



Supplement of

Extending and understanding the South West Western Australian rainfall record using a snowfall reconstruction from Law Dome, East Antarctica

Yaowen Zheng et al.

Correspondence to: Yaowen Zheng (yaowen.zheng@vuw.ac.nz)

The copyright of individual parts of the supplement might differ from the article licence.

1 Tests for normality

Figure S1 shows CDFs for DSS snow accumulation, AWAP gridded rainfall and 15 BoM stations rainfall. All of these 17 CDFs are in agreement with their corresponding normal distributions with negligible biases. Not only are the shapes between the empirical and normal CDFs similar, but also the distances between them are negligible. This visual validation has shown consistency with the results from one-sample KS tests that we cannot reject the null hypothesis that the data comes from normal distributions. Therefore, all of the rainfall data passes the normality tests. Therefore, we can apply the Pearson correlation coefficients and also perform parametric tests on any of the rainfall data.

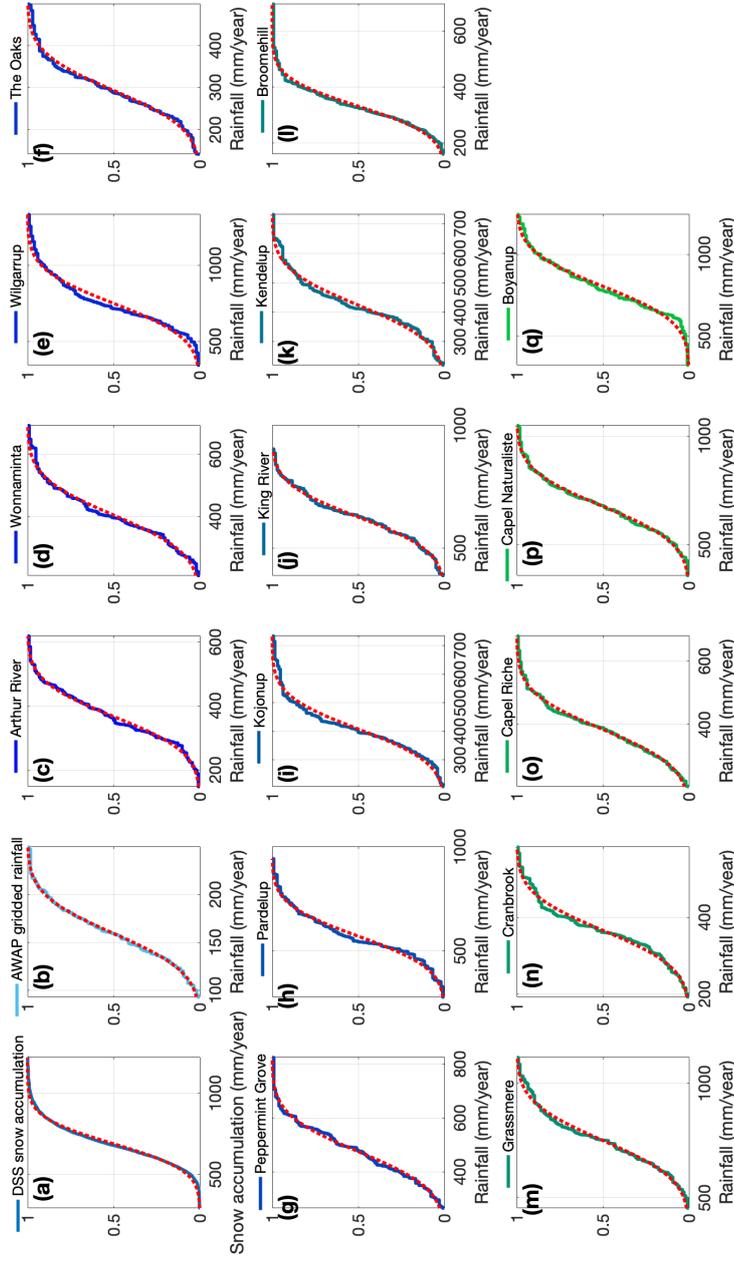


Figure S1. The CDF of observational data for testing normality. Curves are empirical CDF of DSS snow accumulation, AWAP gridded rainfall and 15 BoM stations rainfall data, red dotted lines are CDF for normal distribution corresponding to each sample's empirical CDF with equal mean and standard deviation, respectively. For each panel, (a) is the DSS snow accumulation, (b) is the AWAP gridded rainfall, (c) to (q) are each of the 15 BoM stations rainfall, respectively.

2 Defining the window size for smoothing

We test the effect of smoothing, using window sizes of 1–10 years, on the correlation between SWWA rainfall and DSS accumulation data. We calculate the Pearson correlation coefficient, estimate the ESS (Equation 1) and calculate Student's t-statistic (Equation 2) for each window of the AWAP gridded rainfall and BoM stations rainfall. Figure S2(a) is the results of the Pearson correlation coefficient and the number of the grids that have statistically significant ($p < 0.05$) correlations for the AWAP gridded rainfall. A six-year window maximizes the number of the grids (Figure S2a) with statistically significant ($p < 0.05$) correlations, and negligibly changes the magnitude of the correlation coefficient compared with the adjacent window sizes (Figure S2a). Therefore, a six-year window is the optimal window size for moving average smoothing on the AWAP gridded rainfall.

The results of the 15 BoM stations show differences compared with the AWAP gridded rainfall. A two-year window maximizes the number of the stations (Figure S2b) with statistically significant ($p < 0.05$) correlations. But the correlation is relatively low compared with the larger window sizes (Figure S2b). The correlation increases as the window size increases (Figure S2b). For consistency with the AWAP gridded rainfall, we also use six-year window to smooth the BoM stations rainfall.

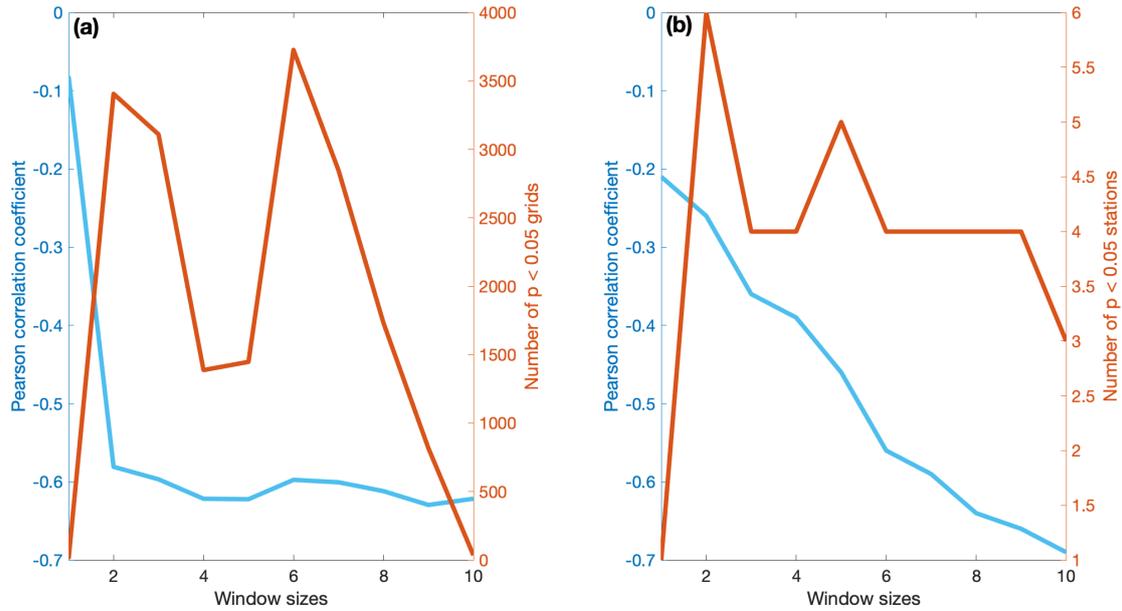


Figure S2. (a) Pearson correlation coefficient and the number of the statistically significant ($p < 0.05$) grids for AWAP rainfall data under different window sizes of moving average smoothing. (b) Pearson correlation coefficient and the number of the statistically significant ($p < 0.05$) stations for 15 BoM stations rainfall data under different window sizes of moving average smoothing. For both panels, blue lines and the left-hand side y-axis are the average of the Pearson correlation coefficient of the statistically significant ($p < 0.05$) grids/stations, red lines and the right-hand side y-axis are for the number of the statistically significant ($p < 0.05$) grids/stations.

3 Significance testing for 110 Local Government Areas

We independently calculate the Pearson correlation coefficients and test their statistical significance for each Local Government Areas (LGAs), and then combine the areas which are statistically significant ($p < 0.05$) to make the "MASK" region. Table S1 shows the results for each LGA. The rainfall data for each LGA is smoothed by using 6-year moving average smoothing (see section 2 about how to define the window size). The ESS (N_6^{eff}) and Student's t-statistic (for testing the statistical significance) are calculated by using Equation 1 and Equation 2.

Table S1: The table for all 110 Local Government Areas (LGAs) with their Pearson correlation coefficients (r_6) and ESS (N_6^{eff}) (under 6-year moving average smoothing). For some LGAs, "-" means the area of this LGA is less than one grid area of the geospatial resolution of the AWAP data. The bold numbers of correlation are statistically significant ($p < 0.05$).

Local Government Area	r_6	N_6^{eff}	Local Government Area	r_6	N_6^{eff}
Albany	-0.35	0.17	Dalwallinu	-0.46	0.17
Armadale	-0.51	0.13	Dandaragan	-0.44	0.14
Augusta Margaret River	-0.48	0.15	Dardanup	-0.54	0.14
Bassendean	-0.48	0.15	Denmark	-0.44	0.16
Bayswater	-0.45	0.15	Donnybrook Balingup	-0.53	0.15
Belmont	-0.47	0.14	Dowerin	-0.43	0.18
Beverley	-0.50	0.15	Dumbleyung	-0.41	0.15
Boddington	-0.51	0.15	Dundas	-0.31	0.21
Boyanup Brook	-0.53	0.17	East Fremantle	-	-
Bridgetown Greenbushes	-0.51	0.16	Fremantle	-0.38	0.14
Brookton	-0.49	0.15	Gingin	-0.46	0.14
Broomehill Tambellup	-0.45	0.15	Gnowangerup	-0.42	0.15
Bruce Rock	-0.46	0.17	Goomalling	-0.45	0.17
Bunbury	-0.55	0.14	Gosnells	-0.48	0.14
Busselton	-0.49	0.15	Greater Geraldton	-0.36	0.16
Cambridge	-	-	Harvey	-0.51	0.15
Canning	-0.46	0.14	Inwin	-0.48	0.15
Capel	-0.55	0.14	Joondalup	-0.47	0.14
Carnamah	-0.48	0.15	Kalamunda	-0.50	0.14
Chapman Valley	-0.39	0.16	Katanning	-0.51	0.15
Chittering	-0.50	0.14	Kellerberrin	-0.42	0.19
Claremont	-	-	Kent	-0.45	0.15
Cockburn	-0.42	0.14	Kojonup	-0.47	0.15

Collie	-0.53	0.15	Kondinin	-0.44	0.19
Coorow	-0.46	0.15	Koorda	-0.38	0.17
Corrigin	-0.45	0.16	Kulin	-0.43	0.18
Cottsloe	–	–	Kwinana	-0.46	0.14
Cranbrook	-0.51	0.16	Lake Grace	-0.45	0.16
Cuballing	-0.48	0.15	Mandurah	-0.42	0.14
Cunderdin	-0.47	0.18	Manjimup	-0.54	0.16
Melville	-0.42	0.14	South Perth	–	–
Merredin	-0.42	0.20	Stirling	-0.45	0.15
Mingenew	-0.49	0.16	Subiaco	–	–
Moora	-0.48	0.16	Swan	-0.49	0.15
Morawa	-0.39	0.16	Tammin	-0.46	0.18
Mosman Park	–	–	Three Springs	-0.51	0.15
Mount Marshall	-0.40	0.16	Toodyay	-0.46	0.15
Mukinbudin	-0.42	0.17	Trayning	-0.36	0.19
Mundaring	-0.48	0.15	Victoria Park	-0.44	0.14
Murray	-0.49	0.14	Victoria Plains	-0.50	0.15
Nannup	-0.52	0.15	Vincent	–	–
Narembeen	-0.43	0.19	Waggin	-0.43	0.16
Narrogin	-0.45	0.16	Wandering	-0.53	0.14
Nedlands	-0.41	0.14	Wanneroo	-0.48	0.14
Northam	-0.42	0.16	Waroona	-0.49	0.15
Northampton	-0.36	0.15	West Arthur	-0.54	0.15
Nungarin	-0.41	0.20	Westonia	-0.34	0.20
Peppermint Grove	–	–	Wickepin	-0.45	0.15
Perenjori	-0.43	0.15	Williams	-0.53	0.15
Perth	-0.42	0.15	Wongan Ballidu	-0.45	0.17
Pingelly	-0.49	0.15	Woodaniling	-0.49	0.15
Plantegenet	-0.47	0.16	Wyalkatchem	-0.41	0.18
Quairading	-0.46	0.17	Yalgoo	-0.18	0.17
Rockingham	-0.44	0.14	Yilgran	-0.20	0.19
Serpentine Jarrahdale	-0.52	0.14	York	-0.47	0.15

4 Significance testing and linear model construction for BoM stations

Table S2 shows the results of significance testing for each of the 15 BoM rainfall stations. King River shows the statistically significant ($p < 0.05$) correlation on the raw data. We have discussed in section 2 that 5-year window maximizes the number of the stations with statistically significant ($p < 0.05$) correlations. For consistence with AWAP gridded rainfall, we here also calculate and test the 6-year smoothing rainfall for 15 BoM stations data. With 6-year moving average smoothing, the number of the stations that show statistical significance ($p < 0.05$) rises to four, and also the correlations become stronger.

Figure S3 shows the scatter plot for each BoM stations which have statistically significant ($p < 0.05$, 6-year smoothing) correlation. The distributions of data all show negative trends. We also build linear models for each station. Table S3 shows the gradients, intervals and RMSE for each stations. For each of these four stations, the gradient is always negative (Table S3). Negative gradients show consistency with the results of the Pearson correlation coefficients that the r_6 for each of these four stations are statistically significant ($p < 0.05$) negative (Table S2), and also the negative trend distributions for these four stations (Figure S3).

Table S2. The ID and location for each of the 15 BoM rainfall stations and their rainfall record periods with the calculated results of Pearson correlation coefficients and the estimated ESS. r and N^{eff} are Pearson correlation coefficients and ESS for raw data. r_6 and N_6^{eff} are Pearson correlation coefficients and ESS for moving average smoothed data with 6-year window size.

Station	ID	Longitude	Latitude	r	N^{eff}	r_6	N_6^{eff}	Period (CE)
Arthur River	10505	117.03 °E	33.34 °S	-0.11	121	-0.55	19	1891–2015
Boyanup	9503	115.73 °E	33.48 °S	-0.18	114	-0.62	16	1898–2013
Broomehill	10525	117.64 °E	33.85 °S	0.01	122	-0.35	21	1891–2015
Cape Naturaliste	9519	115.02 °E	33.54 °S	-0.16	110	-0.40	16	1904–2015
Cranbrook	10537	117.57 °E	34.30 °S	-0.08	123	-0.54	19	1891–2015
Cape Riche	9520	118.75 °E	34.61 °S	-0.12	117	-0.01	19	1897–2015
Grassmere	9551	117.76 °E	35.02 °S	-0.07	109	-0.39	16	1903–2015
Kendenup	9561	117.63 °E	34.49 °S	-0.15	113	-0.42	14	1901–2015
King River	9564	117.92 °E	34.94 °S	-0.21	102	-0.35	15	1904–2007
Kojonup	10582	117.15 °E	33.84 °S	0.01	127	-0.32	19	1885–2015
Pardelup	9591	117.38 °E	34.64 °S	-0.04	114	-0.46	17	1900–2015
Peppermint Grove	9594	119.36 °E	34.44 °S	-0.18	107	-0.13	31	1904–2015
The Oaks	10636	117.67 °E	33.16 °S	0.02	104	-0.31	17	1907–2012
Wilgarrup	9619	116.02 °E	34.15 °S	-0.11	112	-0.40	16	1901–2014
Wonnaminta	10658	116.99 °E	32.83 °S	-0.15	109	-0.55	16	1905–2015

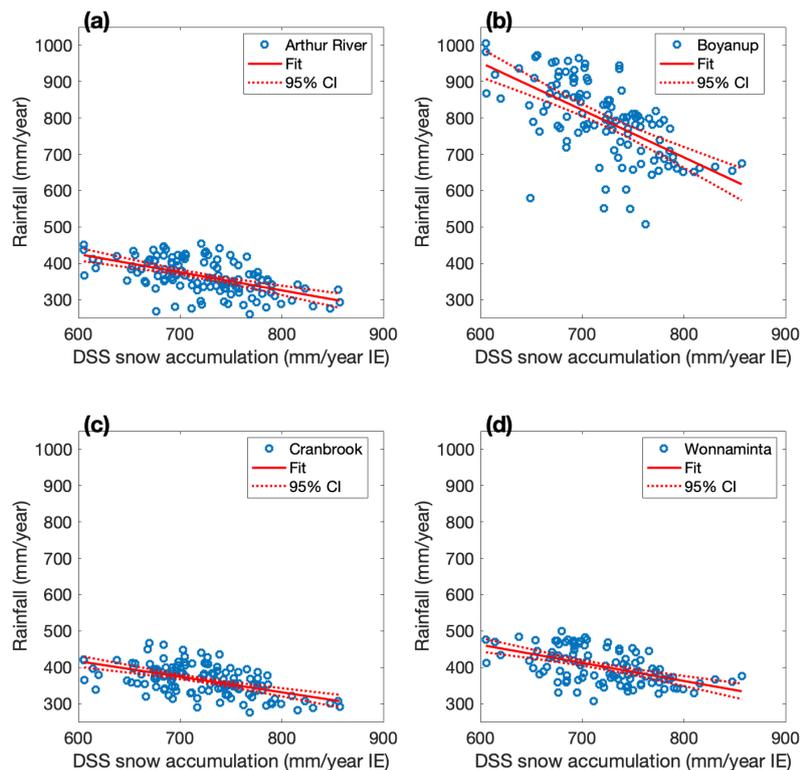


Figure S3. The scatter plot for four BoM stations rainfall that have statistically significant correlation (6-year smoothing, $p < 0.05$) and their linear model with 95% CI. For each panel, (a) is the Arthur River station, (b) is the Boyanup station, (c) is the Cranbrook station and (d) is the Wonnaminta station.

Table S3. The gradients and intervals of the linear models of each of the four BoM stations rainfall, with RMSE and periods.

Sample	Gradient	Interval	RMSE	Period (CE)
Arthur River	[-0.63, -0.36]	[627, 821]	40.0 mm	1891–2015
Boyanup	[-1.60, -1.00]	[1517, 1952]	83.5 mm	1898–2013
Cranbrook	[-0.55, -0.31]	[588, 759]	35.1 mm	1891–2015
Wonnaminta	[-0.64, -0.35]	[657, 864]	39.7 mm	1905–2015

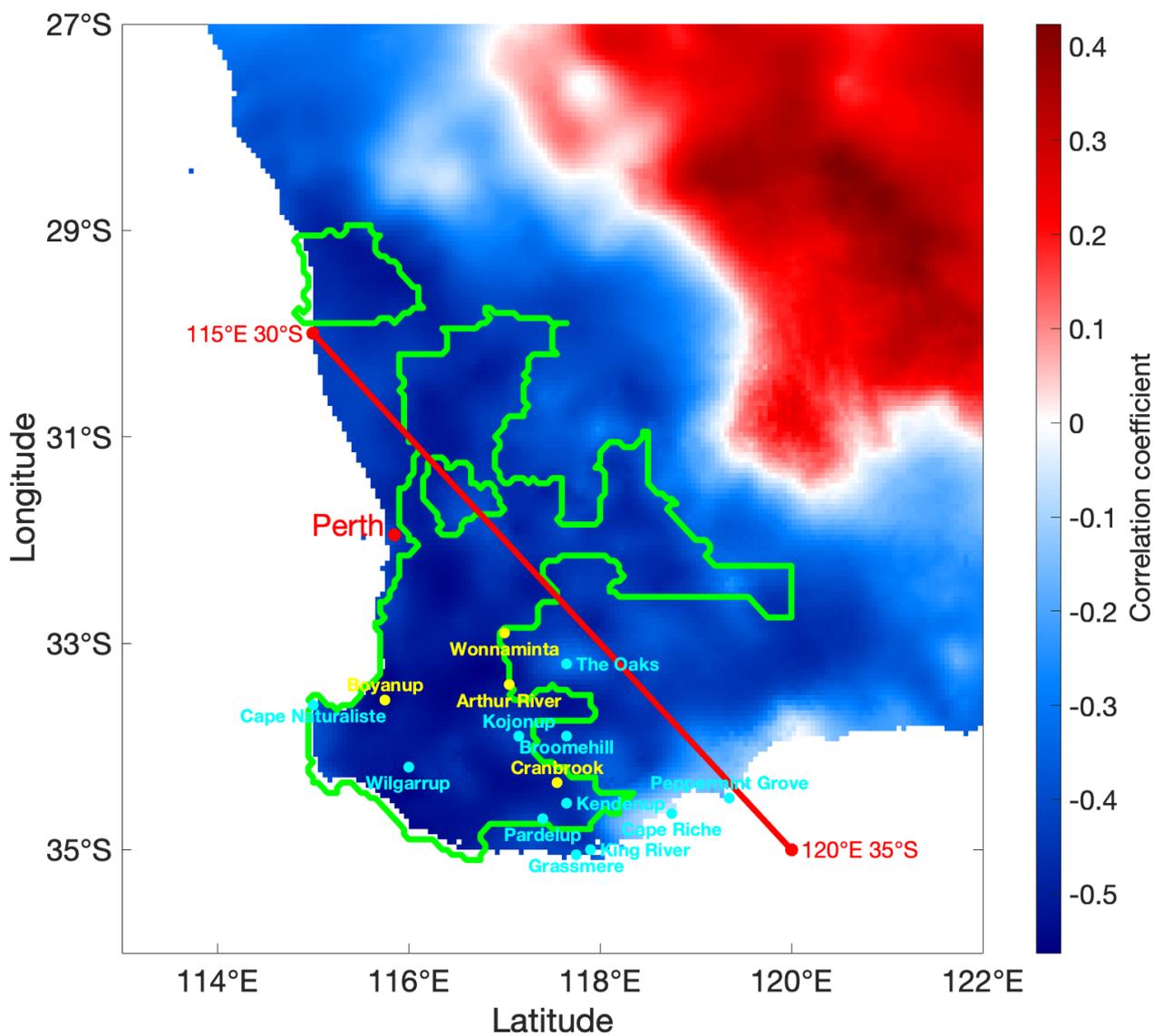


Figure S4. The correlation map for the southwest part of WA region for 6-year window AWAP rainfall and DSS snow accumulation from 1900 CE to 2015 CE. The outline area (green line) is the MASK region where the correlation is statistically significant ($p < 0.05$). Boyanup, Wonnaminta, Arthur River and Cranbrook are the four significant (6-year window, $p < 0.05$) stations. Blue "." marked stations are the other 11 non-significant stations.

40 5 Validate the reconstruction

To validate the reconstruction, we have now performed a jackknife analysis over the period 1900-2015 for the mean AWAP data in the "MASK" region. Specifically:

1. We determine the autocorrelation length by calculating the autocorrelation at various time lags (e.g. lag-1, lag-2, lag-3, ..., lag-6, ...) on the unsmoothed observational data until the autocorrelation coefficient decreases to zero.
- 45 2. We use this autocorrelation length to perform a (modified) jackknife analysis.
3. For each subsample, we perform 6-year smoothing then calculate the correlation coefficient and construct the linear model.

The autocorrelation time-scale is 12 years. The results of the jackknife analysis are shown in the upper section of Table S4. The correlation coefficients for the individual members of the jackknife ensemble are tightly clustered around the value of -
50 0.529 for the full period. Furthermore, the overlap between the 95% confidence intervals for the gradient and intercept indicates that the models derived for each jackknife ensemble member are statistically indistinguishable at the 5% probability level. This demonstrates the robustness of the reconstruction technique.

To further explore whether the relationship between Law Dome accumulation and SWWA rainfall has changed during the current drought, the middle section of Table S4 repeats the jackknife analysis but increases the duration of the period omitted
55 to 45 years. Although we find greater scatter in the values for the correlation coefficient, gradient and intercept, the 95% confidence intervals continue to overlap. We therefore find no evidence to suggest that the relationship between Law Dome accumulation and SWWA rainfall has changed.

We have verified that the CSIRO Mk3L runs pick up large-scale features that underpin the Law Dome end of the teleconnection by examining the correlation fields between mean sea level pressure and Law Dome precipitation in each member of
60 OGSV (Figure S5). These show that the large scale circulation both matches the pattern identified in van Ommen and Morgan (2010) and is stable through time. This demonstrates that Law Dome accumulation is a robust proxy for the large-scale Southern Hemisphere circulation, which is a prerequisite for it to be a robust proxy for SWWA precipitation.

We calculate the mean of each region's nine cells for each member of ensemble and each ensemble mean and perform 6-year smoothing for each series (for consistency), and then calculate the 100-year running correlation (Figure S6). The model
65 simulations exhibit a lack of stationarity on decadal to centennial timescales, which should be considered when interpreting the reconstruction. The lack of a strong or consistent correlation between the simulated Law Dome and SWWA precipitation is not surprising, given the mechanism outlined in van Ommen and Morgan (2010). Correlation is essentially connected with periods of enhanced meridional flow which will be less apparent over extended periods which mix meridional and zonal modes of circulation.

Table S4. The correlation coefficient between the smoothed ice core record and the mean of the AWAP rainfall in the "MASK" region. The three sections represents the results for a 12-year jackknife, a 45-year jackknife and the full period, respectively. x1 and Intercept are the coefficients for the linear model: $\text{Rain} = \text{Snow} * (x1 \pm 95\% \text{ CI}) + \text{Intercept} \pm 95\% \text{ CI mm/year}$. The 95% confidence interval (CI) is estimated by multiplying the standard error of the model by 1.96.

Section	Period	Correlation coefficient	x1	Intercept (mm/year)
12-year jackknife analysis	1912–2015	-0.536	-0.385 ± 0.118	667 ± 85
	1900–1911 & 1924–2015	-0.513	-0.363 ± 0.118	651 ± 85
	1900–1923 & 1936–2015	-0.532	-0.378 ± 0.117	662 ± 85
	1900–1935 & 1948–2015	-0.524	-0.405 ± 0.128	684 ± 93
	1900–1947 & 1960–2015	-0.545	-0.407 ± 0.122	685 ± 88
	1900–1959 & 1972–2015	-0.499	-0.385 ± 0.130	671 ± 94
	1900–1971 & 1984–2015	-0.506	-0.427 ± 0.141	699 ± 101
	1900–1983 & 1996–2015	-0.492	-0.374 ± 0.129	662 ± 92
	1900–1995 & 2008–2015	-0.512	-0.356 ± 0.116	651 ± 82
1900–2007	-0.593	-0.379 ± 0.098	670 ± 71	
45-year jackknife analysis	1945–2015	-0.511	-0.351 ± 0.139	635 ± 103
	1900–1944 & 1990–2015	-0.414	-0.389 ± 0.202	672 ± 144
	1900–1925 & 1971–2015	-0.489	-0.403 ± 0.170	679 ± 125
	1900–1970	-0.296	-0.193 ± 0.147	548 ± 102
Full period	1900–2015	-0.529	-0.389 ± 0.114	672 ± 82

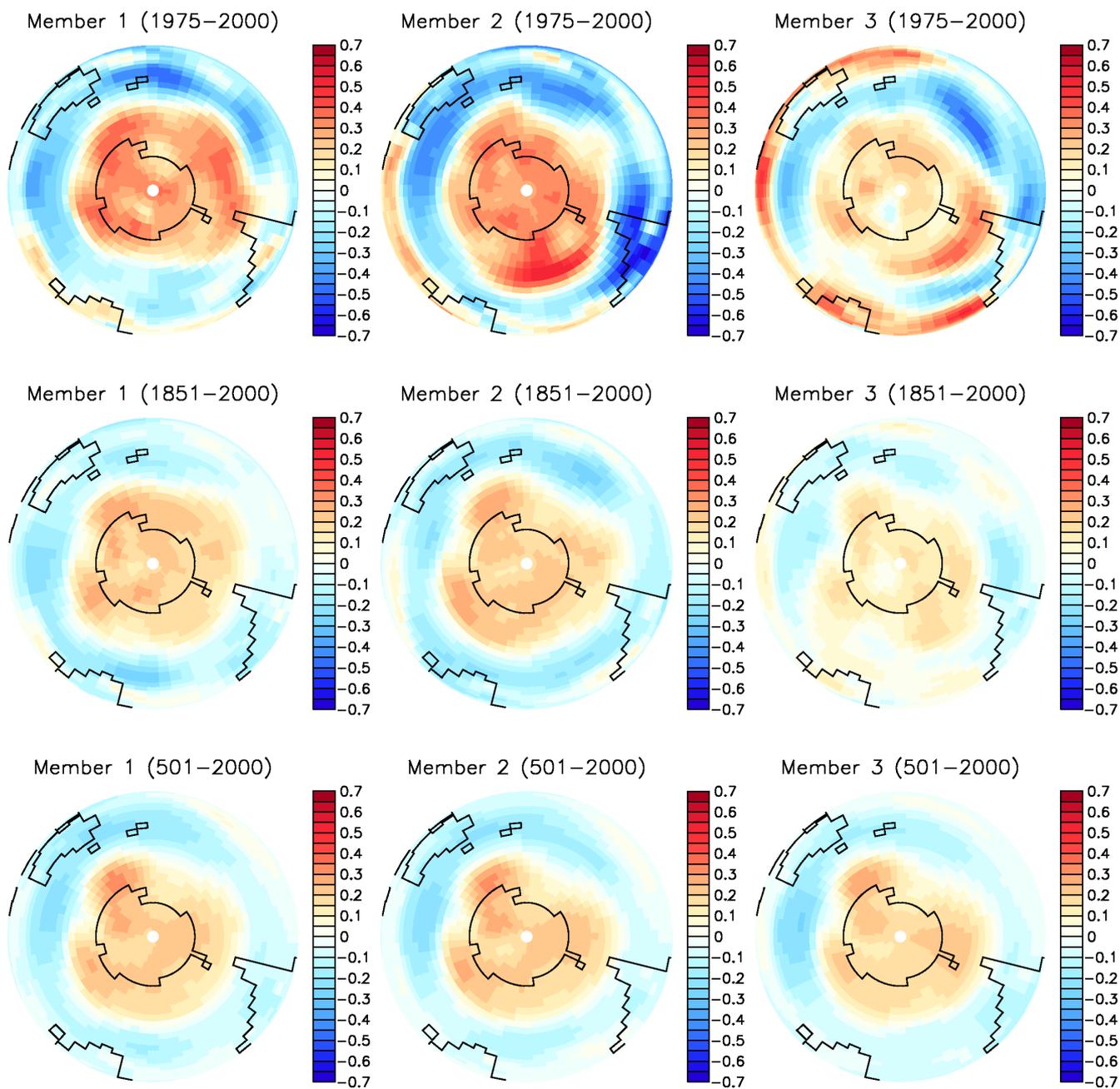


Figure S5. Correlation between precipitation at Law Dome and Southern Hemisphere mean sea level pressure for each member of OGSV.

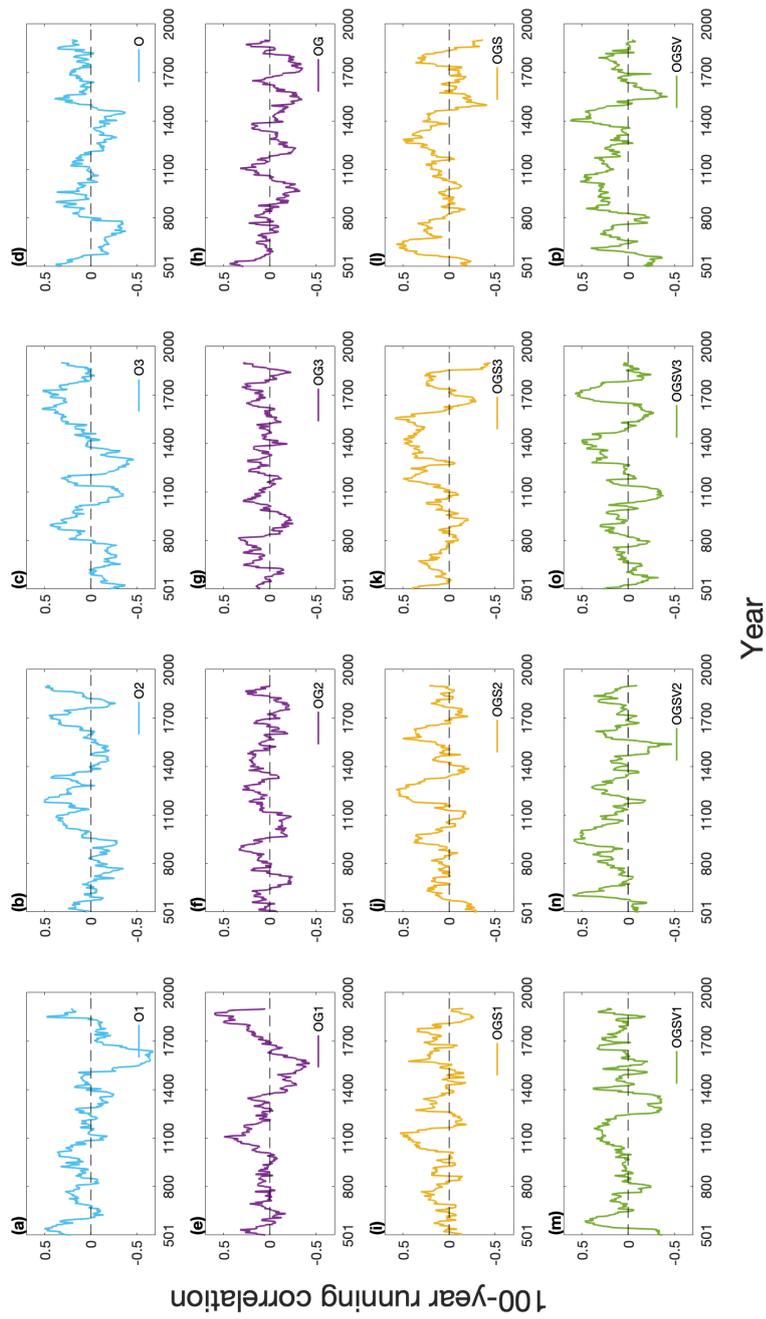


Figure S6. 100-year running correlation of the CSIRO Mk3L precipitation simulations between SWWA and Law Dome for each member and the each ensemble mean from 501 to 2000.

70 6 Rainfall observation

Figure S7 is the latest rainfall data from the Australian Government Bureau of Meteorology for the growing season in southwestern Australia from 1900 to 2020. The mean growing season rainfall in southwestern Australia from 1900 to 1970 is 564.97 mm, from 1972 to 2014 is 481.26 mm and from 2016 to 2020 is 431.35 mm. The drought continued during 2016–2020.

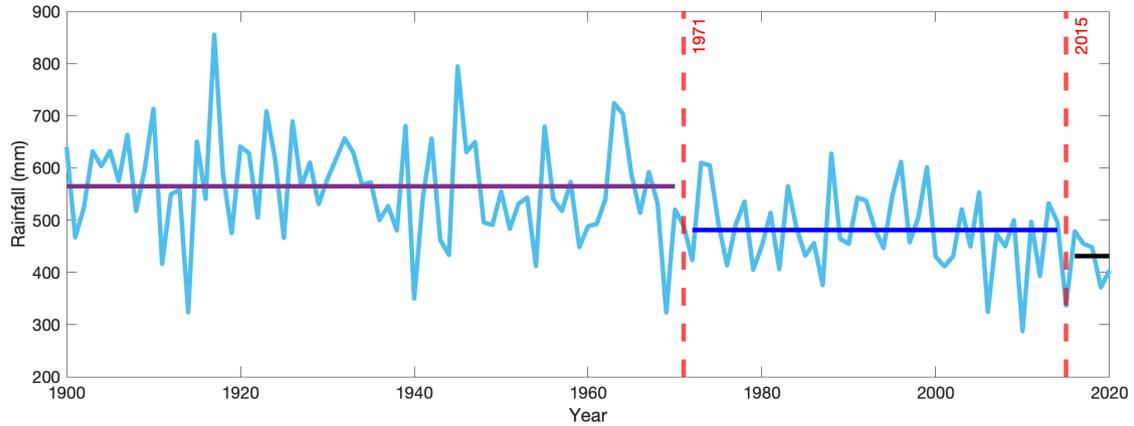


Figure S7. Time series of BoM rainfall in southwestern Australia at growing season from 1900 to 2020.

7 CUSUM analysis on each member of the model ensembles

Table S5. The mean and standard deviation for each of the growing season rainfall time series from 501 CE to 2000 CE.

Time series	Mean	Standard deviation
Rainfall reconstruction	406.00	22.61
CONTROL1	220.59	17.39
CONTROL2	223.75	17.16
CONTROL3	221.96	17.40
O1	223.21	17.95
O2	224.12	16.79
O3	226.60	17.47
OG1	226.01	17.86
OG2	224.21	16.95
OG3	222.56	17.78
OGS1	226.26	18.96
OGS2	226.16	17.74
OGS3	226.99	18.69
OGSV1	226.98	19.08
OGSV2	226.26	19.38
OGSV3	225.63	17.97

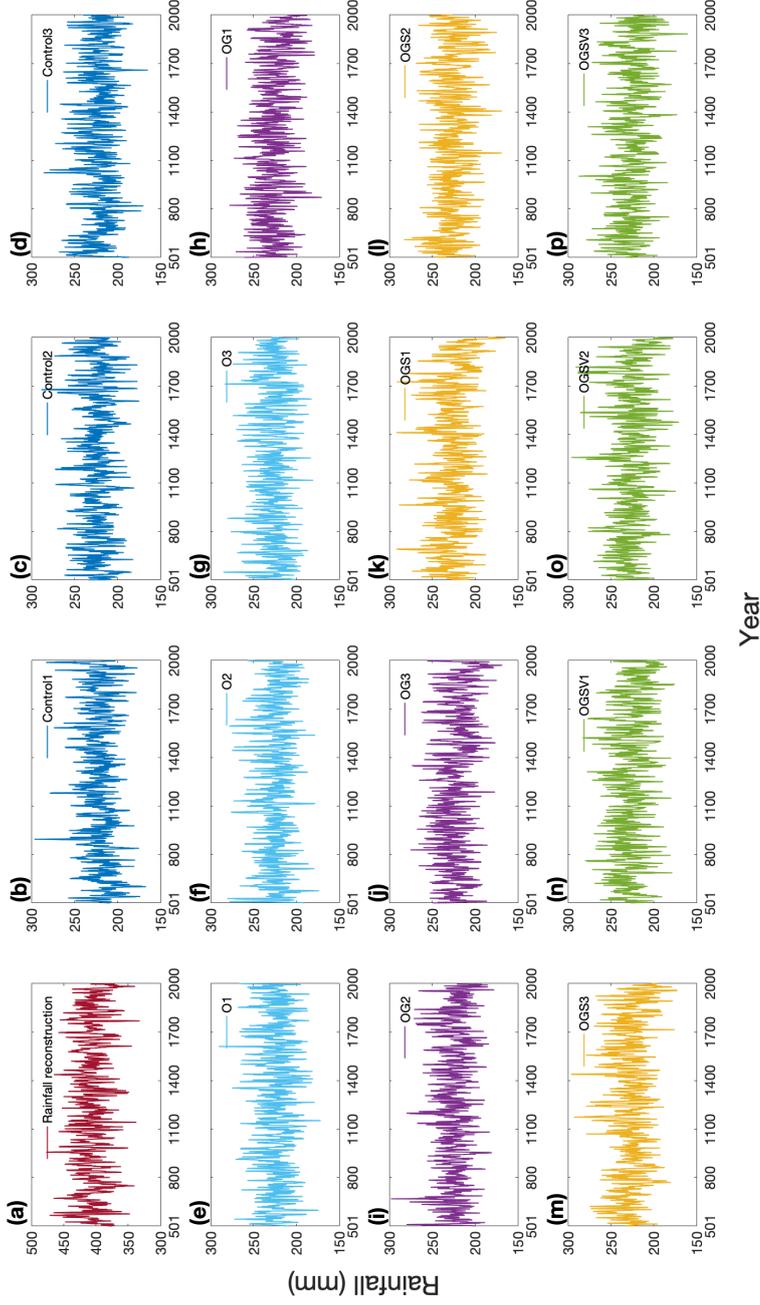


Figure S8. Growing season rainfall for SWWA rainfall reconstruction and each member of the CSIRO Mk3L model rainfall simulations in the MASK region from 501 CE to 2000 CE. For each panel: (a) is the rainfall reconstruction, (b), (c) and (d) are the each member of CONTROL simulations, (e), (f) and (g) are the each member of the O (orbital forcing (Table 2) simulations, (h), (i) and (j) are the each member of the OG (orbital and greenhouse gases (Table 2) simulations, (k), (l) and (m) are the each member of the OGS (orbital, greenhouse gases and solar irradiance (Table 2) simulations, (n), (o) and (p) are the each member of the OGSV (orbital, greenhouse gases, solar irradiance and volcanic aerosols (Table 2) simulations).

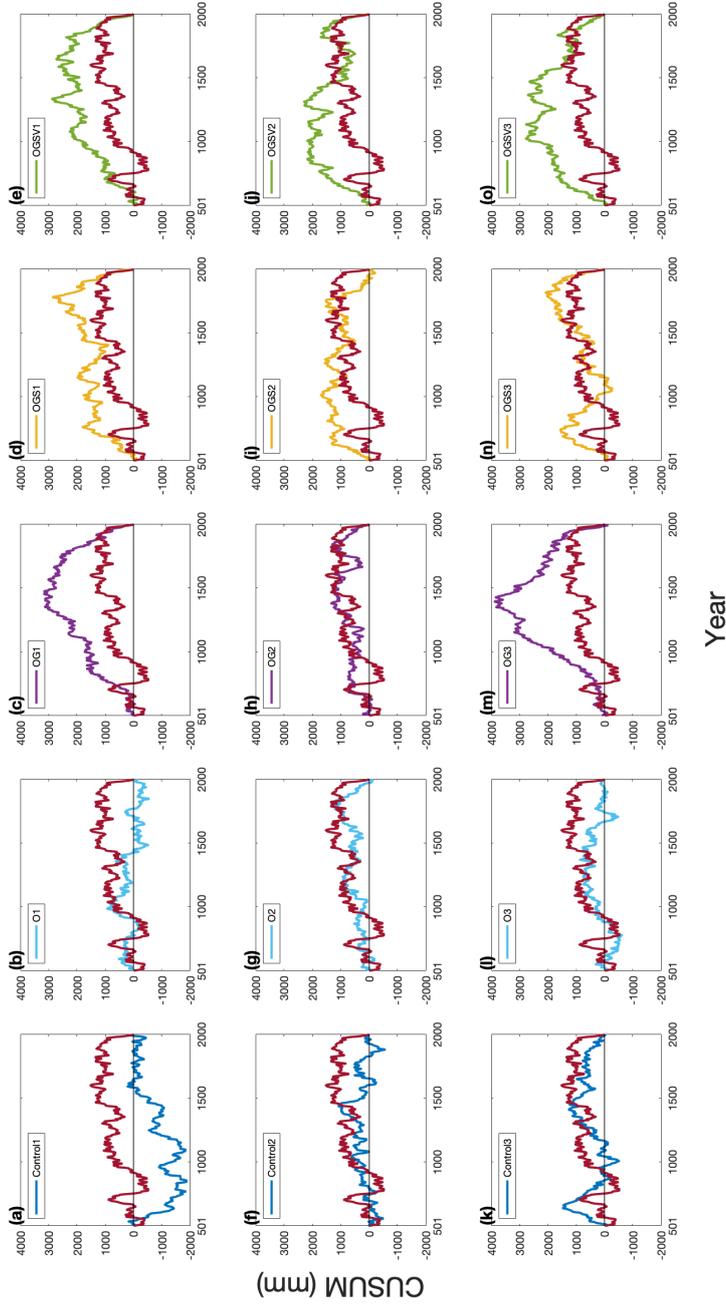


Figure S9. CUSUM time series for each member of the CSIRO M3L model rainfall simulations with the rainfall reconstruction in the MASK region from 501 CE to 2000 CE. For each panel: (a), (f) and (k) are the each member of CONTROL simulations with the rainfall reconstruction, (b), (g) and (l) are the each member of the O simulations with rainfall reconstruction, (c), (h) and (m) are the each member of the OG simulations with rainfall reconstruction, (d), (i) and (n) are the each member of the OGS simulations with rainfall reconstruction, (e), (j) and (o) are the each member of the OGSV simulations with rainfall reconstruction. For each panel, the red curve is the CUSUM time series for rainfall reconstruction, and the black horizontal line equals zero.

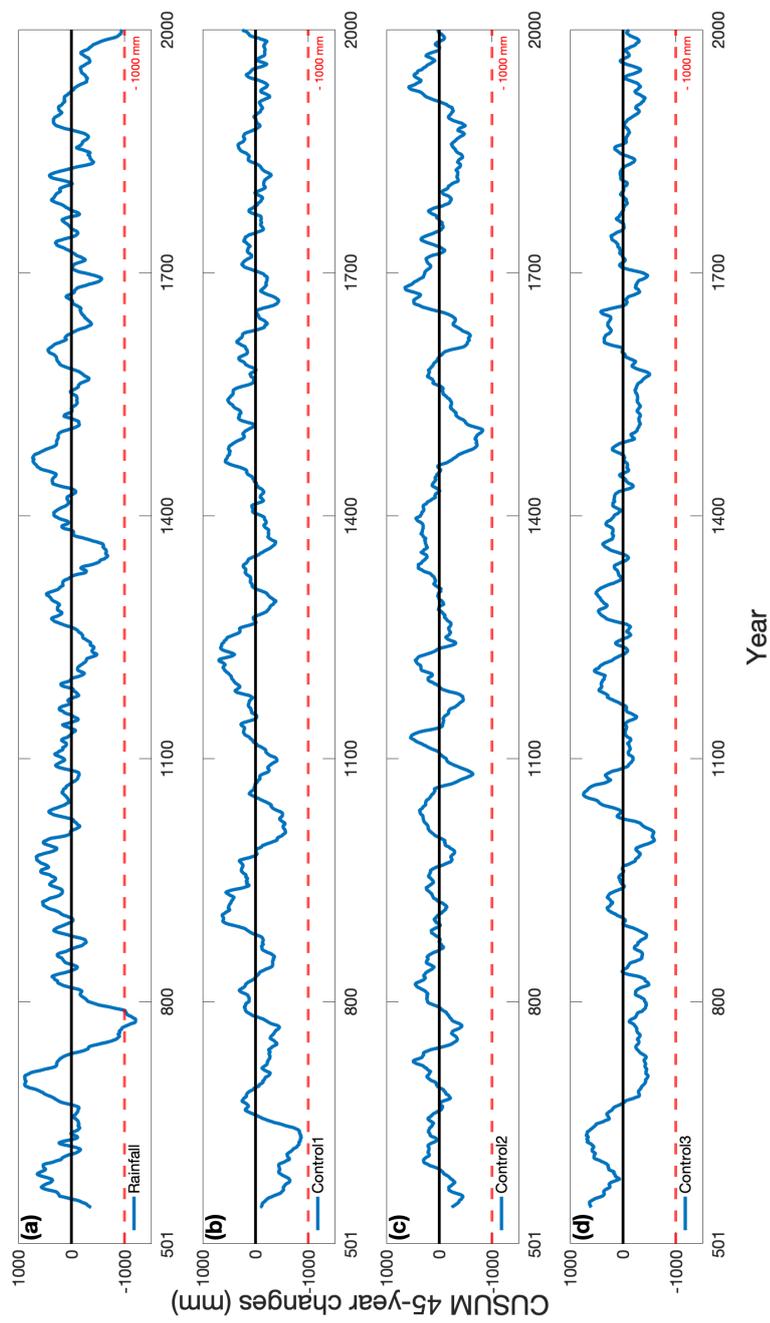


Figure S10. The CUSUM 45-year running change from 501 CE to 2000 CE. For each panel: (a) is the rainfall reconstruction, (b), (c) and (d) are each member of CONTROL simulations. The black horizontal line equals zero. Red horizontal dash line equals the -1000 mm (accumulated change).

75 **References**

van Ommen, T. D. and Morgan, V.: Snowfall increase in coastal East Antarctica linked with southwest Western Australian drought, *Nature Geoscience*, 3, 267–272, 2010.