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Inflows and river heights in Australia's Murray Darling Basin: impacts of decreased catchment rainfall on water availability.

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ABSTRACT

The Murray Darling Basin (MDB) is Australia's most important agricultural region. The southern MDB receives most of its annual catchment runoff during the cool season (April-September). Focusing on the Murrumbidgee River measurements at Wagga Wagga and further downstream at Hay, river heights in the cool season decreased markedly in variability over a century prior to 1991. Box and whisker plots of 27-year April-September Hay and Wagga Wagga river heights reveal decreases not matched by declining April-September catchment rainfall. However, permutation tests of both means and variances of late autumn (April-May) dam catchment rainfall and inflows, produced p-values indicating a highly significant decline since the early 1990s. Consequently, dry catchments in late autumn, even with average cool season rainfall, have reduced dam inflows and decreased river heights downstream from Wagga Wagga, before water extraction for irrigation. It is concluded that lower April-September mean river heights at Wagga Wagga and decreased river height variability at Hay, since the mid-1990s, are due to combined lesser April-May catchment rainfall and increased mean temperatures. If these drying and warming trends continue, they will drastically reduce water availability for the Murrumbidgee River catchment and, consequently, for a vital part of the southern MDB.

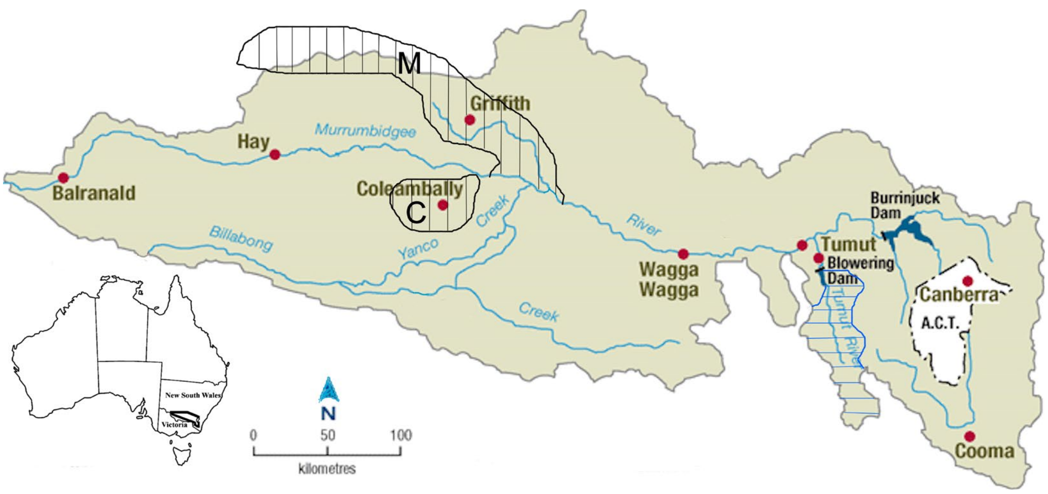
Keywords: Murray Darling Basin; Murrumbidgee River; catchment rainfall and inflows; statistical analysis; water availability; climate impacts.

1. Introduction

The Murray-Darling River basin (MDB), located in south eastern Australia, is Australia's most important agricultural area, producing almost 40% of the national food supply [1]. In comparison, the agricultural area of the central valley of California provides approximately 20% of the total US food production [2]. Drought conditions since the mid-1990s in the MDB have resulted in rivers running dry and low water storages, affecting communities, businesses, animals, and the environment. The southern half of the MDB, in which the Murrumbidgee River catchment is located (Fig.**1**), occupies a large geographical area of southeast Australia where the growing season is in the cooler half of the year (April-September) [3]. To ensure the supply of catchment rainfall, it is crucial to receive average or close to average rainfall during this period. Along the catchment Burrinjuck Dam and Blowering Dam receive 57%, Tumut 56%, Wagga Wagga 52% and Hay 52% of their annual average rainfall in this period. Notably, stream flows have been declining across the MDB, particularly since the 1970s (Figs.2**a**,**b**).

Fig. **1**. **The Murrumbidgee River and catchment area.**

M = Murrumbidgee Irrigation Area (hatched black), C = Colleambally Irrigation Area (hatched black). Snowy Mountains Hydroelectric Scheme (hatched blue). The inset identifies the catchment location in southeast Australia.



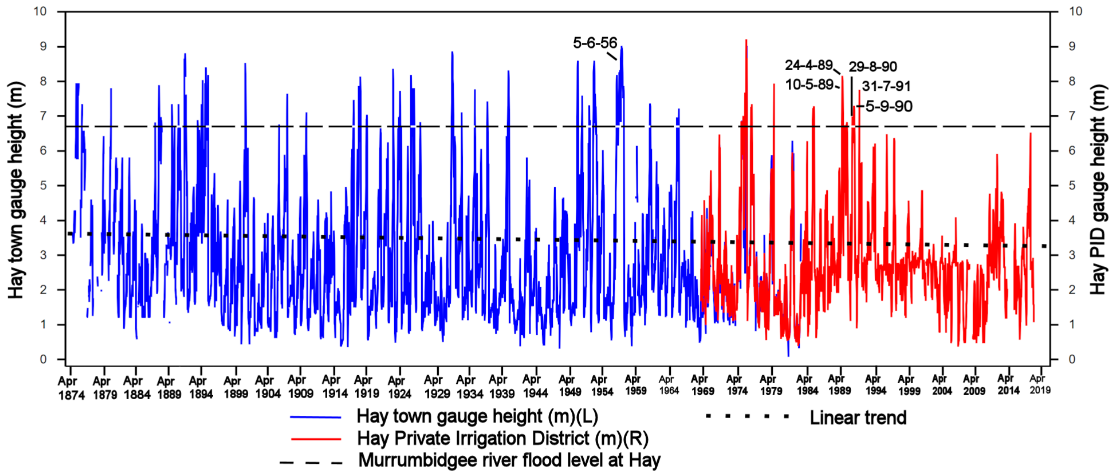


Fig.2**a** **Murrumbidgee river heights (m) at the Hay town gauge and Hay PID for (April-September) 1874 to 2019.** There are concurrent readings at the two locations from 1968 to 1982. The first April height every 5 years is indicated. The river flood level is marked (dashed black line) at 6.7 m. Six maximum April-September weekly river heights exceeding the flood level of 6.7 m, including the most recent (31 July 1991), are designated.

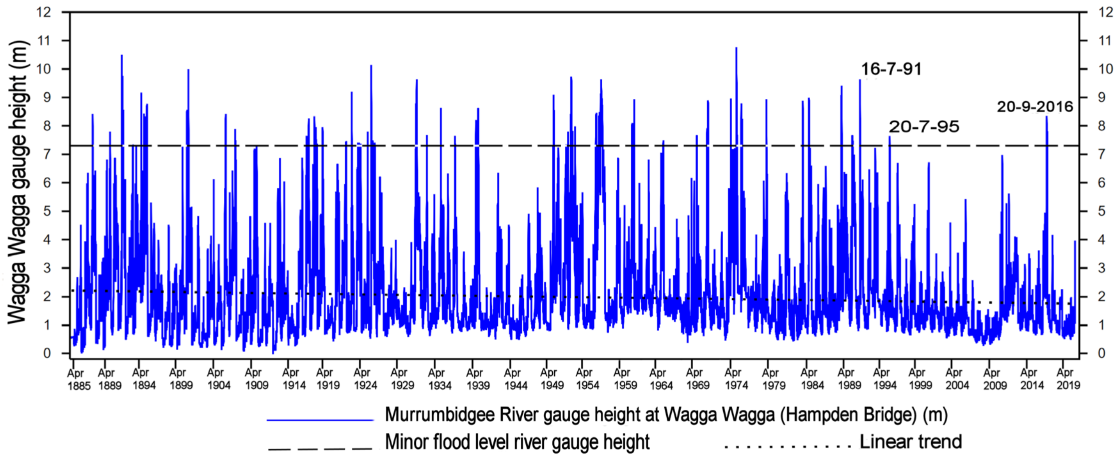


Fig.2**b** **Murrumbidgee river heights at Wagga Wagga (April to September) 1885-2019.** The minor flood level is marked (dashed black line) at 7.3 m. The most recent minor flood levels reached since 1991 are marked.

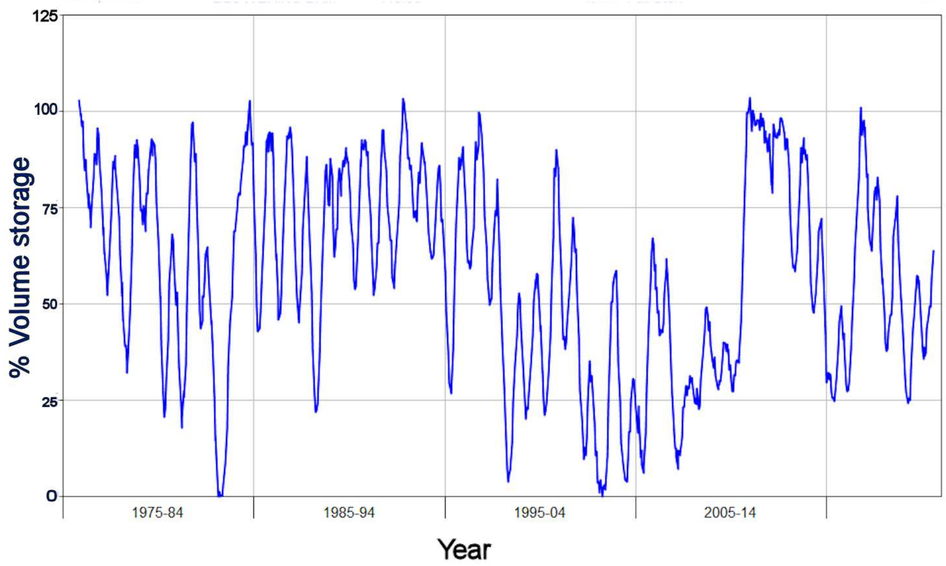


Fig.2c **Annual volume storage (%) for Blowering Dam indicating precipitation inflows from 1975-2019.**

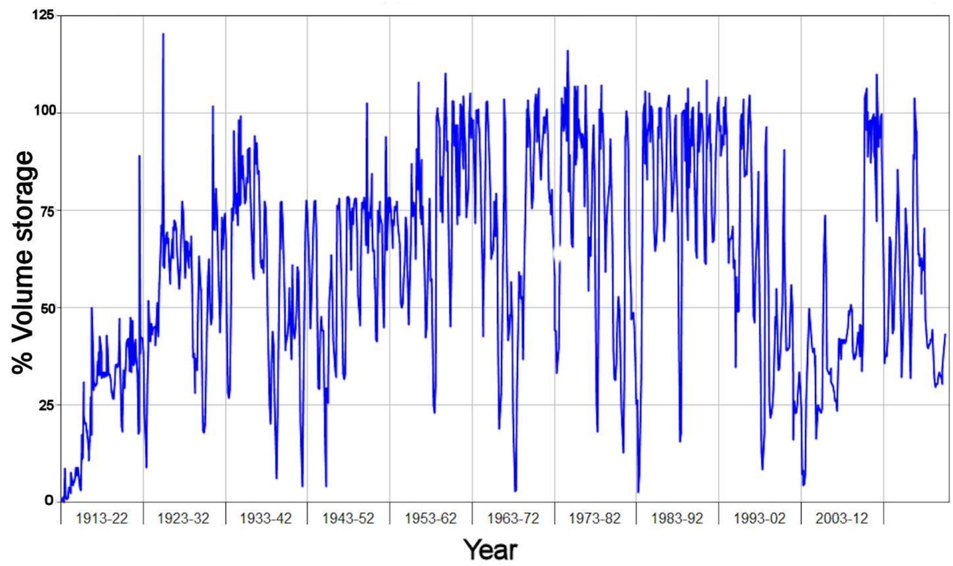


Fig.2d **Annual volume storage (%) for Burrinjuck Dam indicating precipitation inflows from 1913-2019.**

Aside from the current drought, starting from 2013, the MDB previously experienced major multi-year droughts in 1997–2009 (Millennium Drought), 1938–

1946 (World War II Drought) and 1895-1903 (Federation Drought). There are downward trends in rainfall since the 1990s in southern parts of eastern Australia, and in the higher rainfall areas of the MDB that generally are located in the highlands of the Great Dividing Range [4]. These trends are concentrated in the winter or cool season half of the year from April to September [3]. A major influence on this drying trend has been the strengthening and extension of the subtropical high pressure ridge during winter, which shifts rain-bearing weather systems southward [4,5]. Specifically, the lack of negative-phase Indian Ocean Dipole (IOD) events has been identified as a contributing factor to the drying and drought in the southeast since the 1990s [6], the region of Australia where the influence of the IOD is greatest in the June–October period [7].

Prior to the 1990s, the main regulation of the Murrumbidgee River upstream of Hay occurred over two periods during which large storages were built. These were the Burrinjuck Dam in 1910-1927 and Blowering Dam 1956-1961 (Fig.**1**). Before the Burrinjuck Dam was built, annual river flows at Hay followed a pattern of variability and quantity similar to annual river flows measured at Wagga Wagga (Fig.**1**). After the Burrinjuck Dam was built (1928), the water flows diverged in quantity although annual patterns of variability coincided [8]. After the Blowering Dam construction was completed in the 1960s, the relationship between river flows at Wagga Wagga and Hay were affected. There were similar patterns of variability but there was a substantial difference in the quantity of water reaching Hay from Wagga Wagga, compared with that before river regulation [8,9]. It was concluded that there was a 56% reduction in the lower Murrumbidgee River at Hay [10], which occurred mostly after 1957 when there was a change point between low regulated flow and high regulated flow. Even after the 1957 change point, river flows were seasonal, driven by reliable winter and spring rainfall together with headwater ice and snow melt, and much of the flow reached the floodplain below Hay [8]. However, there has been a sharp drop to zero in JJAS Murrumbidgee River flooding events at Hay since 1991 (Fig. 2a) and one only minor flood in 1995 at Wagga Wagga (Fig.2**b**), in addition to much reduced dam inflows since the mid-1990s (Figs.2**c**, **d**). In Figure 2**a** there is a data overlap of about 13 years at Hay town gauge and Hay Private Irrigation District (PID) gauge for which the mean height is the same and data quality is good taking into account missing values, outliers, continuity between the two gauge locations and measurement practice [11]. The flooding level of 6.7 m at Hay is defined as the level above which water starts to spill over the riverbanks at Hay [11] and the minor flood level at the river gauge at Wagga Wagga is 7.3 m.

It is hypothesized here that from the mid-1990s the main influence on decreased downstream river water availability is due to the reduction in dam inflows from decreased precipitation. It is well-known that rainfall in southeast Australia, where the Murrumbidgee River catchment is located, usually is highest in winter and has a minimum through summer into early autumn [3]. Hence the so-called 'winter cropping season' starts with planting in autumn and harvesting in spring-summer. Most river height exceedances above 6.7 m at Hay in JJAS occur in July, August and September (Table 1**a**) after sufficient catchment wetting. Spring (SON) floods are the most common (Table 1**b**) as river and dam inflows are a result of both rainfall and snowmelt. However, since 1991 there has been just one April to September flood at both Hay and Wagga Wagga resulting from Burrinjuck Dam overspill which was in September 2016 (Table 1**b**). Extreme SON precipitation totals are associated with La Niña over eastern Australia [12]. In terms of river flood events at Hay and Wagga Wagga, and inflows at the catchment dams of Burrinjuck and Blowering in southeast Australia, this relationship broke down, as shown by the presence only of neutral phases of ENSO after the 1970s (Table 1**b**) and in agreement with eastern Australian rainfall in general [12].

YEAR	Jun	Jul	Aug	Sept	JJAS count
1874		7.92	7.92	7.92	3
1875	7.25	7.32			2
1876				8.0	1
1887		7.86		7.22	2
1889		7.32		7.31	2
1890					
1891		8.78	7.62	6.9	2
1893		6.86	8.3		2
1894		6.71	8.38	8.3	3
1905			6.74		1
1906				7.62	1
1909				7.08	1
1916				7.43	1
1917			7.85	8.1	2
1918			6.89	8.1	2
1922			8.33		
1923		6.94	7.69	6.7	3
1925	8.15	7.77		7.77	3
1926			6.81		1
1931	8.33	8.83	6.7		3
1932				7.08	1
1934				7.74	1
1936			7.39		1
1939				8.2	1
1949			7.56		1
1950			7.55		1
1951				6.85	1
1952	8.22	8.56	7.62		3
1955				8.15	1
1956	8.31	8.99	8.78	7.84	4
1960			7.35	6.82	2
1964			6.93	7.19	2
1974		7.24	7.35	8.99	3
1984			7.2	7.26	2
1989		6.72	6.8		2
1990		6.96	7	7.27	3
1991		7.73			1

Table 1**a** Table showing wet season (JJAS) monthly maximum weekly Murrumbidgee river heights at Hay (southern MDB) that exceed/equal flood level (6.7 m), and seasonal count, in the 125 years 1874-2018.

YEAR	Sep.	Oct.	Nov.	SON Total count	ENSO Strength & sign
1874	7.92	7.77		2	N/A
1877			8.17	1	mod. -
1878		8.99	7.92	2	mod-strong +
1879	8.0			1	very strong +
1886	6.95			1	mod +
1887	7.22			1	very strong +
1888		7.65		1	mod. -
1889	7.31			1	mod. +
1890	6.7			1	strong +
1891	6.9	7.16	7.01	3	weak -
1893		7.25		1	mod-strong +
1894	8.3			1	very strong +
1905		8.08		1	mod. -
1906	7.62	8.08		2	mod. +
1909	7.08			1	weak -
1916	7.43	8.2		2	mod. +
1917	8.11	8.31	8.31	3	very strong +
1918	7.01			1	weak -
1923	6.7	6.93		2	mod. -
1925	7.77			1	mod -
1932	7.08			1	weak -
1934	7.74		8.29	2	NEUTRAL
1939	8.29			1	weak -
1950			8.31	1	mod-strong +
1951	6.85	7.54		2	NEUTRAL
1952		7.8	7.8	2	NEUTRAL
1955	8.15		7.13	2	mod. +
1956	7.84	7.96	8.23	3	weak +
1959			7.07	1	NEUTRAL
1960	6.82	8.41		2	weak +
1964	7.19	8	7.35	3	weak +
1970		8.56		1	weak +
1974	8.99	8.63	8.64	3	weak +
1975			8.62	1	mod-strong +
1976			7.71	1	NEUTRAL
1978		7.6		1	NEUTRAL
1984	7.26	6.76		2	NEUTRAL
1990	7.27			1	NEUTRAL
2016		8.45		1	NEUTRAL

Table 1**b**. Table showing spring (SON) weekly maximum Murrumbidgee river heights at Hay (southern MDB) that exceed flood level (6.7 m), and seasonal count, in the 125 years 1874-2018. Also included is the strength of the ENSO signal as determined by the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/enso/lnlist/index.shtml). Note the neutral ENSO association with flood heights since the mid-1970s.

In autumn (MAM) there are very few flood events (Table 1**c**) because the catchment normally dries out sufficiently through summer to reduce river flow. Monthly to seasonal precipitation typically exhibits large ranges due to its episodic nature even if seasonal means show little change. Therefore, an important part of this

YEAR	Mar	Apr	May	MAM count
1888		6.8		1
1894		7.32	8.02	2
1950		8.5	7.04	2
1956		6.89	8.23	2
1974			6.85	1
1989		8.41	7.93	2
2012	8.6			1

Table 1**c** Table showing autumn (MAM) monthly maximum weekly Murrumbidgee river heights at Hay (southern MDB) that exceed flood level (6.7 m), and seasonal count in the 126 years 1874-2019. (http://www.bom.gov.au/climate/enso/lnlist/index.shtml). Note the neutral ENSO association with flood heights since the mid-1970s.

study is to analyse trends in the means and variances of catchment rainfall and inflows, in addition to JJAS river heights at both Hay and Wagga Wagga. The focus is on the period after the 1960s, since from then there has been no new regulatory infrastructure upstream of Hay and particularly from the early to mid-1990s when the global warming signal has accelerated [13].

Considering changes in regulation of the Murrumbidgee River, box and whisker plots and permutation testing are used to analyse changes in both JJAS and April-May inflows at Burrinjuck/Blowering Dams, and precipitation at key rainfall catchment locations including Burrinjuck Dam, Blowering Dam and Tumut, in addition to river heights at both Hay and Wagga Wagga. Wavelets are then used to provide some understanding of possible climate drivers affecting precipitation and inflows at these locations, and how their influence has changed over time.

2. Results

As shown in Figs. 3(**a-c**), Burrinjuck Dam and Blowering Dam each records a mean JJAS precipitation of about 300 mm, while Tumut receives approximately 350 mm.

There are fewer percentiles near the extremes from the 1990s, with no years above the 95th percentile apart from 2016 and a reduction in years below the 5th percentile. Statistical significance is discussed in the next section. Similarly, with April-May precipitation there are no years above the 90th percentile from the late 1990s for the three locations (Figs. 3**d-f**).

Fig. **3** **Precipitation time series in the Murrumbidgee River catchment area.** JJAS precipitation at, **a** Burrinjuck Dam from 1910-2019, **b** Blowering Dam from 1955-2019 and **c** Tumut from 1883-2019; April-May precipitation at, **d** Burrinjuck Dam from 1910-2019, **e** Blowering Dam from 1955-2019 and, **f** Tumut from 1883-2019. Dashed lines indicate percentiles 5th and 95th (red); 10th and 90th (orange); 15th and 85th (light blue); 20th and 80th (brown); and 25th and 75th (dark blue).

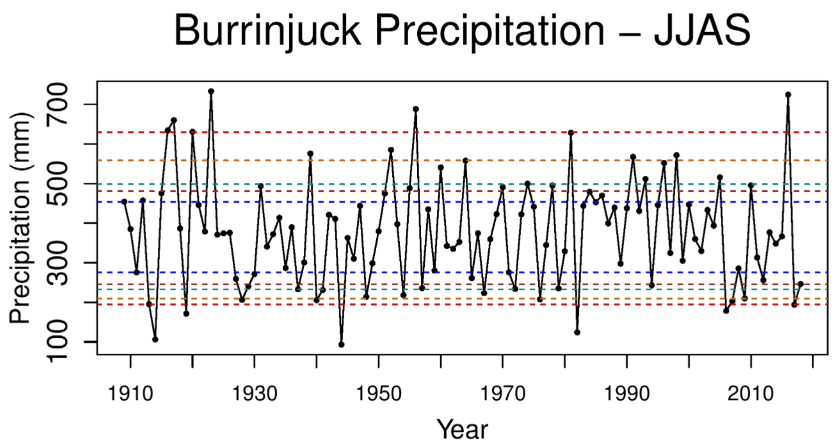


Fig.3(**a**)

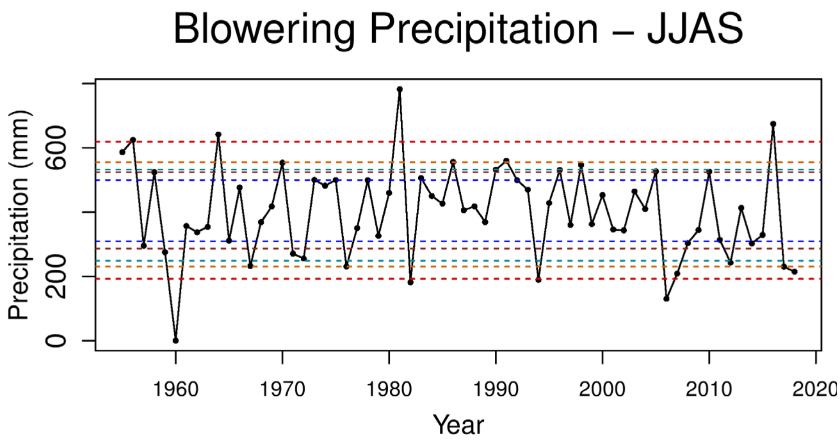


Fig.3(**b**)

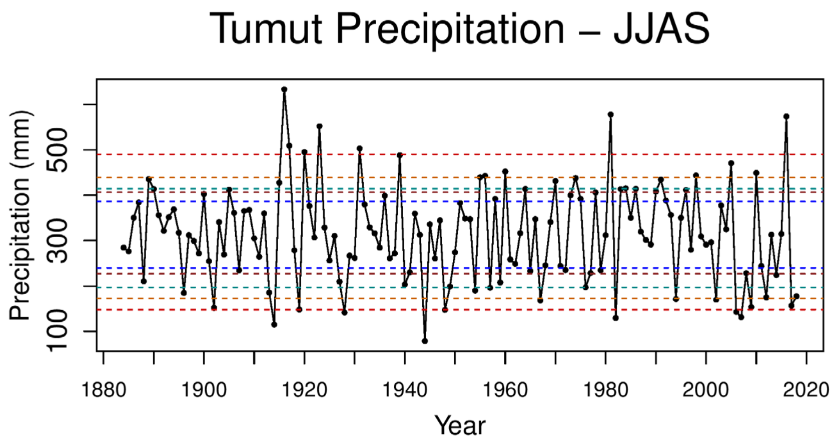


Fig.3(**c**)

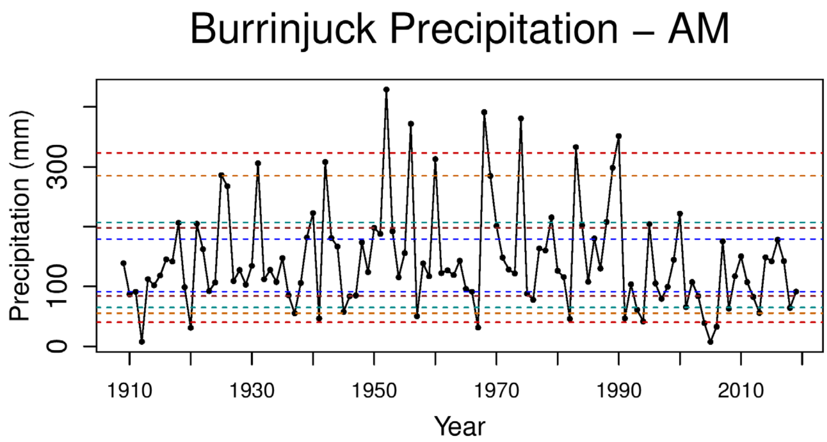


Fig.3(**d**)

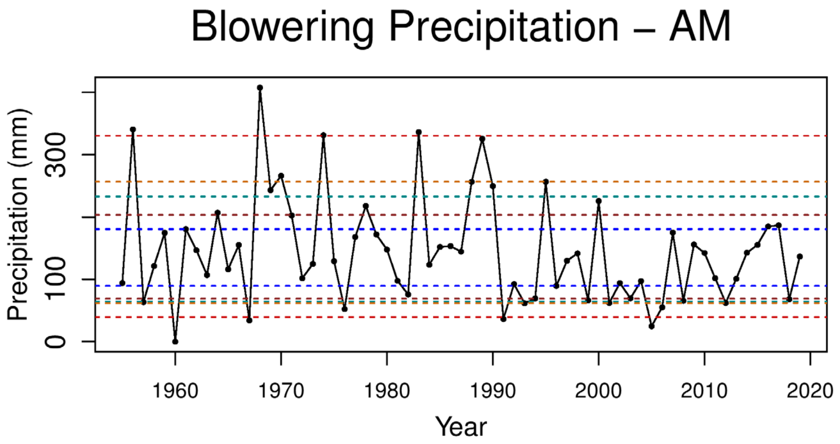


Fig.3(**e**)

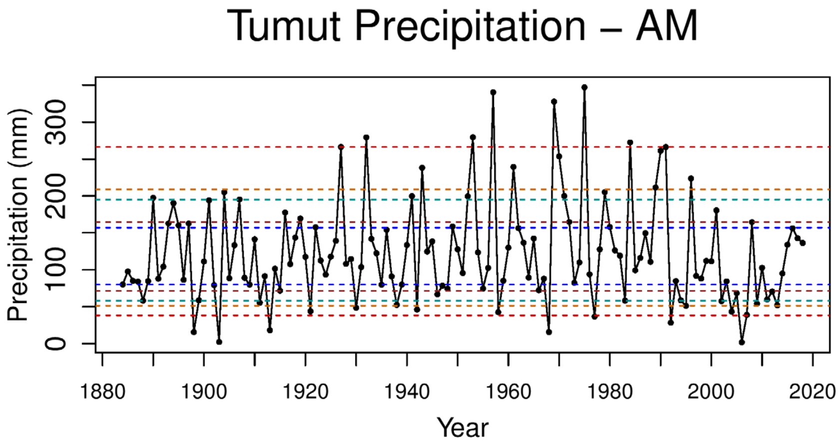


Fig.3(**f**)

All three locations, particularly Burrinjuck Dam and Blowering Dam, are exposed to topographically influenced precipitation from mid-latitude wet season (JJAS) cold frontal weather systems. For each location there has been no statistically significant trend after bootstrapping and box plotting the precipitation into 27-year intervals, for 1965-1991 and 1992-2018. While their JJAS means appear to have decreased slightly (not shown), no locations have observed statistically significant changes (Table **2**). For Tumut JJAS, precipitation was significantly more variable prior to 1965 (p-values = 0.045 and 0.0984; Table **2**). However, for all three locations, their mean late autumn (April-May) precipitation shows a decline in both the mean and variance in the 27-year boxplots between 1965-1991 and 1992-2018 (Figs.4**a, b, c**). Statistically, there is a highly significant decrease in both their means (p-values < 0.01; Table **2**), and their variances (p-values ~ 0.05; Table **2**). It is noteworthy that while neither the mean nor variance of Tumut April-May precipitation between 1884-1910 and 1992-2018 is significant, their variances are similarly very low (Fig.4**c**-right panel), owing to the very low rainfall that occurred during the Federation Drought (1895-1903).

	Precipitation				Inflows (% Volume)				Murrumbidgee River level			
Catchment Location	Apr-May		JJAS		Apr-May		JJAS		Apr-May		JJAS	
	mean	var.	mean	var.	mean	var.	mean	var.	mean	var.	mean	var.
Blowering Dam												
1965-1991 vs 1992-2018	0.007*	0.012*	0.202	0.978	----------	-------	----------	----------	---------	-------	--------	-------
1976-1997 vs 1998-2019	---------	---------	----------	-------	0.0348*	0.301	0.0018*	0.0714*	0.0346*	0.426	0.0024*	0.087*
Burrinjuck Dam												
1911-1937 vs 1992-2018	0.102	0.237	0.918	0.422	----------	-------	--------	---------	----------	-------	----------	-------
1938-1964 vs 1965-1991	0.772	0.644	0.846	0.424	0.145	0.093*	0.058*	0.352	0.357	0.268	0.094	0.605
1938-1964 vs 1992-2018	0.0034*	0.0486*	0.905	0.818	0.566	0.391	0.104	0.0708*	0.476	0.544	0.0706*	0.051*
1965-1991 vs 1992-2018	0.0024*	0.002*	0.761	0.635	0.0676*	0.517	0.003	0.328	0.148	0.606	0.0026*	0.115
Tumut												
1884-1910 vs 1938-1964	0.149	0.289	0.463	0.045*	----------	-------	---------	----------	----------	-------	----------	-------
1938-1964 vs 1965-1991	0.528	0.278	0.308	0.984	----------	-------	---------	----------	----------	-------	----------	-------
1884-1910 vs 1992-2018	0.285	0.46	0.353	0.008*	----------	-------	---------	----------	----------	-------	----------	-------
1965-1991 vs 1992-2018	0.0062*	0.0026*	0.227	0.505	----------	-------	---------	----------	----------	-------	----------	-------
Wagga Wagga												
1911-1937 vs 1938-1964	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.399	0.55
1911-1937 vs 1992-2018	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.0002*	0.013*
1938-1964 vs 1965-1991	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.374	0.275
1965-1991 vs 1992-2018	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.0044*	0.095*
Hay												
1911-1937 vs 1965-1991	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.19	0.683
1911-1937 vs 1992-2018	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.0068*	0.001*
1938-1964 vs 1965-1991	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.309	0.332
1965-1991 vs 1992-2018	----------	----------	----------	-------	----------	-------	----------	----------	----------	-------	0.236	0.005*

Table **2**. P-Values from permutation testing differences in interval means and variances for, April-May and JJAS precipitation Blowering Dam, Burrinjuck Dam, and Tumut; inflows into Blowering Dam and Burrinjuck Dam; Murrumbidgee River heights at Blowering Dam, Burrinjuck Dam, Wagga Wagga and Hay. Significant values (P < 0.10) are italicized with an asterisk. Note that the P-value for each variance test is calculated after one sample has had bias correction in the mean.

There is an apparent decrease in the mean and variance of JJAS Murrumbidgee River heights at Hay between the bootstrapped intervals 1938-1964 to 1965-1991 highlighted by their low p values (Table 2; figure not shown), which corresponded to a change from low to highly regulated river flow [10]. However, the apparent mean and variance decrease is not statistically significant, whereas the variance between the 27-year bootstrapped intervals 1965-1991 to 1992-2018 is highly significant (p-value ~ 0.005; Table **2**). The mean river height in this period for Hay (p = 0.236; Table 2) is not statistically significant most likely due to snow melt starting to reach Hay in September. Both Hay and Wagga Wagga river heights are significantly lower in both mean and variance from 1911-1937 to 1992-2018 owing to a high rainfall period 1911-1937 compared to the period 1992-2018 (p values = 0.0068, 0.001, respectively for Hay; 0.0002, 0.013, respectively for Wagga Wagga). For Wagga Wagga the decrease in both the mean and variance from 1965-1991 to 1992-2018 is highly significant (p-values ~ 0.0068 and 0.001, respectively; Table **2**). Importantly, the significant mean decrease at Wagga Wagga suggests that the cause is climate related with river water used for irrigation not a major contributor since irrigation occurs downstream between Wagga Wagga and Hay. There is no significant change in October-March precipitation mean or variance from 1965-1991 to 1992-2018 for the three catchment rainfall locations (p-values not shown).

Fig. **4** **Box and whisker plots representing mean and variance of April-May catchment precipitation.**

Bootstrapped 27-year intervals of mean (left panel) and variance (right panel) of April-May precipitation for, **a** Blowering Dam, **b** Burrinjuck Dam, **c** Tumut.

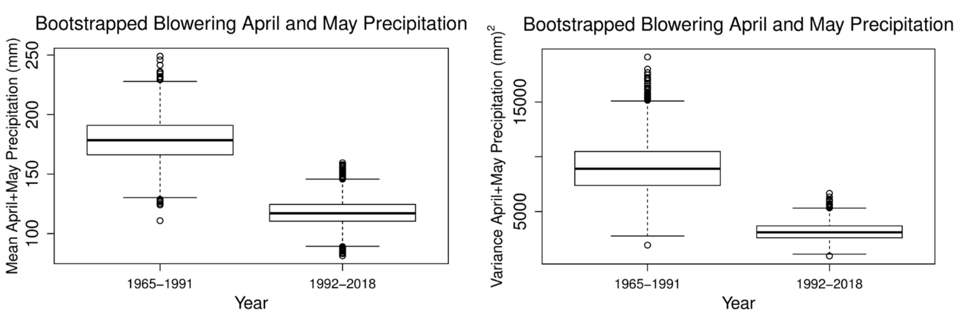


Fig.4**a**

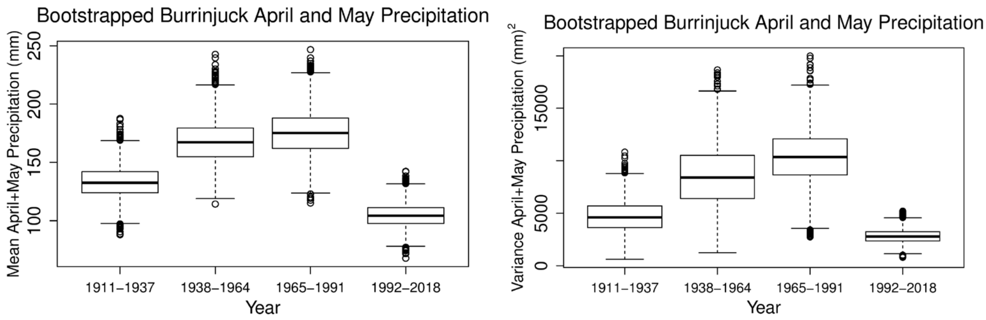


Fig.4**b**

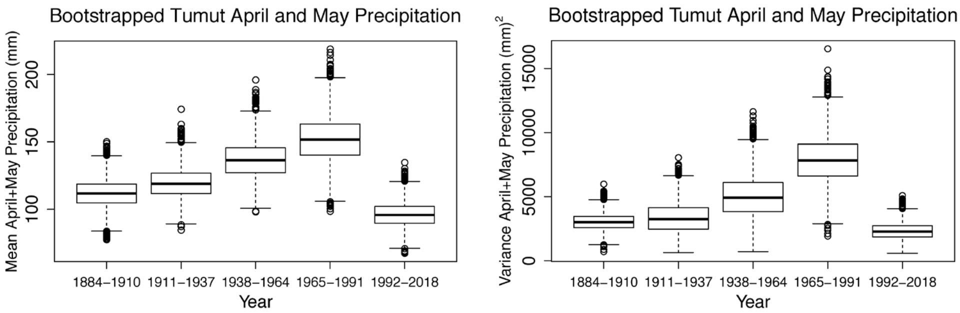


Fig.4**c**

The mean JJA precipitation wavelets for Burrinjuck Dam, Blowering Dam, Tumut and the mean JJA weekly Murrumbidgee River heights at Hay (Figs.5**a-d**), respectively, exhibit a significant ENSO-like periodicity of approximately 2-7 years, which mostly weakens in the three precipitation locations from the 1990s, and, in the case of the river heights at Hay, disappears after the 1990s. A possible reason for the weakening ENSO-like periodicity is that the nonlinear ENSO amplitude has weakened (less strong El Niños) in response to global warming [14,15].

Fig. **5** **Wavelets of JJAS precipitation and river height.** JJAS wavelets and global power spectra of precipitation for, **a** Burrinjuck Dam, **b** Blowering Dam, **c** Tumut; and **d** JJAS mean weekly Murrumbidgee river heights at Hay. Power significance is indicated by areas within thick black or red contours the 5% or 10% confidence levels, respectively.

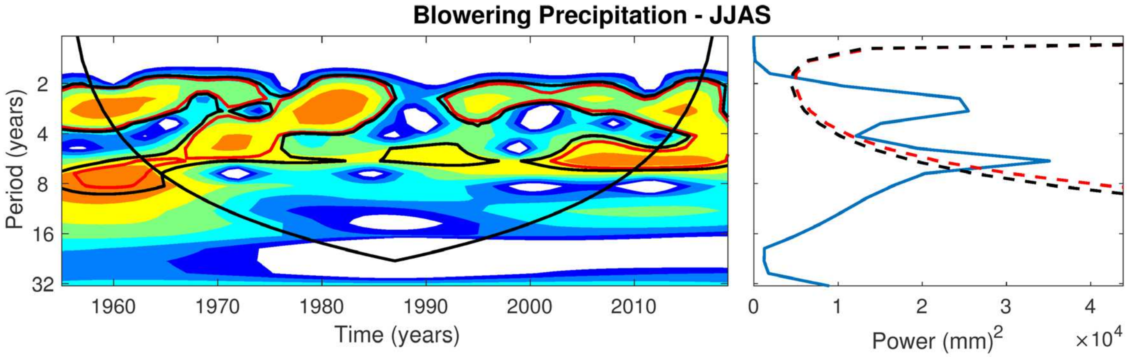


Fig.5**a**

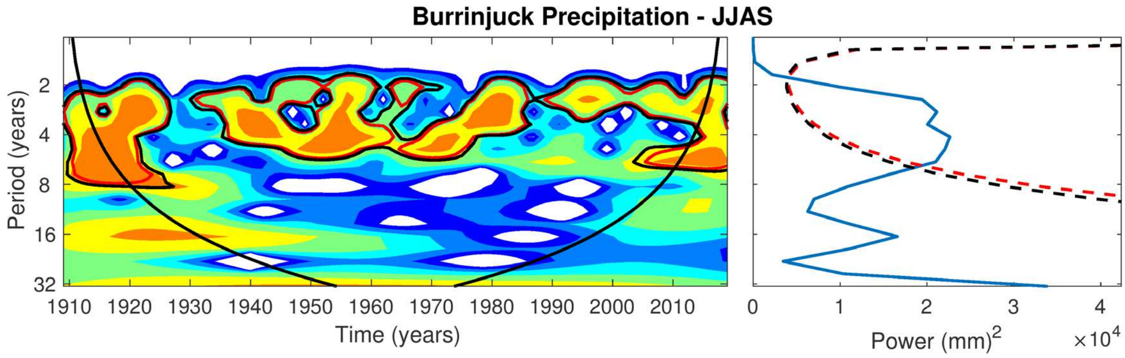


Fig.5**b**

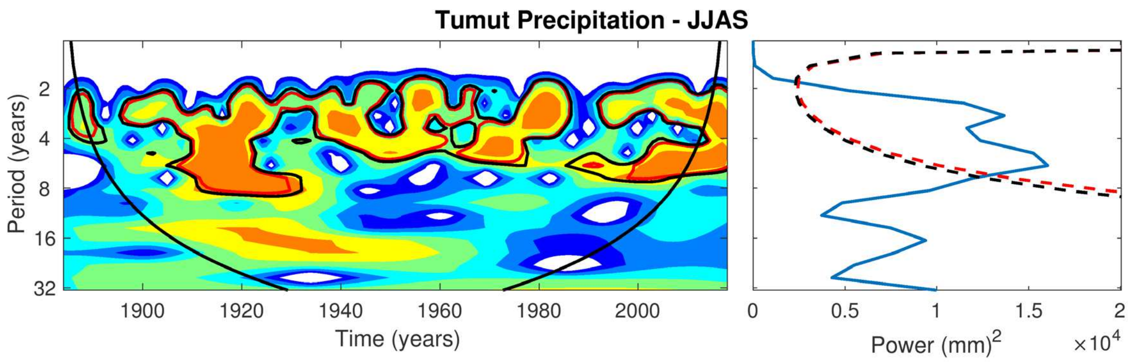


Fig.5**c**

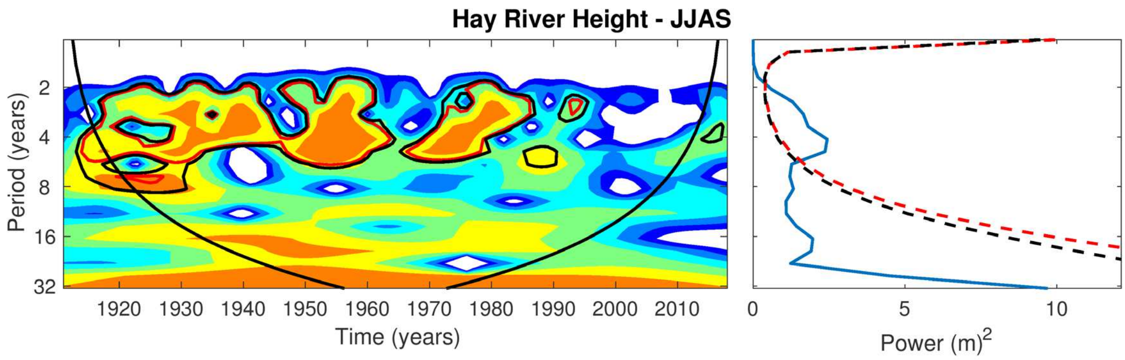


Fig.5**d**

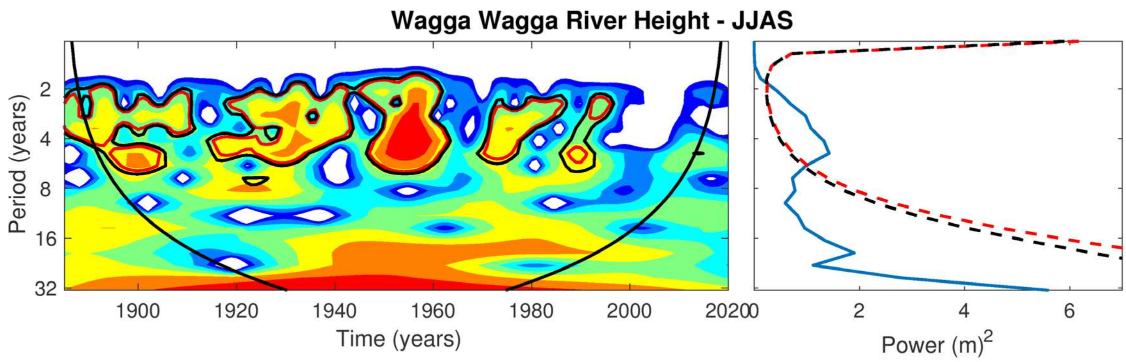


Fig.5**e**

There is clear periodicity of 2-7 years resembling the ENSO time scale at the three catchment precipitation locations (Figs. 5**a, b, c). However**, the ENSO signal disappears from the late 1990s for the downstream river heights at Wagga Wagga and Hay (Figs. 5**d, e**).

There is a clear increasing trend in JJAS mean TMax and TMin at both Burrinjuck Dam and Cabramurra (located close to Blowering Dam), revealed by their 27-year interval boxplots (Figs.6**a**, **b**, **c**, **d**), and consistent with the known global warming signal since 1950 [16] which has accelerated in the last 50 years [17,18] and particularly since the mid-1990s in Australia [12]. This is confirmed by the very high levels of significance (all p-values are < 0.05) for the difference in TMax and TMin means between the intervals 1965-1991 to 1992-2018 (Table **3**).

27-year Bootstrapped Interval	**Statistic**	**JJAS Burrinjuck Dam P-values**		**JJAS Cabramurra P-values**	
		TMax	TMin	TMax	TMin
1965-1991 vs 1992-2018	Mean	*0**	*0.0452**	*0**	*0.002**
	Variance	0.849	0.926	0.613	0.647

Table 3 P-values from permutation testing differences in JJAS mean maximum (TMax) and mean minimum (TMin) temperature (0C) relative to 27-year bootstrapped intervals for Burrinjuck Dam and Cabramurra (nearby surrogate for Blowering Dam). Significant values (P < 0.05) are italicized with an asterisk.

Fig. **6** **Box and whisker plots of mean temperature in the Murrumbidgee River catchment.**

a Bootstrapped 27-year interval Burrinjuck JJA mean TMax (^{0}C), **b** bootstrapped 27-year interval Cabramurra JJA mean TMax (^{0}C), **c** bootstrapped 27-year interval Burrinjuck Dam JJA mean TMin (^{0}C), and **d** bootstrapped 27-year interval Cabramurra JJA mean TMin (^{0}C).

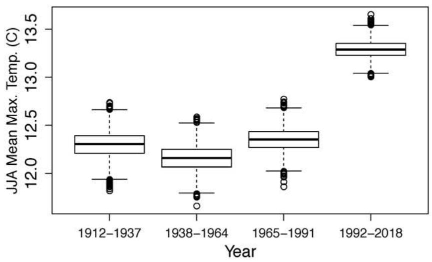


Fig.6**a**

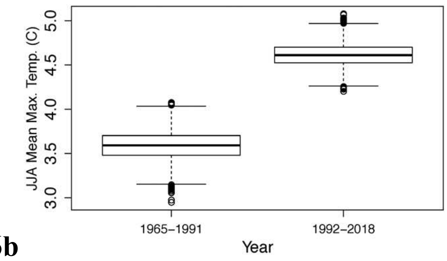


Fig.6**b**

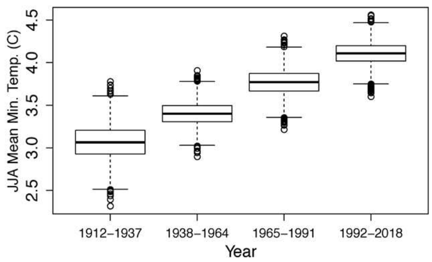


Fig.6**c**

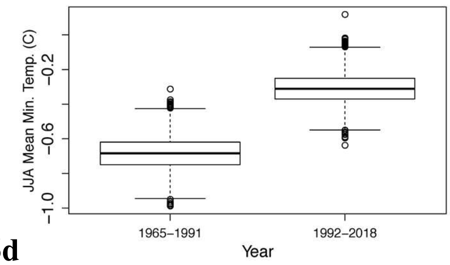


Fig.6**d**

Cabramurra (altitude 1482 m) shows a highly significant increase in TMin between the two bootstrapped intervals in contrast to a non-significant increase at Burrinjuck Dam (altitude 390 m). With such a large difference in altitude between the two locations, it is possible that other factors may be involved, including local differences in meteorological variables such as wind speed/wind direction and/or cloud cover.

3. Discussion

The JJAS river heights at Hay (Fig.2**a**) have clearly reduced variability over the 27-year period 1965-1991 compared with 1992-2018 (p-value = 0.005, Table **2**). Despite the apparent decrease in the mean and variance of JJAS Murrumbidgee River heights at Hay from the 1960s, as shown by the low p values (0.309, 0.332), respectively, for the 27-year intervals 1938-1964 to 1965-1991 (Table **2**), the decrease is not statistically significant. However, the decrease is consistent with the suggestion that a change point occurred from the late 1950s between unregulated to regulated flow at Hay [10].

While the mean JJAS precipitation of the three catchment locations of Burrinjuck Dam, Blowering Dam and Tumut indicate a slight decrease in percentile extremes from the 1990s, with 2016 (due to September) only above the 95th percentile (Fig.**3**), they exhibit no significant change in mean or variance based on the bootstrapped intervals JJAS 1964-1991 to 1992-2018. Consequently, the question arises of why the significant decrease in mean and variance of the JJAS Murrumbidgee River height at Wagga Wagga and in variance at Hay does not match a similar significant decrease in mean or variance of JJAS catchment rainfall. A rainfall decline in recent decades was found to be most pronounced in late autumn [19,20] and that without sufficient autumn rainfall to moisten catchments in southern Australia, follow-up rainfall in winter cannot be efficiently converted to run-off and catchment inflows [21]. There have been statistically significant decreases in April-May mean precipitation at the catchment locations of Blowering Dam, Burrinjuck Dam and Tumut from 1964-1991 to 1992-2018 and also for the mean inflows to the two Dams (Table **2**). Furthermore, as a result of the Millennium Drought (1997-2009), modelling experiments indicate that, starting from very dry conditions, the run-off response to rainfall only will return to the normal pre-drought conditions after about 10-20 years of average rainfall [22]. Therefore, the significant decrease in variance of Murrumbidgee River heights at Hay and in mean and variance at

Wagga Wagga, is most likely due to the April-May reduced dam inflows and precipitation, and from average JJAS catchment precipitation since 1991. Any role played by water extraction for irrigation between Wagga Wagga and Hay, where irrigation is concentrated, is likely to be small owing to the highly significant mean river height reduction at Wagga Wagga which is upstream from Hay. In a different southern MDB catchment study of the Millennium Drought 1997-2000, factors for a disproportionate reduction in rainfall run-off were reduced mean annual rainfall, less interannual variability of rainfall, changed seasonality of rainfall and lastly increased potential evaporation [23]. However, the last two factors mentioned have since become well established in the last decade with reference to the work in this study. It was suggested that a rainfall reduction alone does not explain the observed inflow reduction trend [24]. Even after a major rain event, the soils are so dry that they absorb more water than before the rain event, and less reaches the dams and rivers than on a wet catchment. In the last three decades it is unknown what the effect on run-off into dams and the Murrumbidgee river has been in JJAS from major rain events because, apart from August-September 2016, there have been no major catchment inflows since 1991 (Figs. 2**c**, **d**). In June and July 1991 there was a series of rain-producing cut-off low pressure systems over inland NSW and the adjacent coast influencing the catchment, interspersed with persistent, precipitation-producing frontal systems embedded in the westerly airflow during July and August. Rain producing inland cut-off low pressure systems over southeast Australia are the main influence on enhancing JJAS rainfall totals [7].

Decreased JJAS rainfall in continental southeast Australia has been evident for at least the last two decades, as anticipated by climate scientists. The naturally periodic La Niña phenomenon provided spring and summer rainfall during much of 2010 to 2012, which ended the Millennium Drought (1997-2009). The only other recent widespread significant rainfall in southeast continental Australia was in August-September 2016 due to a negative phase of the Indian Ocean Dipole (IOD). A negative IOD phase typically is associated with wetter than normal spring conditions for southeast Australia [6,7].

The MDB plan, introduced from 2013 [25] provided, for the first time, regulated allocations to environmental flows for ecosystem sustainability of rivers in southeast Australia such as the Murrumbidgee. However, the plan requires that each year on 1 July a fixed amount of water is locked in for future consumption, split three ways with the highest priority for human consumption and irrigation for permanent crops (e.g., fruit trees and nuts). The remaining allocations are split between non-permanent crops (e.g., cotton, rice) and environmental flow. A problem is that the forecast inflows upon which the allocations are based are the minimum inflows experienced in the 120 years up to the end of the 20th century. However, as shown, even lower inflows have been experienced in the past two decades. It is not surprising that there is a significant decrease in the JJAS variance of the Murrumbidgee River height at Hay (p-value = 0.005) and both the JJAS mean and variance at Wagga Wagga from the periods 1965-1991 to 1992-2018 (mean p-value = 0.0044, variance p-value = 0.095; Table **2**) since this period corresponds with the significantly reduced mean April-May catchment precipitation and mean April-May dam inflows. The fact that there has been no significant change in the mean Murrumbidgee River height since 1991 is an indication that there has been a lack of major April-September rain events. The lack of significant catchment rainfall events from April to September is the reason for the reduction in the mean and variance of river heights at Wagga Wagga. Floods in April-May are rare along the Murrumbidgee River and the six years since 1874 in which April-May floods occurred at Hay prior to 1991 (Table 1**c**), were dominated by precipitation that occurred as a result of mid-latitude interaction with either tropical or subtropical moisture, whereas the last flood that occurred in March 2012, was the result of a rain-producing tropical low pressure system over central Australia. Moreover, given the significant decline in April-May, Murrumbidgee catchment rainfall, JJAS run-off into the dams and Murrumbidgee river height at Wagga Wagga since 1991, the implication for water allocations of irrigated agriculture downstream from Wagga Wagga and for flood plain environmental flows required for sustainable wetlands downstream from Hay, will continue to be a problem.

4. Conclusions

Both the mean and variability of JJAS river height data at Wagga Wagga and the variability of JJAS river height data at Hay on the Murrumbidgee River in the MDB have decreased significantly since the early 1990s, owing to one only July minor flood level exceedance at Wagga since 1995 and one only September flood level exceedance in 2016. In sharp contrast, the flood level at both Hay and Wagga Wagga was exceeded every few years in JJAS from 1874 to the early 1990s. There has been no new regulatory infrastructure built upstream from Hay since the 1960s. Bootstrapped data box plots for 27-year periods covering JJAS months exhibit no statistically significant decline in the mean catchment rainfall at locations including Burrinjuck Dam, Blowering Dam and Tumut for the period 1992-2018, to match the statistically significant lower mean and variability in river heights at Wagga Wagga or the variability further downstream at Hay. Water extraction for irrigation is unlikely to be a major cause between Wagga Wagga and Hay because the river height had already decreased significantly at Wagga

Wagga. However, there is a *highly significant* decline in late autumn (April-May) mean and variance of catchment rainfall between the periods 1965-1991 and 1992-2018. Insufficient late autumn moistening of the dams' catchment areas reduces run-off during JJAS months even when the mean JJAS rainfall has not declined significantly. A further contributing factor is likely to be the observed mean temperature increase during April-September, thereby increasing evapotranspiration, and reducing run-off into rivers and dams. The contributions of decreased April-May rainfall, decreased April-May and JJAS dam inflows, and increased mean temperatures, which represents the accelerated global warming signal since the 1990s, all reduced catchment area run-off. Future work therefore is planned to address the high priority of searching for attributes, to assist in identifying and understanding the role of the key meteorological drivers, especially those related to the April-May decrease in catchment rainfall.

Regardless of the mandated environmental flows in the last decade and the annually determined sustainable extraction limits on irrigation, water availability from the Murrumbidgee River at Wagga Wagga and Hay over recent decades continues to be affected by changes in catchment rainfall and run-off. In this study the decreased river heights at Wagga Wagga and Hay in the 27-year period, 1992-2018, occurred as a result of a change in seasonality of rainfall and increase in potential evaporation during the current accelerated period of global warming as described above, suggesting the need for a new review of water availability and sustainability in the Murrumbidgee River system and also of other river systems in the southern MDB.

5. Methods

The available data sets were Murrumbidgee River heights at Hay in the southern

MDB, monthly precipitation, and maximum and minimum screen temperatures at four stations at Blowering Dam, Burrinjuck Dam, Tumut and Cabramurra. The aims of the Methodology were to identify trends in the data sets and to use wavelet analysis to identify possible climate drivers of the trends.

Trend Analysis

The time series data were first plotted with their percentiles to obtain an overview of any trends which might be present in the data. Each data set was grouped into two equal 27-year periods, by taking account of the accelerated global warming signal from the mid-1990s and the archived length of each variable. Hence, the ending period was 1992-2018, and bootstrap resampling was applied with 5000 resamples. Box plots of the mean and variance of the bootstrapped intervals were created which provides a deeper understanding of any trends which might be present in the data. Permutation testing was applied with replacement to test for statistical significance in any apparent changes between two 27-year periods.

Wavelet Analysis

Wavelet analysis [26,27] was applied to each time series to detect potential climate drivers such as the El-Niño Southern Oscillation. This approach provides both the local wavelet power spectrum (e.g., Fig.6**a**, left panel) and the global power spectrum (e.g., Fig.6**a**, right panel). The local wavelet power spectrum shows how the influence of climate drivers changes over time, while the global power spectrum provides an overview of which drivers are dominant in the time series. In this study, we used the Morlet wavelet as the mother wavelet.

6. Data availability

The rainfall and temperature station datasets in this study are available online at the Australian Bureau of Meteorology. The digitized weekly river height data are available at: - **https://doi.org/10.5281/zenodo.3779490**

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Author contributions: M. Speer conceived much of the study and wrote the first draft; L. Leslie conceived some of the study and assisted in the writing of the manuscript; J. Hartigan provided many of the figures and assisted in reviewing the manuscript; S. MacNamara assisted in reviewing the manuscript.

Competing interests: The authors declare no competing interests (neither financial nor of other forms).

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Table Legends

Table 1**a** Table showing wet season (JJAS) monthly maximum weekly Murrumbidgee River heights at Hay (southern MDB) that exceed/equal flood level (6.7 m), and seasonal count, in the 125 years 1874-2018

Table 1**b** Table showing spring (SON) weekly maximum Murrumbidgee river heights at Hay (southern MDB) that exceed flood level (6.7 m), and seasonal count, in the 125 years 1874-2018. Also included is the strength of the ENSO signal as determined by the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/enso/lnlist/index.shtml). Note the neutral association with flood heights since the mid-1970s.

Table 1**c** Table showing autumn (MAM) monthly maximum weekly Murrumbidgee River heights at Hay (southern MDB) that exceed flood level (6.7 m), and seasonal count in the 126 years 1874-2019. (http://www.bom.gov.gov.au/climate/enso/lnlist/index.shtml). Note the neutral ENSO association with flood heights since the mid-1970s.

Table **2** P-values from permutation testing differences in interval means and variances for, April-May and JJAS precipitation for Blowering Dam, Burrinjuck Dam, and Tumut; inflows into Blowering Dam and Burrinjuck Dam; Murrumbidgee River heights at Blowering Dam, Burrinjuck Dam, Wagga Wagga and Hay. Significant values ($p < 0.10$) are italicized with an asterisk. Note that the p-value for each variance test is calculated after one sample has had bias correction in the mean.

Figure Legends

Figure **1** **The Murrumbidgee River and catchment area.**

M = Murrumbidgee Irrigation Area (hatched black), C = Colleambally Irrigation Area (hatched black). Snowy Mountains Hydroelectric Scheme (hatched blue). The inset identifies the catchment location in southeast Australia.

Figure **2** **Murrumbidgee river heights at Hay and Wagga Wagga; annual inflows at Blowering Dam and Burrinjuck Dam.**

a Murrumbidgee river heights (m) at the Hay town gauge and Hay PID for (April-September) 1874 to 2019. There are concurrent readings at the two locations from 1968 to 1982. The first April height every 5 years is indicated. The river flood level is marked (dashed black line) at 6.7 m. Six maximum April-September weekly river heights exceeding the flood level of 6.7 m, including the most recent (31 July 1991), are designated, **b** Murrumbidgee river heights at Wagga Wagga (April to September) 1885-2019. The minor flood level is marked (dashed black line) at 7.3 m. The most recent minor flood levels reached since 1991 are marked, **c** Annual volume storage (%) for Blowering Dam indicating precipitation inflows from 1975-2019, **d** Annual volume storage (%) for Burrinjuck Dam indicating precipitation inflows from 1913-2019.

Figure **3** **Precipitation time series in the Murrumbidgee River catchment area.**

JJAS precipitation at, **a** Burrinjuck Dam from 1910-2019, **b** Blowering Dam from 1955-2019 and **c** Tumut from 1883-2019; April-May precipitation at, **d** Burrinjuck Dam from 1910-2019, **e** Blowering Dam from 1955-2019 and, **f** Tumut from 1883-2019. Dashed lines indicate percentiles 5th and 95th (red); 10th and 90th (orange); 15th and 85th (light blue); 20th and 80th (brown); and 25th and 75th (dark blue).

Figure **4** **Boxwhisker plots representing mean and variance of April-May Murrumbidgee catchment precipitation.**

Bootstrapped 27-year intervals of mean (left panel) and variance (right panel) of April-May precipitation for, a Blowering Dam, b Burrinjuck Dam, c Tumut.

Figure **5** **Wavelets of JJAS precipitation and river height.**

JJAS wavelets and global power spectra of precipitation for, **a** Burrinjuck Dam, **b** Blowering Dam, **c** Tumut; and **d** JJAS mean weekly Murrumbidgee river heights at Hay. Power significance is indicated by areas within thick black or red contours the 5% or 10% confidence levels, respectively.

Figure **6** **Box plots of mean temperature in the Murrumbidgee River catchment.**

a Bootstrapped 27-year interval Burrinjuck JJA mean TMax (^{0}C), **b** bootstrapped 27-year interval Cabramurra JJA mean TMax (^{0}C), **c** bootstrapped 27-year interval Burrinjuck Dam JJA mean TMin (^{0}C), and **d** bootstrapped 27-year interval Cabramurra JJA mean TMin (^{0}C).

Figures

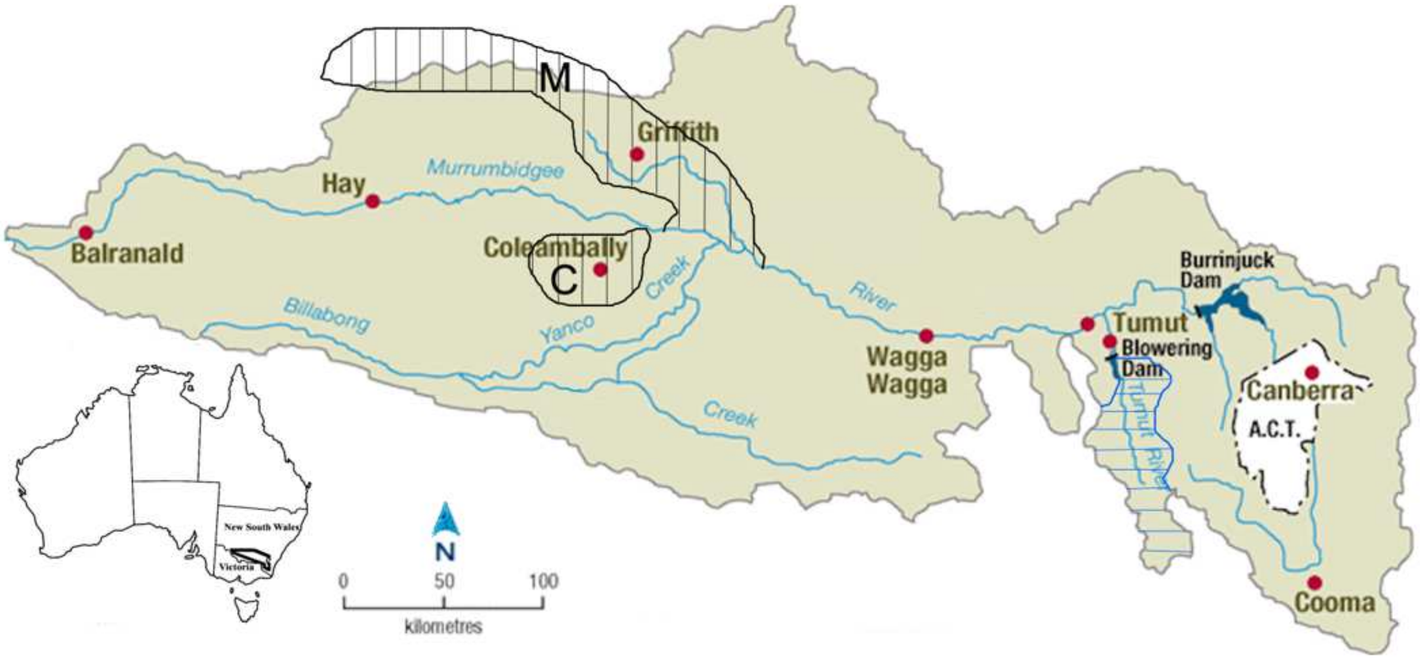

Figure 1

The Murrumbidgee River and catchment area. M = Murrumbidgee Irrigation Area (hatched black), C = Colleambally Irrigation Area (hatched black). Snowy Mountains Hydroelectric Scheme (hatched blue). The inset identifies the catchment location in southeast Australia.

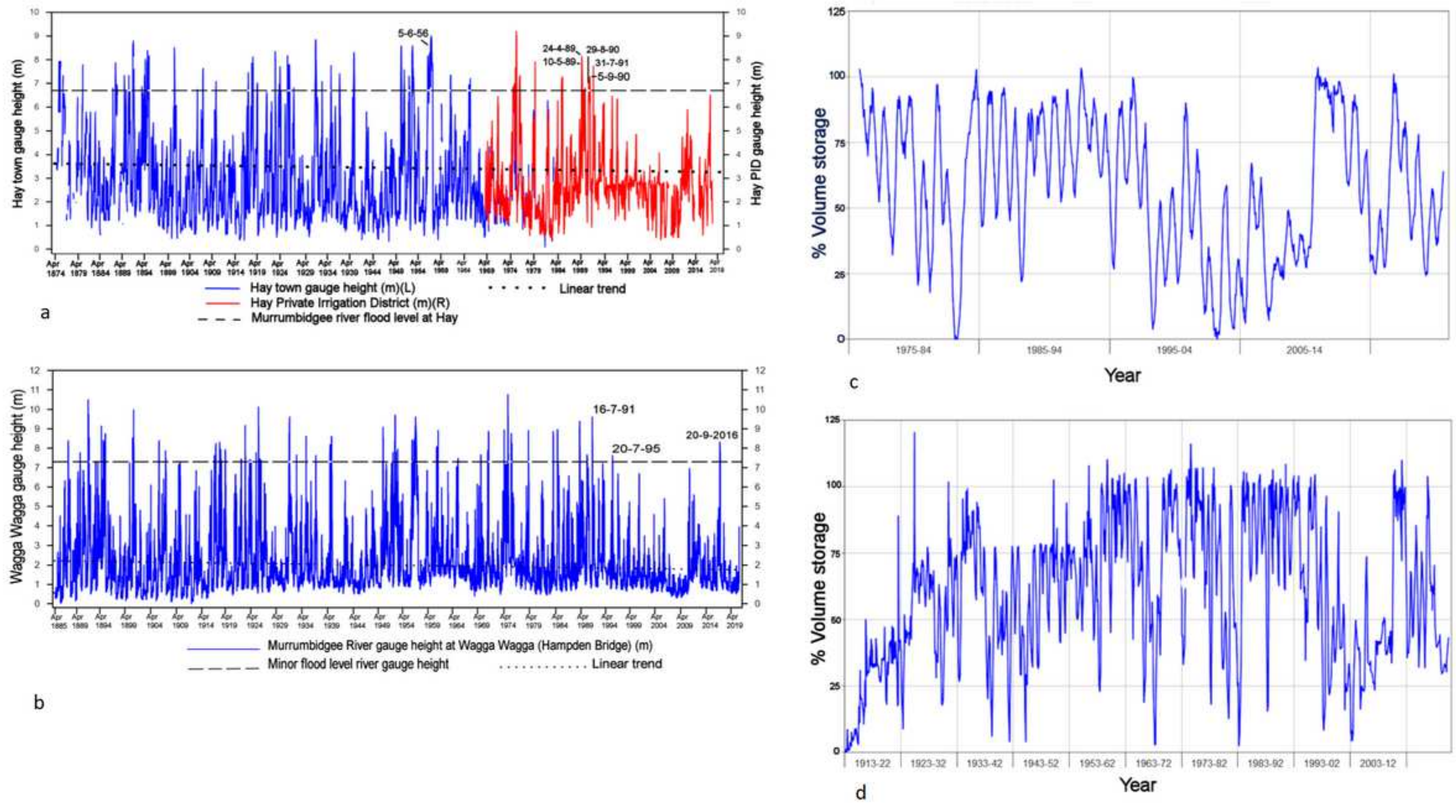

Figure 2

a. Murrumbidgee river heights (m) at the Hay town gauge and Hay PID for (April-September) 1874 to 2019. There are concurrent readings at the two locations from 1968 to 1982. The first April height every 5 years is indicated. The river flood level is marked (dashed black line) at 6.7 m. Six maximum April-September weekly river heights exceeding the flood level of 6.7 m, including the most recent (31 July 1991), are designated. b. Murrumbidgee river heights at Wagga Wagga (April to September) 1885-2019. The minor flood level is marked (dashed black line) at 7.3 m. The most recent minor flood levels reached since 1991 are marked. c. Annual volume storage (%) for Blowering Dam indicating precipitation inflows from 1975-2019. d. Annual volume storage (%) for Burrinjuck Dam indicating precipitation inflows from 1913-2019.

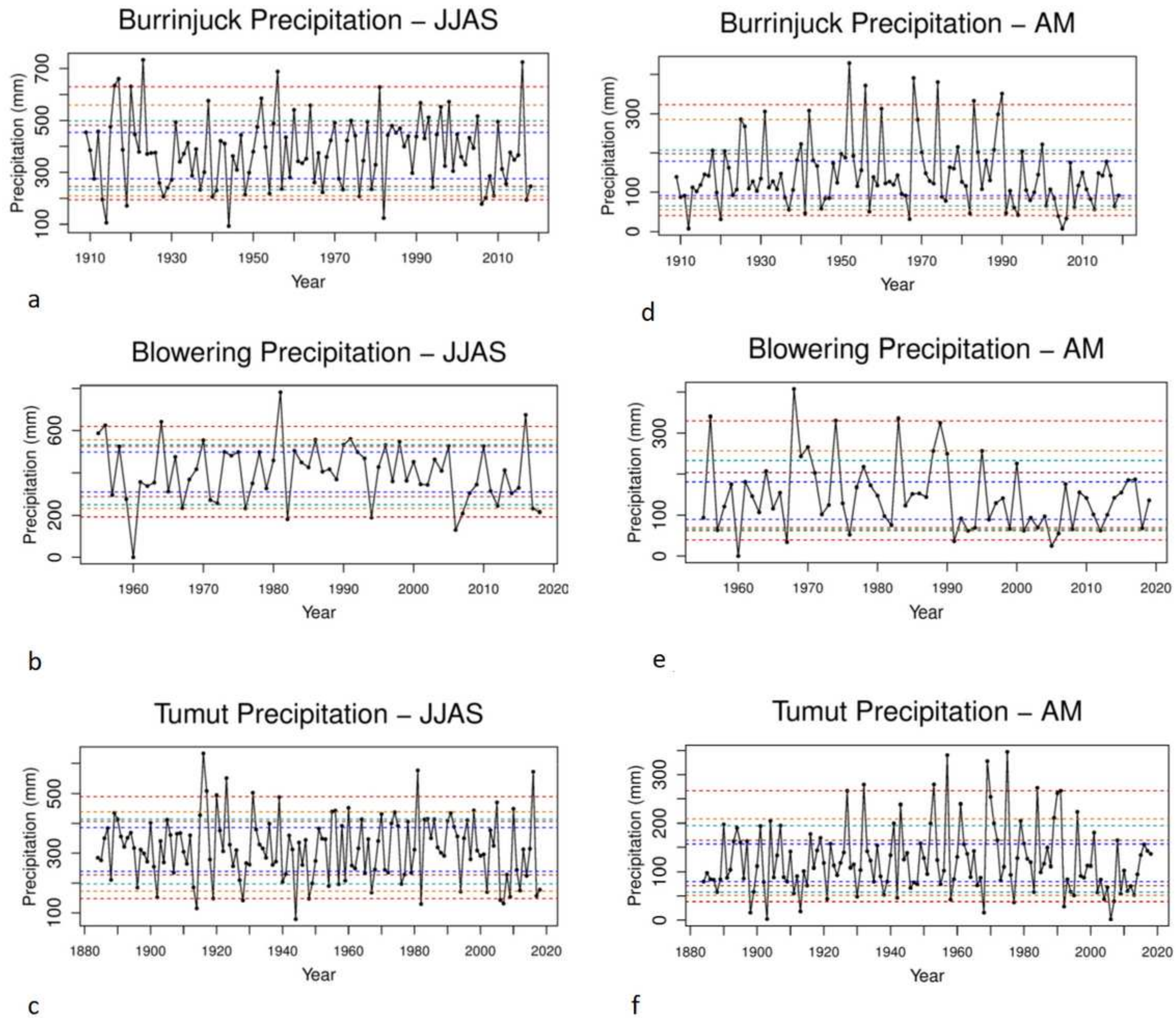

Figure 3

Precipitation time series in the Murrumbidgee River catchment area. JJAS precipitation at, a Burrinjuck Dam from 1910-2019, b Blowering Dam from 1955-2019 and c Tumut from 1883-2019; April-May precipitation at, d Burrinjuck Dam from 1910-2019, e Blowering Dam from 1955-2019 and, f Tumut from 1883-2019. Dashed lines indicate percentiles 5th and 95th (red); 10th and 90th (orange); 15th and 85th (light blue); 20th and 80th (brown); and 25th and 75th (dark blue).

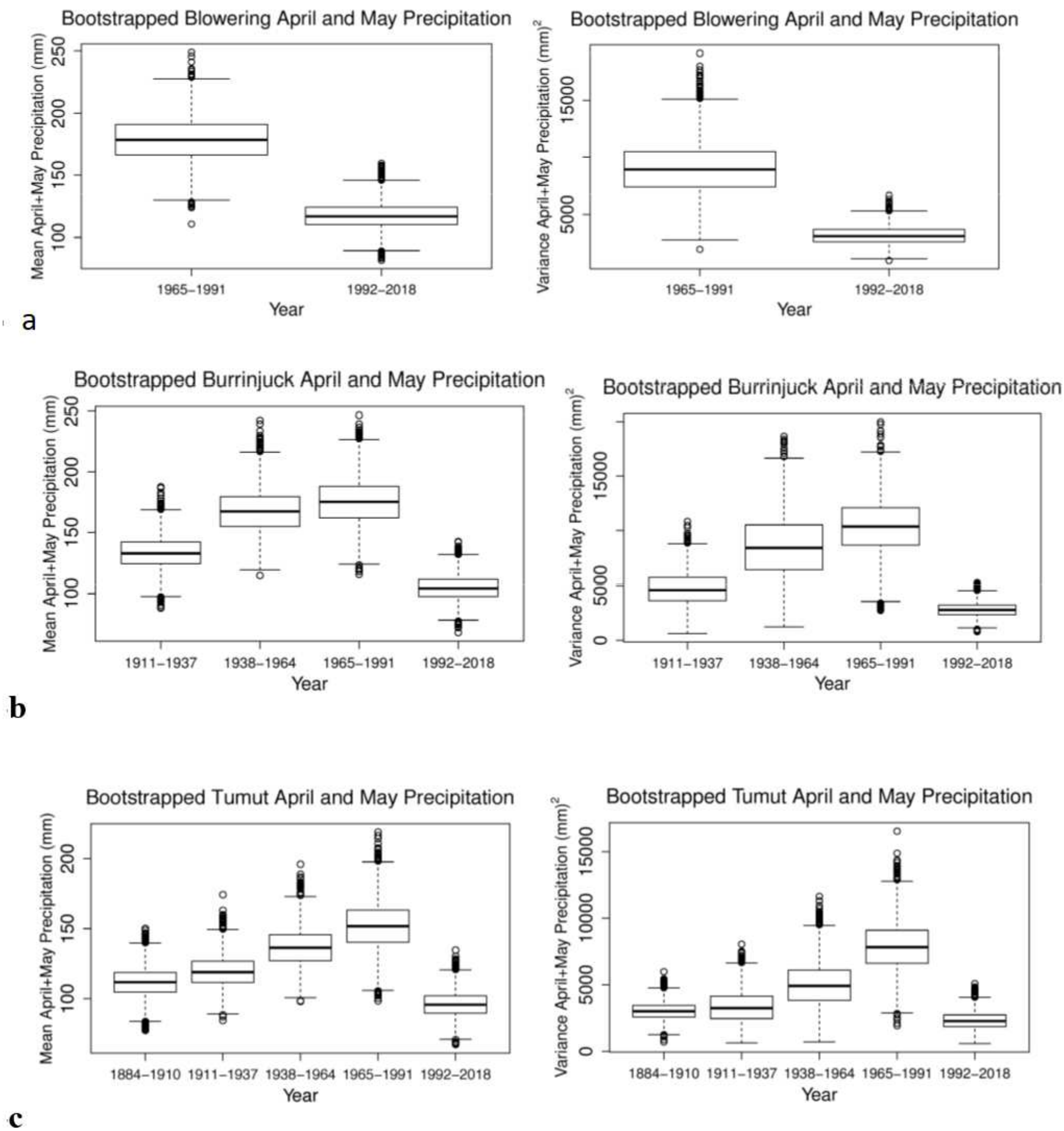

Figure 4

Box and whisker plots representing mean and variance of April-May catchment precipitation. Bootstrapped 27-year intervals of mean (left panel) and variance (right panel) of April-May precipitation for, a Blowering Dam, b Burrinjuck Dam, c Tumut.

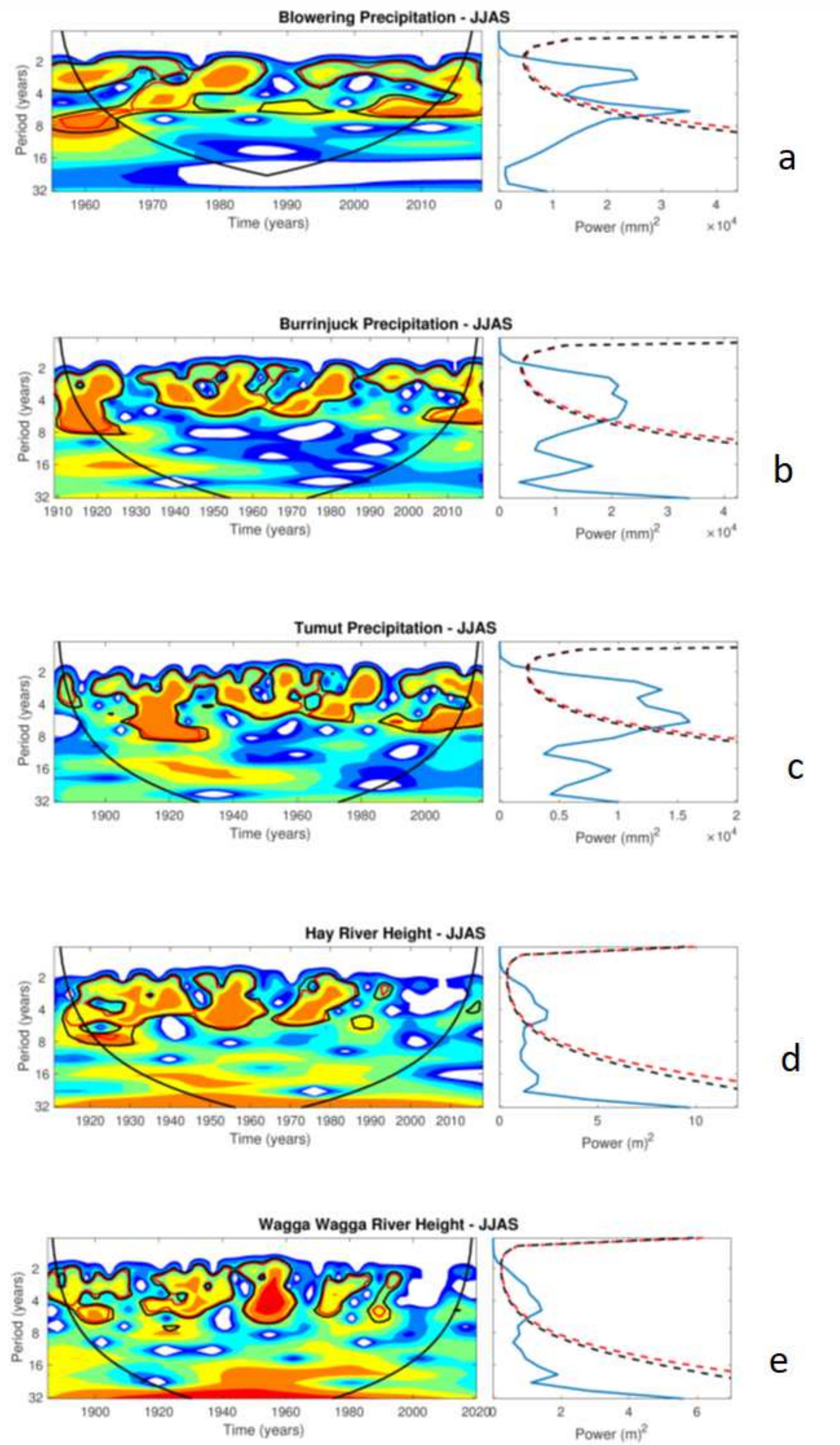

Figure 5

Wavelets of JJAS precipitation and river height. JJAS wavelets and global power spectra of precipitation for, a Burrinjuck Dam, b Blowering Dam, c Tumut; and d JJAS mean weekly Murrumbidgee river heights at Hay. Power significance is indicated by areas within thick black or red contours the 5% or 10% confidence levels, respectively.

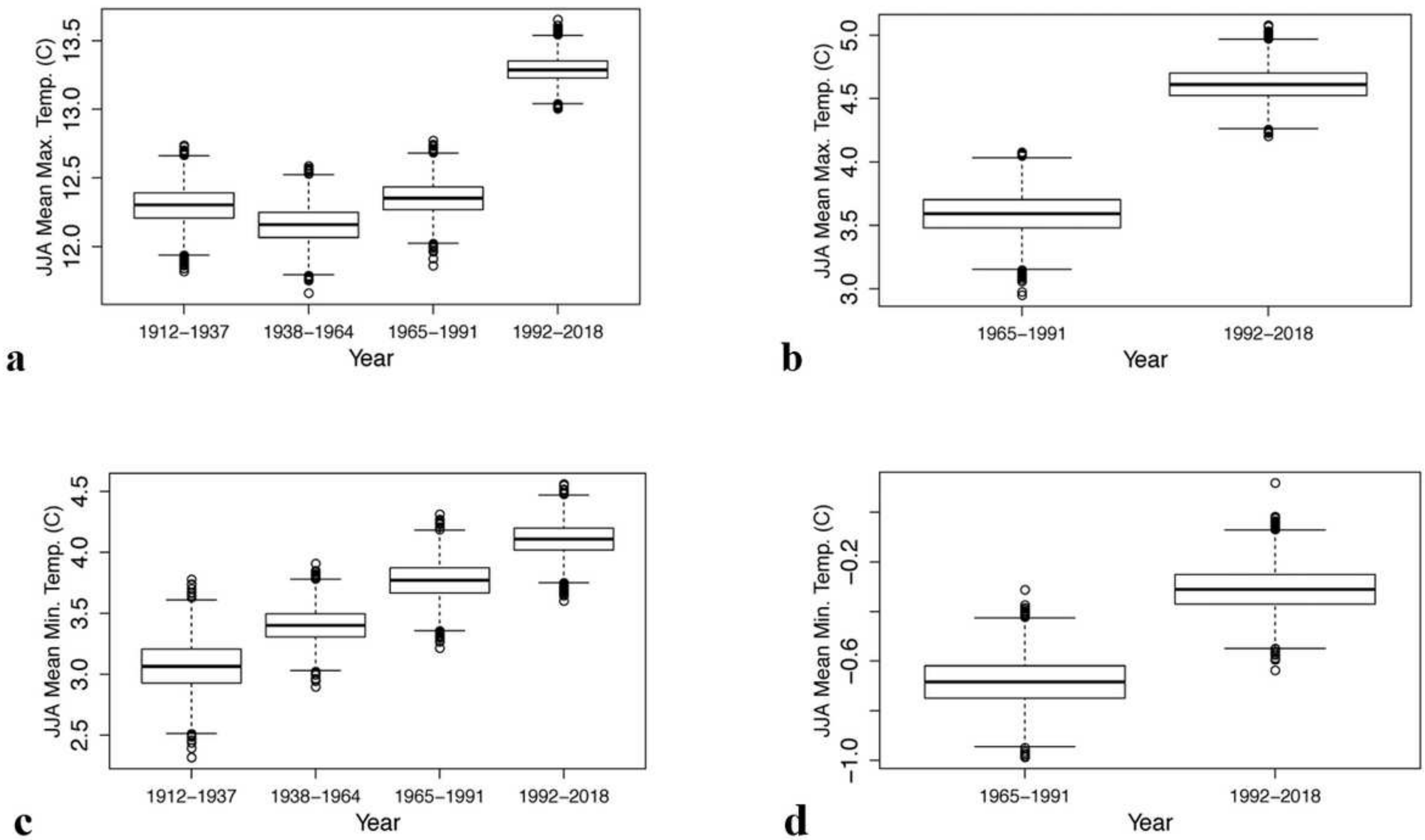

Figure 6

Box and whisker plots of mean temperature in the Murrumbidgee River catchment. a Bootstrapped 27-year interval Burrinjuck JJA mean TMax (0C), b bootstrapped 27-year interval Cabramurra JJA mean TMax (0C), c bootstrapped 27-year interval Burrinjuck Dam JJA mean TMin (0C), and d bootstrapped 27-year interval Cabramurra JJA mean TMin (0C).