.1*** (1954–1985)	1117.4** (1986–1996)
Pine Creek (cont.)									1337.3*** (1997–2006)
Katherine Council (14902)	1874–2010	13.1	1149.1 (1874–1879)	870.5*** (1880–1893)	1106.1** (1894–1901)	861.2** (1902–1966)	1090.3*** (1967–1984)	861.8** (1985–1996)	1230.3*** (1997–2010)
Rosewood (14821)	1895–2009	16.5	685.0 (1895–1907)	564.4 (1908–1912)	686.7 (1913–1927)	541.1** (1928–1941)	816.4*** (1942–1946)	536.2*** (1947–1966)	662.0** (1967–1984)
Rosewood (cont.)								537.4 (1985–1990)	731.5** (1991–2009)
Newry (14820)	1900–2009	21.8		699.5 (1904–1954)	1023.8*** (1955–1960)	639.5*** (1961–1973)	844.2** (1974–1989)	626.7*** (1990–1998)	855.7*** (1999–2009)
Timber Creek Police (14822)	1921–2009	27.0				649.1 (1925–1941)	902.2*** (1942–1951)	824.6 (1952–1971)	974.1*** (1972–2009)
Victoria River Downs (14825)	1887–2009	5.7		522.8 (1887–1895)	650.6 (1896–1904)	583.5 (1905–1971)	742.1*** (1972–1985)	584.7*** (1986–1990)	901.5** (1991–2009)
Newcastle Waters (15086)	1890–2009	11.7				446.1 (1890–1966)	650.3*** (1967–1985)	397.8*** (1986–1998)	660.7*** (1999–2008)
Nutwood Downs (14621)	1935–2009	12.0				628.4 (1941–1971)	822.9*** (1972–1987)	619.5** (1988–1998)	984.8** (1999–2009)
Roper River Police (14620)	!895–1977	15.7				545.4 (1899–1923)	780.4*** (1924–1951)	523.1** (1952–1962)	930.5*** (1963–1977)
Angurugu (14506)	1921–2009	25.8				1247.8 (1924–1971)	1628.1*** (1972–1979)	1148.9*** (1980–1996)	1483.2*** (1997–2009)
Borroloola (14710)	1890–1978	16.9		1009.8 (1890–1899)	662.6** (1900–1929)	859.7*** (1930–1977)			

<0.1%; ** Significant at <0.05%; *** Significant at <0.01%

significantly different for 7 periods (11%), significantly different at the 0.1% level for 6 periods (9%), at the 0.05% level for 19 periods (30%) and at the 0.01% level or less for 32 periods (50%).

Clearly, the historical period is characterized by significant rainfall changes throughout the Top End. CUSUMs are appropriate for identification of the timing of switches in mean annual rainfall.

We also tested for differences between non-consecutive time periods at each station. Wet periods were usually identical statistically, as were the dry periods, but non-consecutive wet and dry periods were usually significantly different. Therefore, non-consecutive wet and dry periods are similar to each other.

DISCUSSION AND CONCLUSIONS

Historical rainfall in the Top End of Australia is characterized by statistically significant, alternating periods of low and high rainfall, which we call flood- and drought-dominated regimes (Erskine & Townley-Jones, 2009). However, many time periods are out-of-phase, suggesting that underlying meteorological causes are complex. Nevertheless, the meteorological cause of alternating rainfall regimes must be related to some cause that repeatedly switches from one state to another. Importantly, these changes are not well represented at Darwin, which is not sensitive for recording temporal rainfall trends in the Top End. Katherine has the longest, most representative rainfall record. Jolly (2001) and Wasson *et al.* (2010) concluded that alternating rainfall regimes at Katherine were reflected in similar changes in runoff of the Daly and Katherine rivers. Wasson & Bayliss (2011) found that streamflow trends paralleled rainfall since 1970 for both Magela Creek and Katherine River. This important observation requires further investigation because of its significance for water resources availability and sediment dynamics in large catchments (Jolly, 2001; Wasson *et al.*, 2010). Wasson *et al.* (2010) concluded that wet periods coincided with more frequent large floods that eroded the channel edge of benches, but deposited sand on the surface of the same benches along the Daly River. Furthermore, these large floods eroded large pockets of riparian vegetation, even where it was in good condition. Therefore, there appears to be a direct connection between rainfall, floods and river channel behaviour, as found in southeastern Australia (Erskine & Townley-Jones, 2009).

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