Use of CLIGEN to Simulate Climate Change in Southeastern Australia

P. Vaghefi, B. Yu

Abstract. *CLIGEN is a stochastic weather generator to reproduce, statistically, daily weather variables, and CLIGEN output has been used to simulate the impact of climate change on runoff and soil erosion. Weather observations from regions with significant climate variability and change could be used to determine how to manipulate the input to or output from CLIGEN to simulate climate change scenarios. Previous studies mostly used simplistic approaches, such as changing the average daily rainfall on wet days by a fixed percentage or multiplying the CLIGEN-generated daily rainfall by a fixed factor. The aim of this article is to develop a method based on available historical data to adjust CLIGEN parameter values when, historically, rainfall has significantly changed. In southeastern Australia, rainfall showed a significant and abrupt increase in a 30-year period since the late 1940s from the preceding three decades. However, rainfall has decreased since the late 1970s, significantly at many sites in the same region. Long-term (90 years) daily rainfall data from 30 sites in this region were used to examine decadal variations in rainfall and to evaluate the changes to CLIGEN parameter values with significant changes in annual rainfall. Average daily rainfall, standard deviations, skewness coefficients, and probabilities of a wet day following a wet day and a wet day following a dry day were analyzed for each of three 30-year periods and for each of 30 sites in southeastern Australia. This article shows that rainfall data for the period from 1919 to 1978 would suggest an increase in rainfall in southeastern Australia. However, from the perspective of the period from 1949 to 2008, the conclusion of decreasing rainfall would be reached. Both these 60-year periods broadly coincide with an underlying trend of increased temperature in Australia and globally. Daily rainfall data for the 90-year period show that there are strong positive correlations between changes in mean monthly rainfall and changes in mean daily rainfall, standard deviation, and the probability of wet-following-dry sequences. There is little evidence to suggest ways of adjusting skewness coefficients or wet-following-wet probabilities to simulate changes in mean monthly rainfall for this region. A set of regression equations was developed to allow easy adjustment of CLIGEN parameter values to simulate monthly rainfall change for both increasing and decreasing rainfall change scenarios. The results show that when CLIGEN parameter values were adjusted using changes in monthly rainfalls and regional relationships for the three important parameter values, output from CLIGEN was able to reproduce the changes in rainfall when compared with historical observations. The proposed methodology for adjusting CLIGEN parameters is not site-specific and could also be used for other similar regions in the world.*

Keywords. *CLIGEN, Climate change, Southeastern Australia, Weather generator.*

The impact of climate change on hydrology has become an issue of great concern in recent years. Future climates are usually predicted using numerical models (global climate models, or GCMs). Model output from GCMs needs to be downscaled to an appropriate spatial and temporal scale to drive hydrologic and biomass production models because climate models have a much coarser spatial resolution (Zhang, 2005, 2007). Stochastic weather generators are tools to produce synthetic weather sequences that are statistically similar to the observed weather data, and these stochastic weather generators have been widely used for downscaling GCM outputs (Semenov and Barrow, 1997; Wilby and Wigley, 1997; Goodess and Palutikof, 1998; Wilby et al., 1998; Zhang and Garbrecht, 2003; Yu, 2005; Zhang and Liu, 2005; Zhang, 2005, 2007).

CLIGEN is one such stochastic weather generator for climate change impact studies (Nicks et al., 1995; Xu, 1999; Prudhomme et al., 2002; Favis-Mortlock and Savabi, 1996; Pruski and Nearing, 2002a; Zhang, 2005; Yu, 2005; Zhang et al., 2010). For each daily simulation period, ten weather variables can be generated to provide input to the Water Erosion Prediction Project (WEPP) for runoff, biomass production, and soil erosion predictions (Nicks et al., 1995; Yu, 2000). WEPP is a physically based daily runoff and erosion simulation model built on the fundamentals of hydrology, plant science, hydraulics, and erosion mechanics (Zhang and Garbrecht, 2003). Typically, input parameter values for CLIGEN are changed to represent the likely climate change scenarios (Pruski and Nearing, 2002a; Zhang, 2004). In particular, mean precipitation amounts on wet days are altered to simulate the likely change to precipitation predicted by the GCM (Pruski and Nearing, 2002b; Zhang, 2004). Zhang (2005) used an empirical relationship between mean monthly rainfall and transitional probabilities to estimate the likely changes in the number of wet days, and used an analytical expression to adjust the standard deviation of daily pre-

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cipitation. However, there is little research on how to change parameter values for stochastic weather generators based on observed weather data from regions where precipitation is known to have significantly changed (Zhang and Garbrecht, 2003; Yu, 2005).

It is well documented that rainfall in a 30-year period since the late 1940s was significantly higher than the preceding three decades in southeastern Australia (Cornish, 1977; Pittock, 1983; Yu and Neil, 1991; Nicholls and Kariko, 1993). These changes were used to indicate how rainfall might change in a CO_2-warmed world (Pittock, 1983; Yu and Neil, 1991). Research by Zhang and Garbrecht (2003) showed the CLIGEN-generated durations were generally too long for small storms and too short for large storms. Yu (2005) reported how to adjust values of CLIGEN parameters to generate storm patterns that varied between wetter and drier period for a single site (Sydney) in the region. The current study extends the work of Yu (2005) to focus on daily rainfall for the entire region of southeastern Australia, where rainfall has significantly increased. This research also attempts to extend the study period by another three decades, up until the end of 2008.

While it is well known that rainfall increased widely in southeastern Australia for the three decades since the late 1940s (Cornish, 1977; Pittock, 1983; Yu and Neil, 1991; Nicholls and Kariko, 1993), in many cases in the region, it is not yet well established that rainfall since the late 1970s has significantly decreased. This significant and contrasting change in rainfall in southeastern Australia not only raises questions about the intrinsic relationship between climate change and statistically significant rainfall change but also about the operational issue of using weather generators to capture significant rainfall change and variability on the time scales of regional climatology, i.e., 30-year periods.

The objectives of this article are:

- To identify and quantify significant changes in rainfall in southeastern Australian for the 90-year period (1919-2008).
- To contrast the CLIGEN parameter values between drier and wet periods.
- To determine how CLIGEN parameter values could be changed to represent historical trends and patterns in rainfall in this and similar regions of the world.

Data and Methodology

Station Selection

At the time of this study, more than 4,800 stations were available for use from the database of the National Climate Centre of the Bureau of Meteorology (BoM). The stations are located in New South Wales and Australian Capital Territory. The spatial extent of this study is defined by 147° 31′ E to 153° 30′ E and from 28° 53′ S to 37° 30′ S. The region has a temperate climate with essentially uniform rainfall throughout the year (BoM, 1989).

To identify the rainfall trends in southeastern Australia, weather stations were selected for three non-overlapping 30-year periods (1919-1948, 1949-1978, and 1979-2008). The year 1949 was reported to be the first year when significant rainfall increase occurred in this region (Yu, 1995, 2005).

In an initial attempt, 41 stations were selected based on their geographical locations. Thirty high-quality stations were finalized for this analysis in consultation of the list of high-quality rainfall stations in Australia (Lavery et al., 1992, 1997) based on the length and quality of the recorded rainfall data. Table 1 shows the station number, location, total number of years of rainfall record, and mean annual rainfall for the three 30-year periods for the 30 stations in southeastern Australia. Spatial distribution of the 30 sites is shown in figure 1.

Daily rainfall data for the 90-year period from 1919 to 2008 were extracted from the national climate database using software known as MetAccess. Daily data was then aggregated into monthly and annual totals for further analysis and for calculating CLIGEN input parameter values.

Methodology

To meet the objectives of this study, three non-overlapping periods were selected for comparison purposes. The selected stations were checked to identify the maximum change in annual rainfall between the first two 30-year periods. The periods from 1919 to 1948 and from 1949 to 1978 led to greater contrast in terms of mean annual rainfall for most of the 30 stations in southeastern Australia, a pattern that is consistent with previous observations (Yu, 1995, 2005).

The annual rainfall totals were tested for significant differences in the mean between the first and second periods, and between the second and third periods. A standard t-test for two samples with equal variance was used for the contrasting periods and for all 30 sites. To qualify the level of significance using the t-test, the classification shown in table 2 was adopted based on the p-value of the one-tail t-test.

In this article, period 1 is defined as the 30-year period from 1919-1948, period 2 is from 1949-1978, and period 3 is from 1979-2008. Spring is defined to include September, October, and November; summer includes December, January and February; autumn includes March, April, and May; and winter includes June, July and August. Summer-half is defined to include the spring and summer months, and winter-half includes the autumn and winter months.

To generate daily rainfall amounts, CLIGEN requires the following input parameter values for each month of the year:

- Average daily precipitation on wet days (P_w)
- Standard deviation of daily precipitation (S_d)
- Coefficient of skewness of daily precipitation (S_k)
- The probability of a wet day following a wet day
- The probability of a wet day following a dry day.

Calculation of basic statistics of daily rainfall is straightforward. Chapter 2 of the WEPP User Manual (Nicks et al. 1995) is the original reference on CLIGEN. In addition, Yu (2005) provided comprehensive definitions and methods to calculate the probability of a wet day following a wet day and the probability of a wet day following a dry day for each month. In that definition, N_{dd} is the total number of dry days in the month following a dry day, N_{wd} is the total number of dry days in the month following a wet day, N_{ww} is the total number of wet days in the month following a wet day, and N_{dw} is the total number of wet days in the month following a dry day. By this classification, all possible combinations are included. Therefore, the probability of a wet day following a wet day and the probability of a wet day following a dry day for each month can be calculated from:

Table 1. Thirty selected stations in southeastern Australia.

Station No.	Location	Longitude	Latitude	Years of Record	Mean Annual Rainfall (mm)		
					1919-1948	1949-1978	1979-2008
50004	Bogan Gate Post Office	147° 48′ E	33° 6′ S	103	452	581	462
50018	Dandaloo (Kelvin)	147° 40′ E	32° 17′ S	115	436	552	497
50028	Trundle (Murrumbogie)	147° 31′ E	32° 54′ S	121	408	549	471
50031	Peak Hill Post Office	148° 11′ E	32° 43′ S	116	492	644	568
52019	Mogil Mogil (Benimora)	148° 41′ E	29° 21′ S	119	445	536	527
53003	Bellata Post Office	149° 48′ E	29° 55′ S	91	529	657	623
53018	Croppa Creek (Krui Plains)	150° 1′ E	28° 60′ S	92	517	629	597
54003	Barraba Post Office	150° 37′ E	30° 23′ S	125	629	764	685
54004	Bingara Post Office	150° 34′ E	29° 52′ S	124	670	771	709
55045	Curlewis (Pine Cliff)	150° 2′ E	31° 11′ S	103	505	650	631
55055	Carroll (The Ranch)	150° 28′ E	30° 58′ S	112	549	675	602
58012	Yamba Pilot Station	153° 22′ E	29° 26′ S	129	1390	1599	1438
58063	Casino Airport	153° 3′ E	28° 53′ S	130	1078	1170	1006
60026	Port Macquarie (Bellevue Gardens)	152° 55′ E	31° 26′ S	139	1401	1669	1395
61000	Aberdeen (Main Rd.)	150° 53′ E	32° 10′ S	107	550	676	516
61010	Clarence Town (Grey St.)	151° 47′ E	32° 35′ S	110	1058	1141	1016
61014	Branxton (Dalwood Vineyard)	151° 25′ E	32° 38′ S	116	771	900	808
61071	Stroud Post Office	151° 58′ E	32° 24′ S	114	1036	1135	1021
62021	Mudgee (George St.)	149° 36′ E	32° 36′ S	135	605	755	705
62026	Rylstone (Ilford Rd.)	149° 59′ E	32° 48′ S	116	607	724	548
63005	Bathurst Agricultural Station	149° 33′ E	33° 26′ S	97	570	723	628
63032	Golspie (Ayrston)	149° 40′ E	34° 16′ S	108	663	827	659
64008	Coonabarabran (Namoi St.)	149° 16′ E	31° 16′ S	127	640	834	790
65022	Manildra (Hazeldale)	148° 35′ E	33° 10′ S	117	624	761	647
68016	Cataract Dam	150° 48′ E	34° 16′ S	99	903	1316	981
68034	Jervis Bay (Point Perpendicular Lighthouse)	150° 48′ E	35° 6′ S	105	1051	1478	1146
69006	Bettowynd (Condry)	149° 47′ E	35° 42′ S	106	732	927	671
69018	Moruya Heads Pilot Station	150° 9′ E	35° 55′ S	131	896	1136	943
70027	Delegate (Weewalla)	148° 60′ E	37° 3′ S	115	607	686	580
70028	Yass (Derringullen)	148° 53′ E	34° 45′ S	105	670	796	670

$$\Pr(W|W) = \frac{N_{ww}}{(N_{dw} + N_{ww})} \quad (1)$$

$$\Pr(W|D) = \frac{N_{dw}}{(N_{wd} + N_{dd})} \quad (2)$$

Mean monthly rainfall is the product of the mean wet day rainfall (P_w) and the number of wet days for the month (N_w). The mean wet day rainfall is one of the input parameters for CLIGEN, the average number of wet days is related to the transition probabilities:

$$N_w = \frac{N_d \times \Pr(W|D)}{[1 - \Pr(W|W) + \Pr(W|D)]} \quad (3)$$

where N_d is the number of days in the month. Therefore, changes in rainfall amount can be effected through changes to wet-day rainfall, or transition probabilities, or both.

Alternatively, rainfall total can be regarded as the product of the number of rainfall events and the average event rainfall. An event is defined in this article as a period of consecutive wet days. Rainfall events are separated by at least one dry day. The average event rainfall in terms of CLIGEN parameters is given by:

$$P_e = \frac{P_w}{1 - \Pr(W|W)} \quad (4)$$

Rainfall changes can be a result of changes to event rainfall amount, or the number of rainfall events, or both. In either case, the CLIGEN parameters provide a rich framework for examining the changes to rainfall attributes, e.g., the amount, duration, and frequency of occurrence in relation to changes to rainfall totals.

Changes to CLIGEN parameter values are related to the underlying changes to mean monthly rainfall for the 30 stations in southeastern Australia. This allows adjustment to CLIGEN parameter values to represent historical changes in rainfall in southeastern Australia, and to determine how CLIGEN parameter values could be changed to simulate climate change scenarios in this and similar regions in the world.

To test this adjustment method, changes in mean monthly rainfall between period 1 (1919–1948) and period 2 (1949–1978) and regression equations for changes in CLIGEN parameter values were used to adjust CLIGEN input parameter values for period 1 to derive parameter values for period 2. The calculated and the adjusted parameter values were then used to simulate the climate for periods 1 and 2, respectively, with CLIGEN. The simulated rainfall changes between periods 1 and 2 were then compared with the changes based on observed rainfall changes as well as changes in simulated rainfall with CLIGEN and calculated parameter values using historical rainfall data for the two periods separately. All the simulated climates were based on CLIGEN runs of 100 years in duration with disparate random seeds for each.

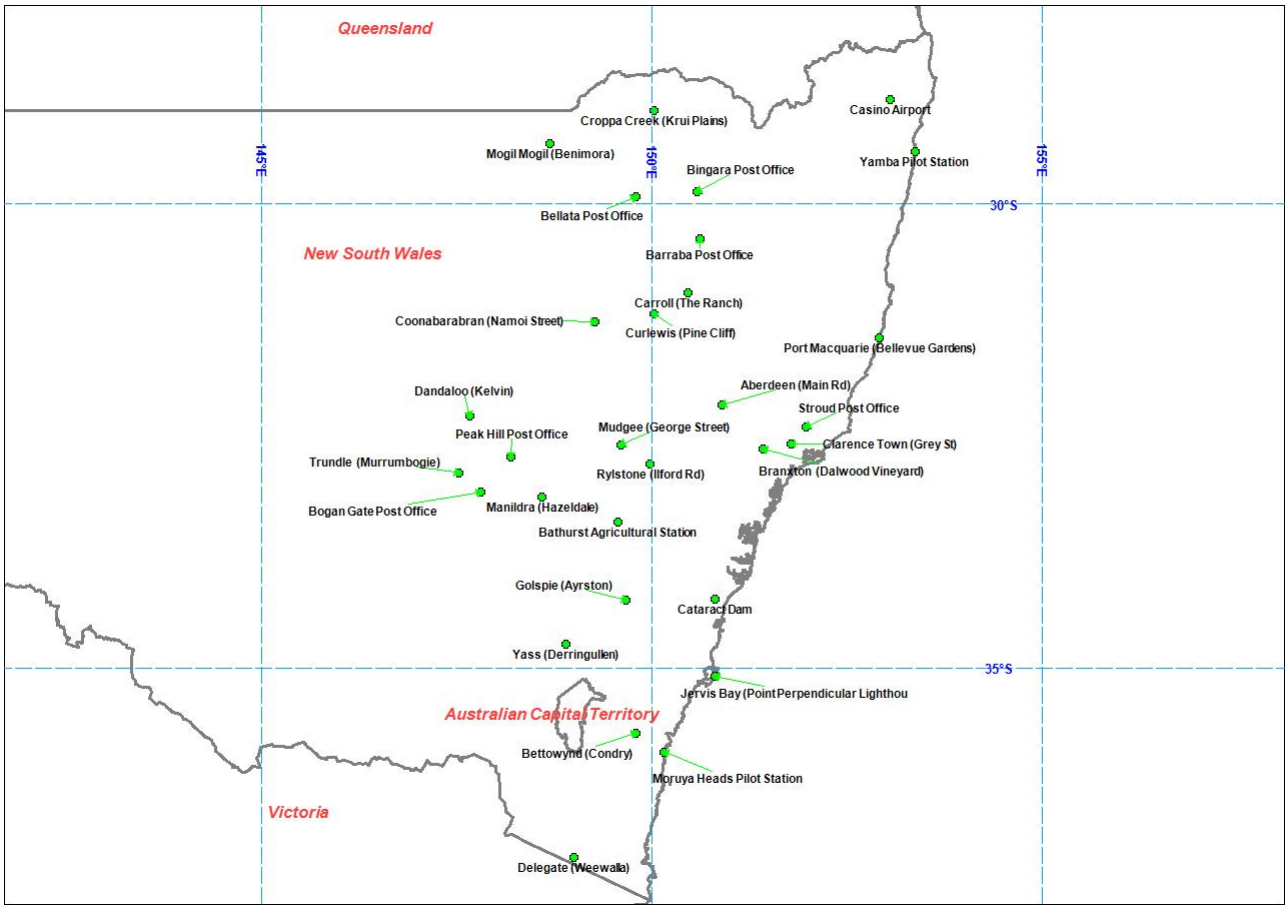

Figure 1. Location of the 30 stations selected in southeastern Australia.

Table 2. Classification of statistical significance based on the p-value.

Criteria	Classification
$p > 0.1$	Not significant
$0.05 < p < 0.1$	Marginally significant
$0.01 < p < 0.05$	Significant
$p < 0.01$	Highly significant

Results

Trends in Mean Annual Rainfall

All the 30 stations had a greater mean annual rainfall in period 2 (1949–1978) than in period 1 (1919–1948). Conversely, the last period (1979–2008) had lower mean annual rainfall in comparison to that in the second period for all the stations tested. As an example, figure 2 shows the time series of annual rainfall at Bogan Gate Post Office. It is clear from the diagram that rainfall at the site experienced a dramatic increase from the first to the second 30-year period (452 to 581 mm year^{-1}). This period of increased rainfall is followed by an equally dramatic decrease during the last 30 years, with mean annual rainfall reduced to 462 mm year^{-1} for 1979–2008, a level that is very similar to that for the first 30 years (1919–1948).

Comparing rainfall for period 1 (1918–1948) and period 2 (1949–1978) shows that 67% of the stations (20 out of 30) recorded a highly significant increase in mean annual rainfall. Seven of the 30 stations showed a significant increase, and two showed marginal increases. Increase in rainfall is not statistically significant for just one of the 30 stations (Clarence Town) (figs. 3 and 4).

In contrast, all the stations showed a lower mean annual rainfall for period 3 in comparison to period 2. Nine of the 30 stations showed highly significant decrease in mean annual rainfall. The other 21 stations are evenly classified into the three other categories.

The largest increase during periods 1 and 2 occurred at the Cataract Dam station, showing a 31% increase in mean annual rainfall (an average of 903 mm for 1919–1948 and an average of 1316 mm for 1949–1978). The smallest increase for the same contrasting periods was a 7% increase at mean annual rainfall at Clarence Town. For the second pair of contrasting periods (1949–1978 vs. 1979–2008), Bettowynd (Condry) showed the highest decrease in mean annual rainfall (38%) of the 30 stations examined. The lowest decrease of 2% in mean annual rainfall occurred at Mogil Mogil (Benimora).

Figure 5 shows a comparison of mean annual rainfall between the contrasting periods. It is clear that rainfall was consistently higher in period 2 than in both the preceding and ensuing 30-year periods. A simple regression between mean annual rainfall for the contrasting periods shows that mean annual rainfall on average increased by 14% between period 1 (1919–1948) and period 2 (1949–1978) and subsequently decreased by 19% between period 2 and period 3 (1979–2008).

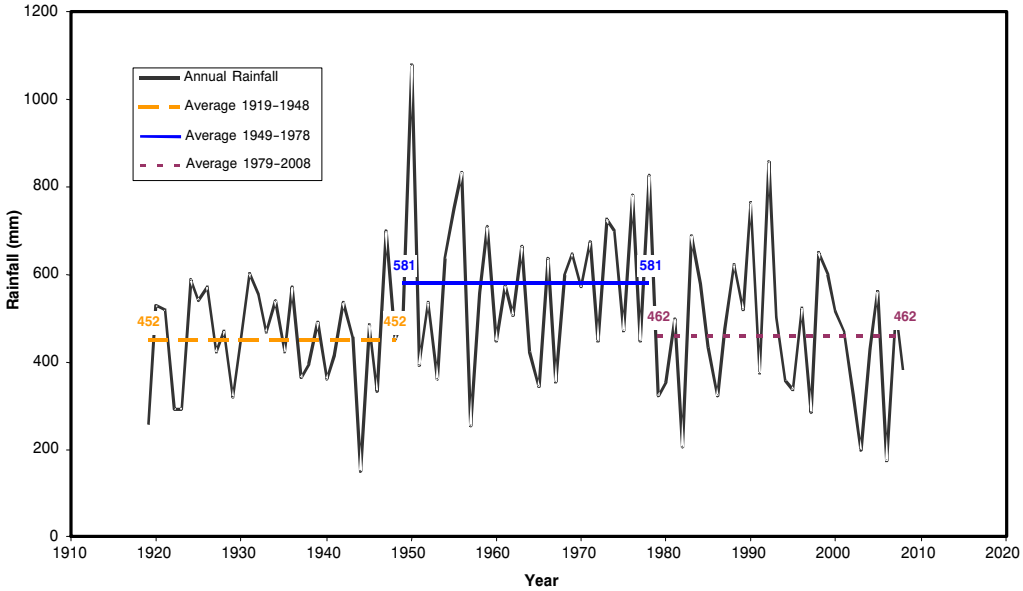

Figure 2. Time series of annual rainfall amount at Bogan Gate Post Office (1919–2008).

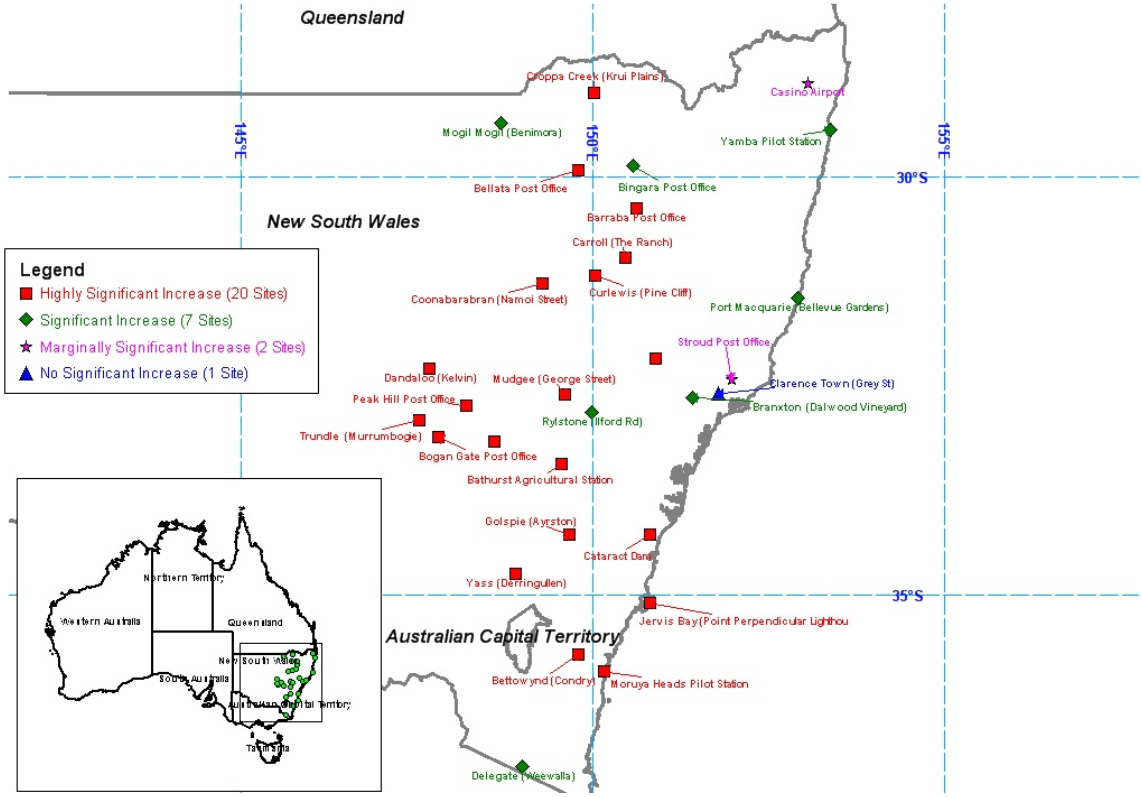

Figure 3. Sites of significant increase in mean annual rainfall between 1919–1948 and 1949–1978 in southeastern Australia.

Seasonal Rainfall

Table 3 shows changes to seasonal rainfall between periods 1 and 2 and between periods 2 and 3. This is a summary of the sites with different degrees of statistical significance with respect to the changes in annual and seasonal rainfall in southeastern Australia (table 3). For most seasons, and for a majority of the sites tested, seasonal rainfall followed the same pattern as annual rainfall, with a significant increase in period 2, followed by a decrease in rainfall for the last 30 years (1979–2008) (tables 3 and 4). For some sites in southeastern Australia, the seasonal rainfall does not follow the increasing and decreasing pattern for annual rainfall, especially for autumn and winter (tables 3 and 4).

Overall, it is clear from table 3 that rainfall increased between periods 1 and 2 and decreased between periods 2 and 3. The increase between periods 1 and 2 was more dramatic

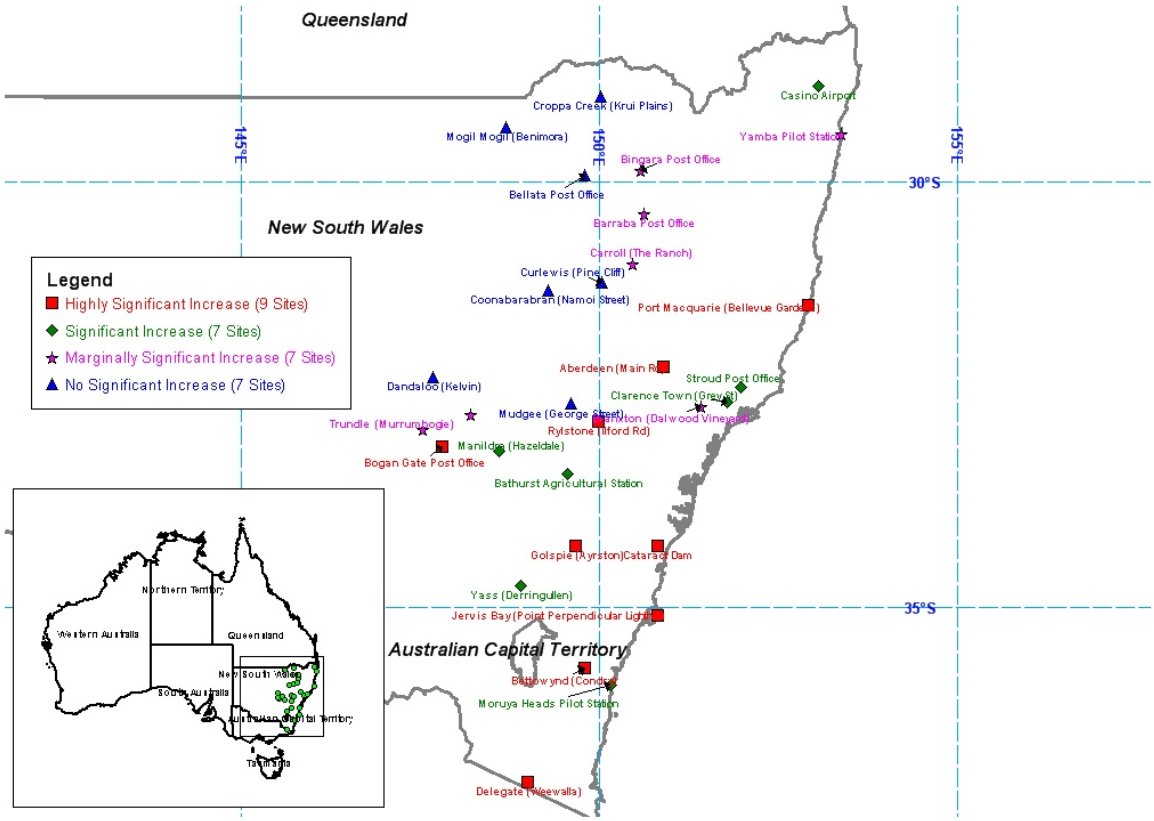

Figure 4. Sites of significant decrease in mean annual rainfall between 1949–1978 and 1979–2008 in southeastern Australia.

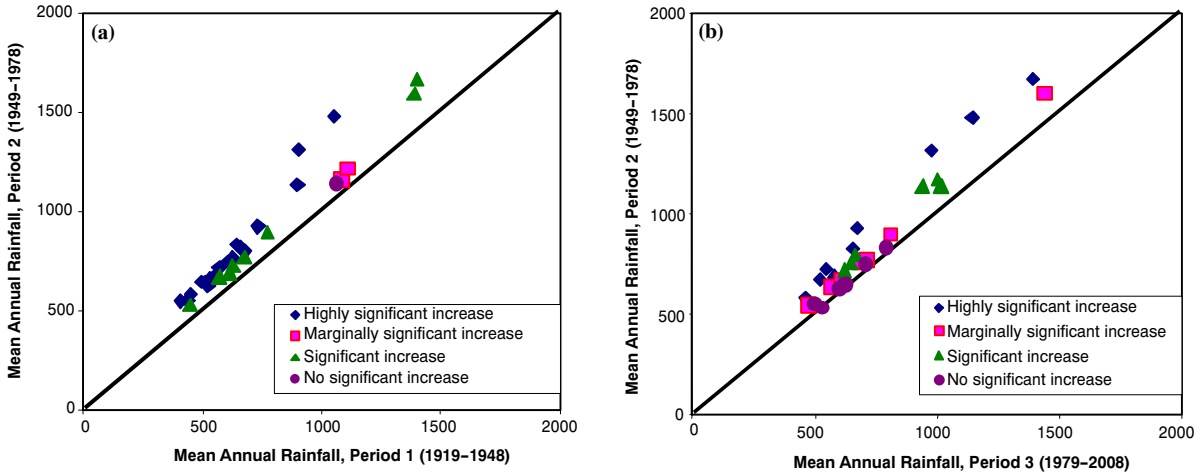

Figure 5. Comparison of the mean annual rainfall between the three 30-year periods for the 30 stations in southeastern Australia: (a) between 1919–1948 and 1949–1978, and (b) between 1949–1978 and 1979–2008.

and more consistent among the 30 sites tested than the decrease between periods 2 and 3. The increase followed by decrease is most consistent for summer rainfall and least consistent for autumn and winter rainfall. In fact, winter rainfall experienced no significant increase between periods 1 and 2 and no significant decrease between periods 2 and 3 for most of sites tested in southeastern Australia.

CLIGEN Parameter Values

Unlike the mean annual rainfall, the mean daily rainfall for each month does not follow a clear pattern. Daily rainfall at some of the sites for some of the months increased, and for others it decreased. The most dramatic increase in mean daily rainfall occurred at Cataract Dam, with a 54.9% increase in March (from 1919–1948 to 1949–1978), and the largest de-

Table 3. Variations in rainfall and statistical level of significance: HS = highly significant, S = significant, MS = marginally significant, NS = not significant, up arrow (↑) = increase, and down arrow (↓) = decrease.

	1919-1948 to 1949-1978					1949-1978 to 1979-2008				
Station	Annual	Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter
Bogan Gate Post Office	HS ↑	HS ↑	S ↑	S ↑	NS ↑	HS ↓	MS ↓	S ↓	S ↓	NS ↓
Dandaloo	HS ↑	S ↑	S ↑	S ↑	NS ↑	NS ↓	MS ↓	MS ↓	NS ↓	NS ↑
Trundle (Murrumbogie)	HS ↑	HS ↑	S ↑	S ↑	NS ↑	MS ↓	NS ↓	MS ↓	NS ↓	NS ↑
Peak Hill Post Office	HS ↑	HS ↑	HS ↑	MS ↑	NS ↑	MS ↓	NS ↓	MS ↓	NS ↓	NS ↑
Mogil Mogil (Benimora)	S ↑	NS ↑	HS ↑	NS ↑	NS ↓	NS ↓	NS ↑	S ↓	NS ↑	NS ↑
Bellata Post Office	HS ↑	S ↑	HS ↑	NS ↑	NS ↓	NS ↓	NS ↑	NS ↓	NS ↓	NS ↑
Croppa Creek (Krui Plains)	HS ↑	S ↑	HS ↑	NS ↑	NS ↓	NS ↓	NS ↓	MS ↓	NS ↑	NS ↓
Barraba Post Office	HS ↑	HS ↑	HS ↑	NS ↑	NS ↓	MS ↓	MS ↓	S ↓	NS ↓	NS ↑
Bingara Post Office	S ↑	MS ↑	HS ↑	NS ↑	NS ↓	MS ↓	NS ↓	NS ↓	NS ↓	NS ↓
Curlewis (Pine Cliff)	HS ↑	HS ↑	HS ↑	NS ↑	NS ↓	NS ↓	NS ↓	NS ↓	NS ↑	NS ↑
Carroll (The Ranch)	HS ↑	HS ↑	HS ↑	MS ↑	NS ↓	MS ↓	MS ↓	S ↓	NS ↑	NS ↑
Yamba Pilot Station	S ↑	NS ↑	HS ↑	NS ↑	NS ↑	MS ↓	NS ↓	S ↓	NS ↑	NS ↓
Casino Airport	MS ↑	NS ↑	S ↑	NS ↓	NS ↑	S ↓	NS ↓	HS ↓	NS ↓	S ↓
Port Macquarie	S ↑	NS ↑	HS ↑	NS ↑	NS ↑	HS ↓	NS ↓	HS ↓	NS ↓	S ↓
Aberdeen (Main Rd.)	HS ↑	MS ↑	HS ↑	NS ↑	NS ↑	HS ↓	S ↓	HS ↓	MS ↓	MS ↓
Clarence Town (Grey St.)	NS ↑	NS ↓	S ↑	NS ↓	NS ↑	S ↓	NS ↑	S ↓	NS ↑	S ↓
Branxton	S ↑	NS ↑	HS ↑	NS ↓	NS ↑	MS ↓	NS ↑	S ↓	NS ↑	MS ↓
Stroud Post Office	MS ↑	NS ↑	HS ↑	NS ↓	NS ↑	S ↓	NS ↑	HS ↓	NS ↑	S ↓
Mudgee (George St.)	HS ↑	S ↑	HS ↑	NS ↑	NS ↑	NS ↓	NS ↓	S ↓	NS ↓	NS ↑
Rylstone (Ilford Rd.)	S ↑	NS ↑	HS ↑	NS ↑	NS ↑	HS ↓	MS ↓	HS ↓	S ↓	MS ↓
Bathurst Agricultural Station	HS ↑	HS ↑	HS ↑	MS ↑	NS ↑	S ↓	NS ↓	S ↓	MS ↓	NS ↓
Golspie (Ayrston)	HS ↑	HS ↑	S ↑	MS ↑	NS ↑	HS ↓	MS ↓	HS ↓	S ↓	MS ↓
Coonabarabran	HS ↑	HS ↑	HS ↑	NS ↑	NS ↓	NS ↓	NS ↓	MS ↓	NS ↑	NS ↑
Manildra (Hazeldale)	HS ↑	HS ↑	HS ↑	MS ↑	NS ↑	S ↓	NS ↓	S ↓	MS ↓	NS ↑
Cataract Dam	HS ↑	HS ↑	HS ↑	NS ↑	HS ↑	HS ↓	NS ↓	HS ↓	NS ↓	S ↓
Jervis Bay	HS ↑	HS ↑	S ↑	S ↑	HS ↑	HS ↓	HS ↓	HS ↓	S ↓	HS ↓
Bettowynd (Condry)	HS ↑	HS ↑	NS ↑	NS ↑	S ↑	HS ↓	HS ↓	HS ↓	S ↓	S ↓
Moruya Heads Pilot Station	HS ↑	HS ↑	NS ↑	NS ↑	HS ↑	S ↓	NS ↓	NS ↓	NS ↓	MS ↓
Delegate (Weewalla)	S ↑	HS ↑	NS ↓	NS ↑	S ↑	HS ↓	S ↓	MS ↓	MS ↓	MS ↓
Yass (Derringullen)	HS ↑	HS ↑	S ↑	MS ↑	NS ↑	S ↓	MS ↓	S ↓	S ↓	NS ↓

Table 4. Direction of change and the statistical level of significance among the 30 sites in southeastern Australia.

	1919-1948 to 1949-1978					1949-1978 to 1979-2008				
Directions	Annual	Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter
Increase	30	29	29	26	22	0	5	0	9	11
Decrease	0	1	1	4	8	30	25	30	21	19
Level of significant	Annual	Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter
Highly significant	20	16	19	0	3	9	2	9	0	1
Significant	7	4	8	4	2	7	2	11	6	6
Marginally significant	2	2	0	6	0	7	7	6	4	6
No significant	1	8	3	20	25	7	19	4	20	17

crease occurred at Port Macquarie (Bellevue Gardens), with a 108.4% decrease in August (from 1949–1978 to 1979– 2008).

To determine how CLIGEN parameter values could be changed to represent historical trends and patterns in rainfall, the ratios for five major CLIGEN parameter values between the three contrasting periods for all stations were calculated. These ratios were then related to the ratios for the mean monthly rainfall for the same contrasting periods.

Figures 6 to 10 show the changes in terms of the ratio of parameter values for the mean, standard deviation, skewness, probabilities of a wet day following a wet day, probabilities of a wet day following a dry day, and number of wet days for all stations in comparison of the ratio of monthly rainfall for the contrasting periods. Figures 6, 7, and 10 and table 5 show that there are significant positive correlations between changes in mean monthly rainfall and changes in mean daily rainfall, standard deviations of mean daily rainfall, and the probability of wet following dry days. As indicated in table 5 and figures 8 and 9, there are no strong correlation between changes in mean monthly rainfall and those in skewness and wet–following–wet probabilities.

Table 5 presents the R^2 values of the linear trend line correlation coefficient squared between the changes in mean monthly rainfall and the changes in the five major CLIGEN parameter values. Linear correlation coefficients show that changes in monthly rainfall are closely related changes in mean daily rainfall, the standard deviation of daily rainfall, and the transition probability for wet following dry days. On the other hand, the relationship between changes in rainfall and changes in the skewness coefficient for daily rainfall and wet–following–wet probabilities is insignificant. To adjust the model parameter values to simulate changes in rainfall, the latter two parameters can remain unchanged based on the data for the 30 sites tested.

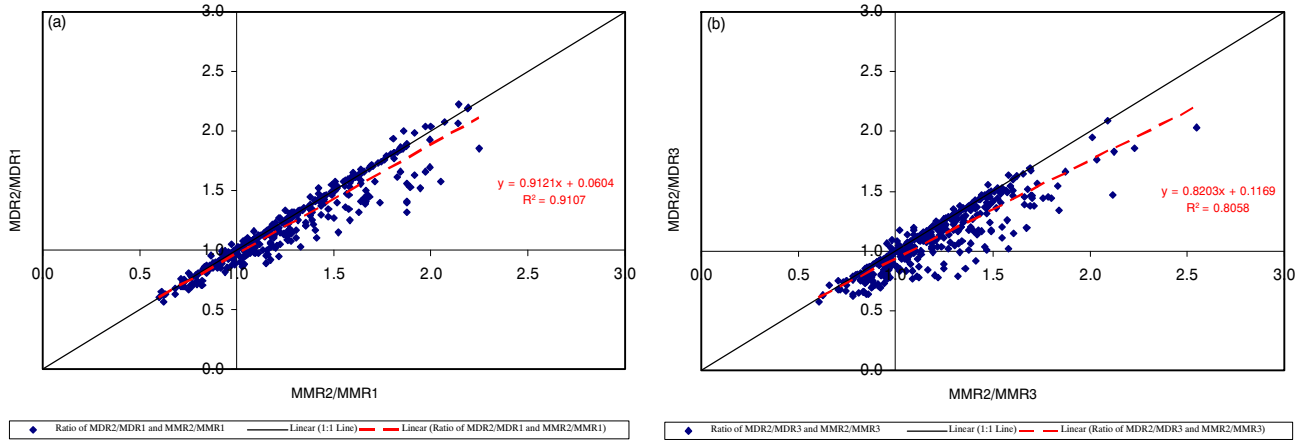

Figure 6. Relationship between changes in mean monthly rainfall (MMR) and changes in mean daily rainfall (MDR): (a) between 1919–1948 and 1949–1978, and (b) between 1949–1978 and 1979–2008.

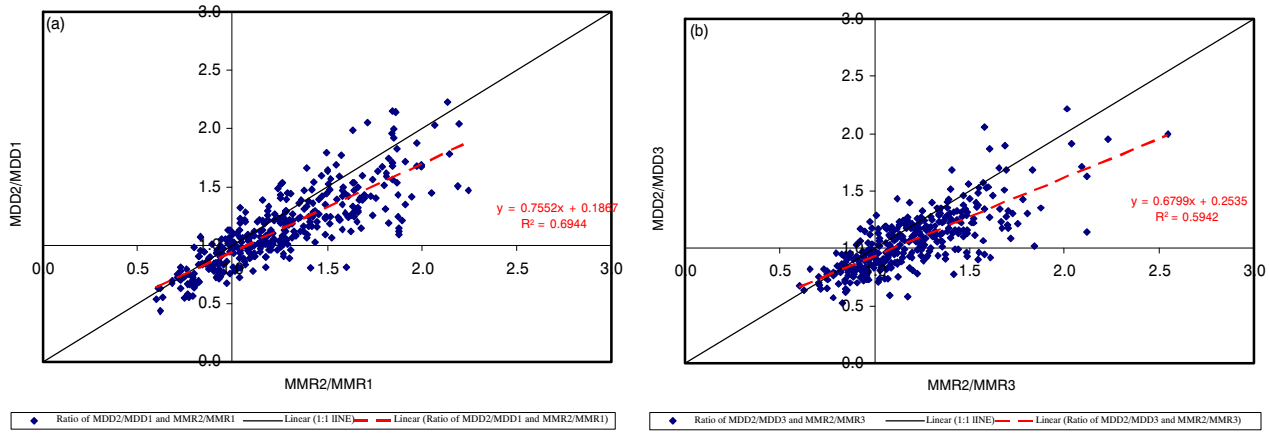

Figure 7. Relationship between changes in mean monthly rainfall (MMR) and changes in the standard deviation of mean daily rainfall (MDD): (a) between 1919–1948 and 1949–1978, and (b) between 1949–1978 and 1979–2008.

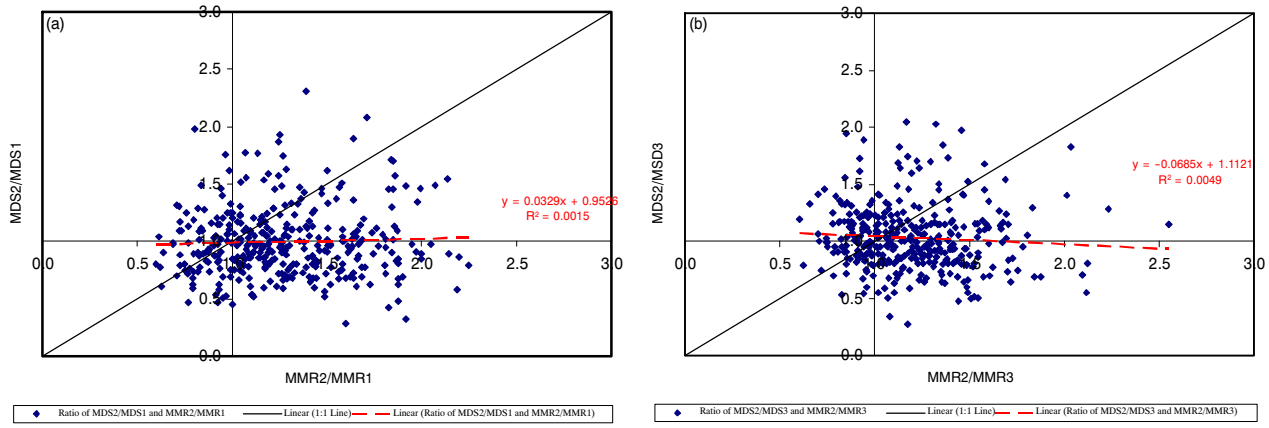

Figure 8. Relationship between changes in mean monthly rainfall (MMR) and changes in the Skewness of mean daily rainfall (MDS): (a) between 1919–1948 and 1949–1978, and (b) between 1949–1978 and 1979–2008.

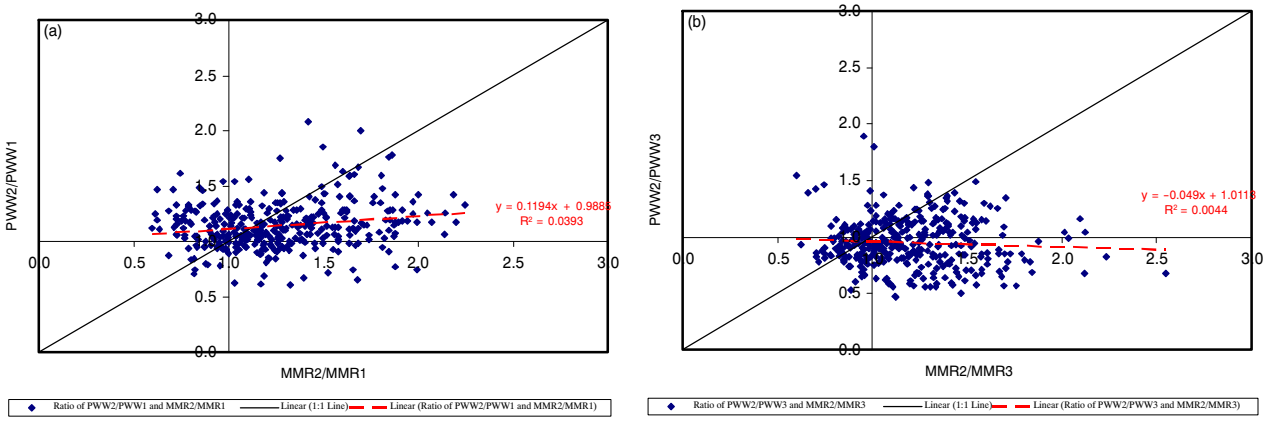

Figure 9. Relationship between changes in mean monthly rainfall (MMR) and changes in the probability of the wet day following a wet day (PWW): (a) between 1919–1948 and 1949–1978, and (b) between 1949–1978 and 1979–2008.

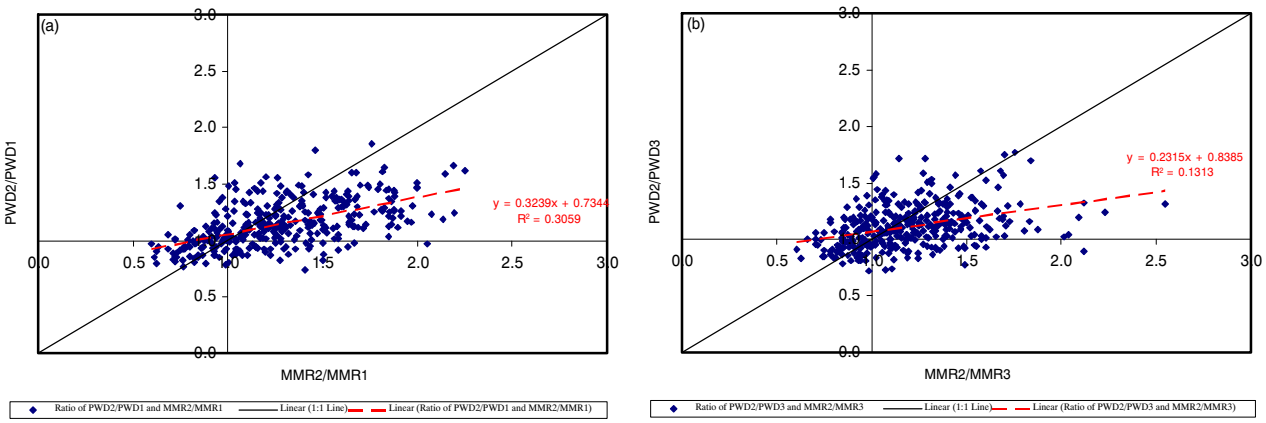

Figure 10. Relationship between changes in mean monthly rainfall (MMR) and changes in the probability of the wet day following a dry day (PWD): (a) between 1919–1948 and 1949–1978, and (b) between 1949–1978 and 1979–2008.

Table 5. R^2 values for linear correlation between changes in mean monthly rainfall and changes in CLIGEN parameters for the two contrasting periods and for summer-half and winter-half of the year (Between 1919–1948 and 1949–1978 periods and between 1949–1978 and 1979–2008).

Parameter	All Months	Summer-Half	Winter-Half
1919-1948 and 1949-1978			
Mean P	0.9107	0.8875	0.9346
SD P	0.6944	0.6381	0.7503
Skew P	0.0015	0.0000	0.0057
Pr(W | W)	0.0393	0.0607	0.0262
Pr(W | D)	0.3059	0.3106	0.2450
1949-1978 and 1979-2008			
Mean P	0.7937	0.7568	0.8206
SD P	0.5715	0.5801	0.5542
Skew P	0.0131	0.0000	0.0496
Pr(W | W)	0.0086	0.0063	0.0120
Pr(W | D)	0.1608	0.2545	0.1117

Table 6. Linear regression equations to predict, from changes in mean monthly rainfall, changes in CLIGEN parameter values of mean daily rainfall, daily standard deviation, and probability of a wet day following a dry day: x = change in monthly rainfall as ratios, and y = changes in model parameter values as ratios (see figures 6, 7, and 10).

Parameter	Equation
1919-1948 and 1949-1978	
Mean P	$y = 0.9121x + 0.0604$
SD P	$y = 0.7552x + 0.1867$
Pr(W | D)	$y = 0.3239x + 0.7344$
1949-1978 and 1979-2008	
Mean P	$y = 0.8203x + 0.1169$
SD P	$y = 0.6799x + 0.2535$
Pr(W | D)	$y = 0.2315x + 0.8385$
Combined	
Mean P	$y = 0.884x + 0.069$, $R^2 = 0.86$
SD P	$y = 0.729x + 0.208$, $R^2 = 0.66$
Pr(W | D)	$y = 0.287x + 0.776$, $R^2 = 0.22$

As mean monthly rainfall is not an input parameter for CLIGEN, some or all the five major parameters for CLIGEN need to be changed to achieve the required change in rainfall. Of the five parameters, table 5 shows that there is hardly any correlation between changes in rainfall and changes in skewness and wet-to-wet transition probabilities. Table 6 presents the linear regression equations that can be used to adjust the CLIGEN parameters based on the changes in rainfall that need to be simulated. It is clear that the regression equations are quite similar whether we consider rainfall increase (1919–1948 vs. 1949–1978) or rainfall decrease (1978–2008). A set of regression equations was derived using the combined data set of data on changes in monthly rainfall and changes on CLIGEN parameters (table 6). These equations

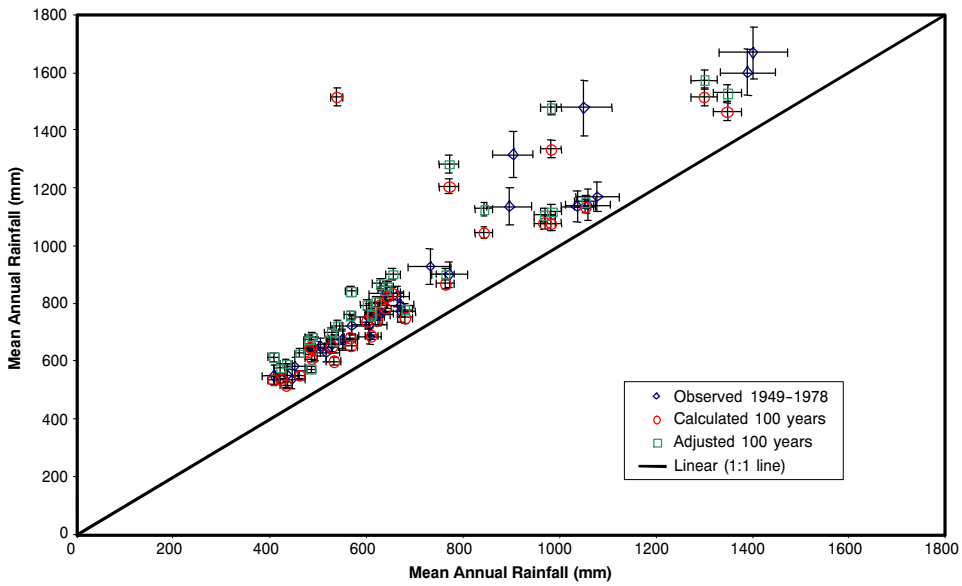

Figure 11. Mean annual rainfall for 30 selected stations using observed data, calculated and adjusted parameter values (error bars represent the standard deviation of the mean).

are recommended for use when mean monthly rainfall can vary by a factor of 2.5.

To test the adjustment method, the combined equations from table 6 were used to adjust the CLIGEN parameter values for period 1 to estimate the parameter values for period 2. These adjusted parameter values were used to simulate 100-year climate sequences for the 30 sites with CLIGEN. Calculated parameter values using historical data for period 2 were also used to simulate 100-year climate sequences for the same 30 sites in southeastern Australia. CLIGEN-generated rainfall changes using adjusted and calculated parameter values were compared with the observed changes between period 1 and 2. The average of the mean annual rainfall for the 30 sites was 716 mm for period 1 and 875 mm for period 2, with an increase of 22%. The average of the mean annual rainfall using calculated parameter values for period 2 was 859 mm for the 30 sites, a difference of -1.8% of the observed average for the 30 sites. Using the parameter values for period 1 adjusted for changes in mean monthly rainfall between the two periods led to an average of 890 mm for the 30 sites, a difference of +1.7% of the observed average for the 30 sites. The difference between calculated and adjusted parameter values was 31 mm in terms of the mean annual rainfall on average, or 3.5% of the observed average for the region. Using paired two-sample t-tests for the differences in means shows that there is no statistically significant difference in terms of the mean annual rainfall for the 30 sites among the three data sets, namely, historical observations and simulated climate with calculated and adjusted parameter values. Figure 11 shows a comparison in the mean annual rainfall between the two contrasting periods. It can seen from figure 11 that mean annual rainfall is consistently higher for period 2 than for period 1 based on historical observations, and using calculated and adjusted parameter values for CLIGEN. It is worth noting that the error bars are generally larger than those for simulated mean annual rainfall because of the difference in record length.

Discussion and Conclusion

Climate change is complex and can have considerable impact on bio-physical systems and human society. To evaluate the impact of climate change, stochastic weather generators are often used to produce daily weather sequences based on broad-scale changes predicted by global climate models. CLIGEN is one such weather generator that has been used for impact analysis. Unlike other weather generators, CLIGEN produces variables describing storm patterns, including time to peak, peak intensity, and storm duration, in addition to rainfall amount and other daily weather variables. While various methods have been proposed to adjust CLIGEN parameter values to simulate climate change scenarios, there is little research on how CLIGEN parameter values could be adjusted to simulate climate change, whereas previous studies have used simplistic approaches, e.g., changing the average rainfall on wet days by a percentage or multiplying the CLIGEN-generated daily rainfall by a fixed factor.

Rainfall in southeastern Australia is highly variable in time. Instrumental records from the region show significant variability and change on the time scale of climatology, i.e., 30 years. These secular changes have been previously used to indicate the likely rainfall change to represent human-induced climate change scenarios. Equally, significant change in historical rainfall can be used to guide and determine how parameter values can be adjusted to simulate climate change using stochastic weather generators.

This article shows that rainfall data for the period from 1919 to 1978 would suggest an increase in rainfall in southeastern Australia. However, from the perspective of the period from 1949 to 2008, the conclusion of decreasing rainfall would be reached. Both of these 60-year periods broadly coincide with an underlying trend of increased temperature in Australia and globally (Plummer et al., 1995; IPCC, 2001). Rainfall data from these 30 sites in southeastern Australia shows that we should not draw any conclusions about the relationship between trends in atmospheric concentration of greenhouse gases and temperature with regional rainfall. Rainfall could be just as likely to increase as to decrease sig-

nificantly on the time scale of regional climatology (30 years) in southeastern Australia.

Nonetheless, southeastern Australia provides a rich setting to examine how CLIGEN parameter values actually vary during contrasting wet and dry periods. Daily data for the 90-year period for each of the 30 sites in the region show that there are strong positive correlations between changes in mean monthly rainfall and changes in mean daily rainfall, standard deviation of mean daily rainfall, and the probability of wet-following-dry sequences. There is little evidence to suggest ways of adjusting the skewness coefficient or wet-following-wet probabilities to simulate changes in mean monthly rainfall for this region.

A set of regression equations was developed to allow easy adjustment of CLIGEN parameter values (namely, mean daily rainfall amount, standard deviation of daily rainfall, and probability of wet days following a dry day) to simulate monthly rainfall change for both increasing and decreasing rainfall change scenarios for southeastern Australia and is potentially applicable in any similar regions in the world. To demonstrate the accuracy and usefulness of these equations, CLIGEN parameter values for period 1 were adjusted to simulate daily rainfall for period 2. Statistical analysis of the observed and simulated mean annual rainfall with calculated and adjusted parameter values showed that the adjustment method can be used to reproduce the observed change in rainfall, at least in the mean for the 30 sites tested. As this method of adjusting CLIGEN parameter values is largely based on an extensive statistical analysis of historical rainfall observations, it is worth noting that further testing may be required for other regions of the world, and for simulating significant changes in other aspects of rainfall in addition to the mean.

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